

The Development and Characterization of a Novel Instrument for Measuring Vaginal Closing
Force: EVE the Elevated-Surface Vaginal Elastometer

By

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Submitted to the graduate degree program in Mechanical Engineering and the Graduate Faculty
of the University of Kansas in partial fulfillment of the requirements for the degree of Doctor of
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Abstract

In 2012 there were an estimated 35.3 million people living with HIV [1]. Microbicides address an important gap in HIV prevention for vulnerable groups unable to implement other prevention strategies [2]. Models are being developed in our lab to optimize microbicide delivery vehicle properties so that the microbicide will coat the entire vaginal epithelial surface, stay in place for the duration of possible exposure, and coat thick enough to deliver sufficient active ingredient to prevent infection.

A complete model should incorporate vaginal closing force to understand how a delivery vehicle will be distributed and retained in the vagina. However, the physiological magnitudes of vaginal closing forces are not known. Several previous methods have been utilized to determine an appropriate magnitude of one or several components, but they all neglect important features to measure the forces relevant to microbicide delivery vehicle spreading. An ideal measurement device to measure all aspects of vaginal closing force should: be controllable, operate in a variety of modes, have a constant contact area, be able to measure at different places along the vaginal axis and in different directions, be modular, be convenient and easy to operate in a clinical environment, and be safe to operate.

This dissertation describes the design and testing of a new instrument to measure vaginal closing force, its calibration process, and the software to control it. Throughout this document the identified obstacles and the strategies used to mitigate them are discussed. Validation testing was performed on tissue phantoms and by bench testing using the calibration instrument. Validation testing shows that the instrument has the ability to differentiate between phantoms. Future testing on more tissue phantoms will allow further quantification of the instrument and a better determination of the precision of the measurements.

Two alternate approaches have also been developed for the possible refinement of the EVE instrument. Utilizing force sensing within the probe body would violate the initial design constraints, but might be a relatively simple way to address the issues which have disrupted the instrument's development. Alternatively a new probe which completely eliminates the hydraulic system in favor of mechanical linkages, although more drastic of a change, might allow for data generation without compromising the initial design requirements.

The EVE instrument is a successful step forward in properly measuring vaginal tissue closing force. Many of the initial design challenges have been overcome, and a majority of the programming necessary has been completed. Measurements of phantom tissue elasticity are now possible. EVE is nearly ready for *in vivo* testing.

Acknowledgements

I would like to express my deepest appreciation and respect for my committee chair, Dr. Sarah Kieweg, who was a wonderful advisor and constant source of optimism through this long project. Without her guidance this dissertation would have been impossible.

I would also like to thank all of my committee members both current members, Dr. Ron Dougherty, Dr. Ken Fischer, Dr. Sara Wilson, and Dr. Erik Van Vleck, and past members, Dr. Terry Faddis and Dr. Lorin Maletsky, who were all of invaluable assistance during this process.

I would also like to give a special thank you to the departmental and outside help that I received along the way from Dr. Carl Weiner, Doug Kieweg, Charles Gabel, Justin Lohrmeyer, and Matt Gifford. All of your technical support made EVE possible.

Finally, I would like to thank my ever patient wife Eryn Pacey for her love and encouragement throughout this long journey, and my parents David and Carol for instilling in me a love of science and engineering.

This work was supported by NIH R21/R33 AI082697 and the Kansas City Area Life Sciences Institute (KCALSI).

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Nomenclature, Variables, and Abbreviations

AIDS – Acquired Immunodeficiency Syndrome, a condition of progressive failure of the human immune system, caused by HIV.

Barbed Tube Fitting – A tube fitting which holds the tubing in place by force fitting the tubing over one or more barbs on the fitting surface.

Bellows – Metal vessels that can be compressed or extended by pressure or force changes, but return to their original shape.

Daughter Bellows – The bellows housed in the probe end of EVE, synonym of Probe Bellows

Driving Bellows – The bellows housed in the driving end of EVE.

Parent Bellows – The bellows housed in the driving end of EVE, synonym of Driving Bellows.

Probe Bellows – The bellows housed in the probe end of EVE.

C – The concentration of gel within a phantom, in g/L of solution.

$c_{\#}$ - A constant used to calculate probe position.

Compression tube fitting – A tube fitting which holds the tubing in place by deforming a malleable collar over the outside of the tubing and held in place by a nut.

C-T-C – Calibrate-Test-Calibrate, an EVE protocol where the calibrate protocol is run three times sequentially, to calibrate EVE, test an unknown material, and then recalibrate EVE.

$d_{\#}$ - A constant used to calculate probe force.

Driving End Displacement – The displacement measured at the driving end of EVE, with zero displacement being the displacement of the driving end at equilibrium when the probe end is fully collapsed.

Driving End Force – The force measured at the driving end of EVE

Driving End Position – A synonym of driving end displacement.

dP/dt – The velocity of the driving end.

E_{agar} – The Young's modulus of an agar phantom.

E_{cal} – The elasticity of the load applied to the calibration instrument.

E_{driving} – The elasticity of the system measured at the driving end of EVE.

E_{gelatin} – The Young's modulus of a gelatin phantom.

Elasticity – The ratio between force and displacement in linear elastic materials.

Encoder – An optical readhead that converts marks on the encoder scale into a digital signal for measuring displacement.

Encoder Tape - The encoder scale that is affixed to the moving body.

EVE - Elevated-surface Vaginal Elastometer.

F – The force measured at the driving end.

F_P – The force measured or calculated at the probe end.

Fingering – The pattern that emerges from gravity driven flows under the influence of surface tension. Instead of a straight leading edge, the fluid forms a sinusoidal pattern.

FPGA – Field Programmable Gate Array, an integrated circuit which can be reconfigured.

HIV - Human Immunodeficiency Virus, a retrovirus that leads to AIDS.

Least-Squares Fit – The method of fitting an equation to a set of data by minimizing the sum of the squares of the errors.

Load Cell – A sensor which creates an electrical signal proportional to the force applied to it.

Microbicides – A topical drug which destroys or inhibits pathogens before they can infect.

P – The position measured at the driving end.

P_P – The position measured or calculated at the probe end.

Phantom – A specially designed object used as a test material to evaluate, analyze, and tune the performance of devices.

PI controller – Proportional-Integral Controller, a control feedback software element which uses the error and the integral of the error to control input to a process.

PID Controller – Proportional-Integral-Derivative Controller, a control feedback software element which uses the error, the integral of the error, and the derivative of the error to control input to a process.

Probe Control Mode – Controlling the probe force or position of EVE based on calibration equations using the measured force and displacement of the driving end.

Probe Displacement – The displacement of the measuring surface of EVE, with zero displacement being fully collapsed.

Probe Force – The force experienced by the measuring surface of EVE.

Probe Position – A synonym of probe displacement.

PWM – Pulse-Width Modulation, a method of controlling the average current supplied to the motor by switching the power supplied on and off at regular intervals, with longer on periods supplying more current.

R^2 – The coefficient of determination, a measure of the goodness of fit.

Relative Error – The percentage error of a calculation compared with a measurement.

Spring Constant – The ratio between force and displacement of a linear spring.

Standard Deviation – The statistical measure of the variation within a set of data.

Strain – The relative displacement of a material with respect to its original length

Stress – The force experienced over an area of material.

Vaginal Closing Force – The combination of forces from tissue properties, intra-abdominal pressure, voluntary squeezing, and involuntary squeezing, which collapse the vaginal canal.

Viscoelasticity – The properties of materials that have both viscous and elastic traits.

Voice Coil Linear Actuator – A linear motor that uses magnetic force from an electromagnet in order to develop displacement.

Young's Modulus – The ratio between stress and strain in linear elastic materials.

Chapter 1) Significance and Relevant Background

HIV: Statistics, Transmission, and Prevention

In 2012 there were an estimated 35.3 million people living with the Human Immunodeficiency Virus or HIV [1]. There were 2.3 million new HIV infections in 2012, and 1.6 million AIDS deaths in 2012 [1]. 70% of all new infections in 2012 were in sub-Saharan Africa [1]. Heterosexual sex is the primary mode of HIV transmission in sub-Saharan Africa, and female commercial sex workers are a key population for prevention efforts [3]. Women have been shown to be at a higher risk of infection than their male counterparts due to various anatomical, social, and cultural factors [2]. In sub-Saharan Africa, women account for approximately 57% of all people living with HIV [1]. Sub-Saharan women in the 15-20 year old age group have a three to six times higher infection rate and are infected, on average, five to seven years earlier than their male peers [4].

Since women are more susceptible to HIV infection, and heterosexual sex is the most common transmission mode, it is important to understand how a woman may contract HIV through vaginal intercourse. The vagina is a tubular passage that connects the introitus to the cervix. The lateral cross-section is often described as having an “H” or “W” shape, while the sagittal cross-section is “S” shaped along the axis between the introitus and the cervix. The vaginal and ectocervix epithelium is multi-layered and stratified [5], as shown in Figure 1, and is supported by the underlying smooth muscles and surrounding pelvic floor structures [6].

During unprotected intercourse with an HIV-infected man, infected leukocytes and cell-free HIV are introduced into the vagina through semen and pre-ejaculate [7]. The epithelial cells themselves are not likely infection sites because they lack the CD4 receptor that the virus requires to infect a target cell [5, 7].

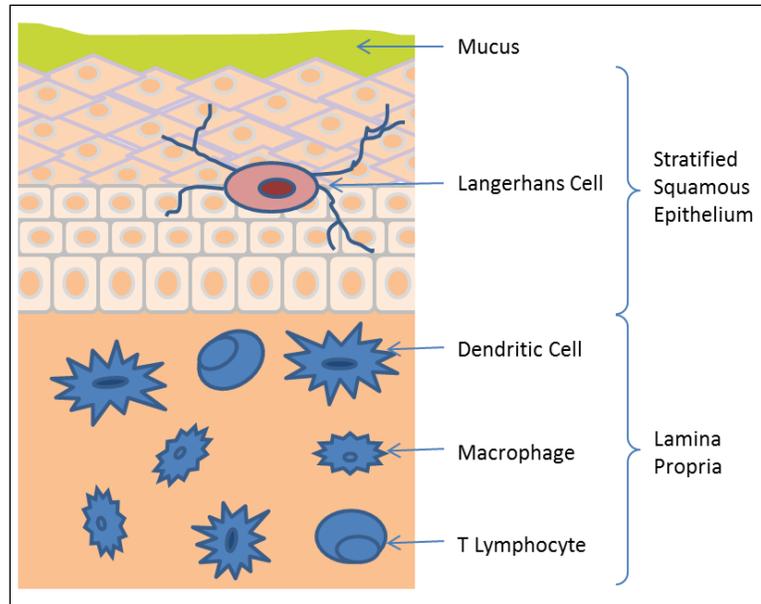


Figure 1: Vaginal epithelium and associated cells pertinent to infection (Adapted from Stone 2002)

Langerhans cells are present in the vaginal epithelium (see Figure 1), and, although they do possess the CD4 receptor, they are unlikely sites for initial infection because they express very little of the co-receptors CCR5 or CXCR4, which are also necessary for infection [5]. The primary infection occurs beneath the epithelium in the lamina propria which contains lymphoid cells, dendritic cells, and macrophages, which all have the necessary receptors and co-receptors for infection [5]. The infection gains access to the lamina propria through disruptions in the epithelial lining caused by traumatic intercourse or pathological conditions like other sexually transmitted infections [7]. It has also been shown that the viron can be transported through the epithelium by Langerhans cells, which have dendrites which reach through the intact epithelial surface [5, 7, 8].

Once infected, treatment for HIV through antiviral medications increases patient life expectancy, and can decrease the chance of passing on the infection by lowering the patient's viral load and thereby reducing the genital secretion of the viron [5]. Nothing has been shown to

reliably cure anyone post-infection, and undiagnosed new hosts are especially likely to spread the infection. In fact, for every two people who are put into antiretroviral therapy, five more become infected [9].

Prevention is the most effective method in combatting the growing HIV pandemic. Ideally a vaccine could be developed that would protect uninfected people from ever acquiring HIV. To be successful, an HIV vaccine will have to deal with a constantly mutating virus and huge viral diversity [10]. A vaccine with only one antigen will not generate effective protection against the broad spectrum of HIV [10]. Vaccines also have additional barriers to overcome in public fears, including fear of vaccine-induced HIV infection, unknown physical side effects, uncertainty about efficacy, and mistrust of government-sponsored medical research [11]. Even without the public fears about vaccination, researchers are not optimistic about developing a human-ready HIV vaccine within the next decade [12].

Comprehensive sex education has been shown to reduce sexual activity and increase protective sexual behaviors [13]. Key to comprehensive sex education is the use of condoms for every sex act. Condoms, when used correctly and consistently, are one of the most efficient technologies to prevent the sexual transmission of HIV [1]. Condom use is not always a viable option, especially in the developing world. Many myths and beliefs have proliferated throughout regions with high infection rates that discourage the use of condoms including: the fear of a condom rupturing and causing infertility, the association with the sex trade and sexually transmitted infections, the concern that condoms have tiny holes that HIV can pass through, and the concern that they limit sexual pleasure [14]. Because of gender inequality and disadvantages in socioeconomic status, women are often subjected to violence and unable to negotiate condom use [1, 8]. When used correctly and consistently, condoms are a great tool to reduce the spread

of HIV; but other less intrusive products, which are under the control of women, are important to increase prevention and slow the spread of HIV.

Microbicides address an important gap in HIV prevention options for vulnerable groups, such as young women, who are at high risk of infection, but are unable to implement other HIV prevention strategies like abstinence, female or male condoms, or monogamy [2]. A microbicide consists of two main parts: the active ingredient and the delivery vehicle. The active ingredient is a drug or chemical that destroys or otherwise inhibits pathogens so that they will not have an opportunity to pass on infection. Delivery vehicles are used to get the active ingredient to the target site. They are often in the form of a gel, foam, or cream, but are sometimes more innovative materials such as rings or films [15]. Ideal delivery vehicles also perform other actions besides transporting the active ingredient. An ideal delivery vehicle also acts as a lubricant, which can help prevent trauma to the vaginal epithelium, preventing the virus from being able to access the lamina propria, where infection occurs. Delivery vehicles can also provide a physical barrier, possibly providing some additional protection from infection.

Relation to Longer-Term Goals

The vehicle's ability to coat the vulnerable surface has been identified as a crucial variable [15]. Otherwise effective active ingredients could easily be rendered ineffective by poor delivery vehicle design which would leave vulnerable tissue unprotected. Mathematical models of delivery vehicle spread due to gravity and squeezing can be used to speed the development of effective vehicles. Models are being developed in our lab to optimize the delivery vehicle properties so that the microbicide will coat the entire vaginal epithelial surface, stay in place for the duration of possible exposure, and have the necessary thickness for the active ingredient to act. Current models include both gravity and squeezing forces, but future models will also

incorporate the effects of shearing forces on the delivery vehicle that are applied during coitus. Once optimal rheological parameters are determined for proper function, a chemical structure can be developed for delivery vehicles with those optimized properties. Relating the delivery vehicle structure, property, and function together enables a rational design process.

Gravity

Previous work done in our lab has focused on the initial spread of non-Newtonian polymer solutions, commonly referred to as gels, under gravity-driven flow conditions. These gels are shear-thinning, meaning that as the rate of shear within the gel increases, the apparent viscosity of the gel decreases. Two rheological models have been incorporated into our group's fluid flow simulations:

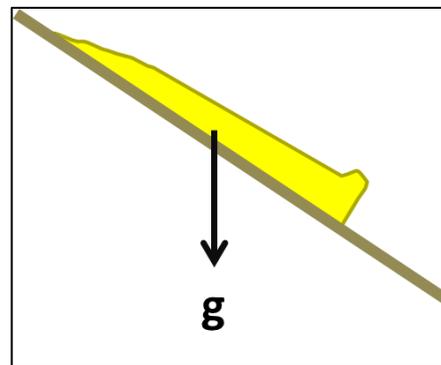


Figure 2: Side view representation of a gel flowing down an inclined plane.

the Ellis model [16] and the power-law model [17]. Both models utilize a no-slip boundary assumption for contact between the gel and an inclined plane, and a free surface for the gel-air boundary, using the setup diagramed in Figure 2. These models have been validated by experiment, having shown the ability to accurately predict how these gels will spread under gravity-driven conditions [16, 17].

More recently, our group has included surface tension in these gravity-driven models [18, 19]. Surface tension within gels can cause an instability that leads to “fingering” at the front edge of the flow, resulting in an uneven distribution of a gel in a wave pattern instead of a constant even coat [19]. Sheer-thinning fluids have suppressed finger growth and wider fingers [19], so the occurrence and wavelength of the delivery vehicle fingering can be optimized by adjusting a gel's sheer-thinning properties. Unmanaged fingering could have a significant

impact on the initial spread of a microbicide, leaving some of the epithelium unguarded and vulnerable to infection.

Squeezing

The replacement of the free surface boundary condition with an elastic boundary condition to mimic forces applied to the gel by vaginal tissue has made models of initial microbicide spread much more physiological. Numerical modeling, such as the model represented in Figure 3, with both Ellis and power-law rheological properties, has shown that the combined effect of an elastic boundary condition and gravity will greatly influence the final coating of the gel [20-22]. High tissue elasticity has even been shown to dominate the spread of

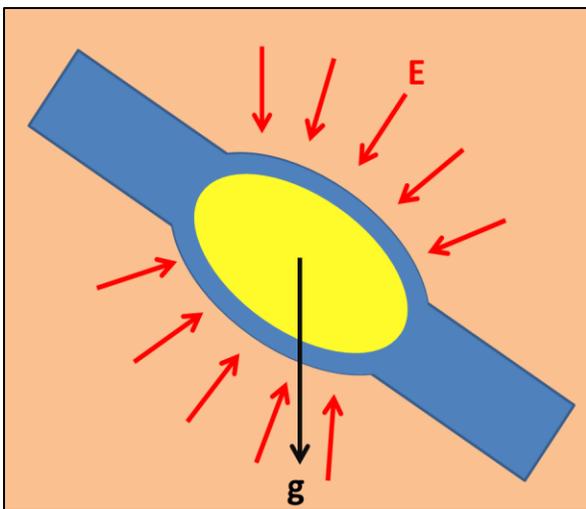


Figure 3: Side view of a representation of a model of gel flowing between two elastic boundaries with squeezing and gravitational forces.

the gel over the force of gravity [20, 22].

Additionally, computational studies have shown that tissue viscoelasticity may also have an impact on gel distribution [23]. Although shown to be important, values of the squeezing forces and the elasticity of the vaginal canal reported in literature are sparse and widely variant. There is a need for measurement of the relevant forces or elasticity that can be applied to the current models.

Other Instruments

A complete delivery vehicle spread model should incorporate the vaginal closing force (the combination of forces arising from tissue properties, intra-abdominal pressure, voluntary squeezing, and involuntary squeezing) as a component force or representative pressure acting to

spread the delivery vehicle. Since this varies as a function of the displacement of the vaginal tissue, it is also important to measure the displacement, and to make force measurements at several displacements. The magnitude of the closing force, as it relates to our spreading models, is unclear. Several methods have been utilized to determine magnitudes of one or several of the components, most notably *ex vivo* tissue tensile testing, skin probes, vaginal pressure manometry, dynamometric speculums, force/displacement leaf spring, and vaginal tactile imaging. Although these methods, summarized next in this section, all result in some measure of one or all of the components of closing force, they are all targeted at pelvic organ prolapse. Thus, they all lack, in one way or another, the ability to measure the forces relevant to microbicide delivery vehicle spreading.

An ideal measurement device should have a constant contact area, be able to measure at many discrete sites along the vaginal axis as well as in different directions, evaluate the entire structure *in vivo*, and have controllable and precise displacement control. Constant contact area is important in order to convert measured force into stress in order to interpret vaginal closing force as elasticity. Having a small enough measuring device to be able to measure in different places and in different directions will allow our models to be more precise in the future, as it is highly unlikely that closing force is uniform and independent of direction. Evaluating the structure as a whole in a living human specimen will make the measurements most directly applicable to the current problem. Finally, having precise displacement measurement allows the calculation of strain, which will allow force measurements to be converted into elasticity for use in our models. Making the displacement controllable allows measurements to be converted not just into elasticity, but possibly into a viscoelastic measure for future studies and models.

Ex Vivo Tissue Tensile Testing

In this method a sample of the vaginal epithelium is excised from the vaginal wall during surgery to correct vaginal prolapse [24-27], during a transvaginal hysterectomy [28], from nonformolised cadavers [29], or from ewes sacrificed for other research [30]. The samples are often frozen [25, 26, 29] before being trimmed and affixed to a variety of tensile testing machines, like the one shown in Figure 4. The tissue samples are then subjected to a variety of strains as high as 30% [28], 40% [25, 26] or even to failure [24, 27, 29, 30]. *Ex vivo* tensile testing has produced varied values for the elasticity with a Young's modulus reported as low as 6.65 MPa [28] to as high as 33 MPa [25]. These results are not applicable to our models because they do not account for all components of the vaginal squeezing force, notably the contributions of intra-abdominal pressure, pelvic floor contractions, and contributions from other support structures.

Additionally, the available human tissue samples are mostly from prolapsed tissues which often have different properties as compared to those of nonprolapsed samples [29].

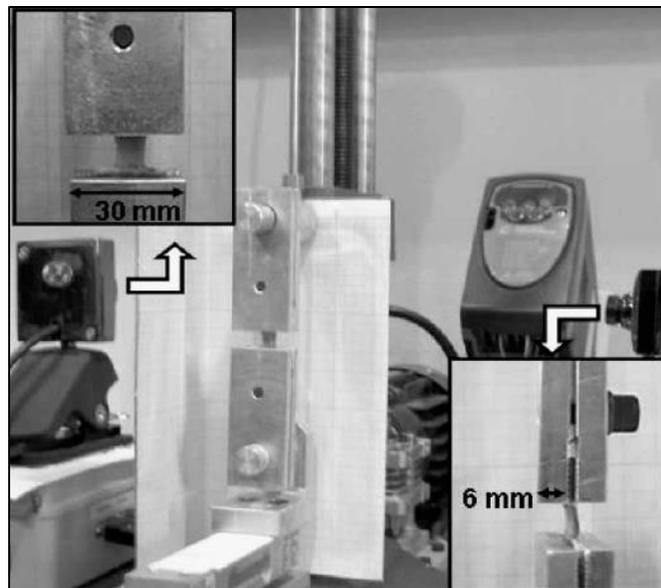


Figure 4: Example of an *ex vivo* tensile test of vaginal tissue copied from Martins *et al.* 2010.

Skin Probe

Probes such as the Cutometer MPA 580 (Courage & Khazaka Electronic) or the DermaLab Skin Probe (Cortex Technology) have also been used to determine vaginal epithelium elasticity [31]. These probes either subject an area of skin to mild suction measuring the

resulting displacement, or measure the amount of suction required to extend the tissue a prescribed amount. These instruments are advantageous for *in vivo* measurements of healthy tissue. They also can be used all along the vaginal axis and in different directions, and they take into account some of the underlying tissue's contribution to the overall vaginal squeezing force. However, they do not measure all of the relevant closing force components, neglecting intra-abdominal pressure, pelvic floor contractions, and most of the underlying structures; and all reported values are in a dimensionless “stiffness index” that cannot be readily adapted to our current models because it is just a comparative method and does not report an elasticity, pressure, or force magnitude.

Newer models, such as the BTC2000™ (SRLI Technologies), incorporate laser altimetry to more precisely measure the tissue uplift [32]. Data from these experiments has been used to fit the vaginal tissue response to a viscoelastic Voigt model yielding Voigt model recovery rates (E/η) between 0.5 and 5.5 sec^{-1} [33]. Although these newer models can provide a much better estimate



Figure 5: The BTC2000™ performing a suprapubic measurement, similar to the procedure for the vaginal measurement, copied from Mosier *et al.* 2011.

of tissue viscoelasticity, they still do not take into account the contributions of intra-abdominal pressure, pelvic floor contractions, and most of the underlying structures to the vaginal closing force; and, as can be seen in Figure 5, these models are large and cumbersome enough that they are only used on human subjects who are already under general anesthesia.

Vaginal Pressure Balloon Manometry

This method uses air filled catheter balloons to measure pelvic floor contractions [34, 35]. A catheter balloon is inserted into the vagina at various depths, and the resting intra-abdominal pressure is used as the zero reference for measurements during voluntary pelvic floor contraction. These instruments are able to be used *in vivo* to measure both a resting vaginal pressure and that due to a pelvic floor contraction. Although some of the balloons are large, smaller balloons can be used to measure at several points along the vaginal axis. Reported values for balloon manometry are as low as 0.49 kPa [34] and as high as 3.1 kPa [35]. These devices measure pressure as a whole and cannot be used to measure force directionally. Since the balloons are flexible silicon rubber, it is never known how far the tissue is being displaced as compared to how much the balloon is elongating under pressure, making it difficult to calculate the proper contact area. These devices come in all different sizes with different technical parameters; so these measurements cannot be compared [6]. Balloon manometry also has no displacement control, and cannot be used to determine viscoelastic properties.

Vaginal Pressure Rigid Manometry

Similar to balloon manometry, vaginal pressure rigid manometry replaces the balloon with a rigid water-infused catheter [36]. These catheters can have from one to several side-holes that can measure pressure in different directions. They have been used to measure the resting and squeezing vaginal pressure profile in four directions with values as low as 0.93 kPa (resting) to as high as 6.67 kPa (squeezing) [36]. Although rigid manometry can be good for measuring absolute pressure and has a constant measurement area, they have a constant displacement; so they cannot be used to generate an elasticity, which our models require.

Dynamometric Speculum

Mounting strain gauges to modified speculums, like the instrument in Figure 6, have also been used to measure the magnitude of vaginal closing force, both resting and during voluntary pelvic floor contractions [37-40].

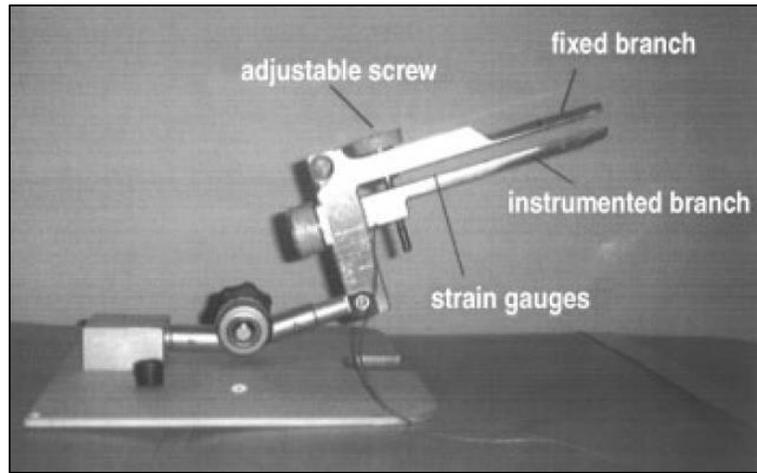


Figure 6: Example dynamometric speculum, copied from Dumoulin *et al.* 2003.

Strain gauges allow for very high

precision measurement of the closing force along the length of the upper and lower measurement arms of the devices. Reported values for these devices also varies widely from a low end of 0.1 ± 0.1 N for incontinent women at the maximum comfortable vaginal opening [41] to the high end of 14.4 ± 3.8 N for healthy women at an unknown opening [38]. This gives a measurement of the summed closing force, but does not offer any spatial resolution. Some dynamometers have no displacement control at all [39], while others have displacement controlled by a hand operated screw [37, 38, 40]. Displacement is measured entirely by eye, and none offer quick and precise displacement control.

Force/Displacement Leaf Spring

Another approach that can measure along the vaginal axis and has the ability to measure in four directions at once is the force/displacement leaf spring concept developed by Constantinou *et al.* [42-44]. Their device consists of four force sensors mounted to individual leaf springs which, after insertion, are allowed to expand in perpendicular directions as shown in Figure 7. The displacement of each sensor is measured by a Hall Effect transducer. This device

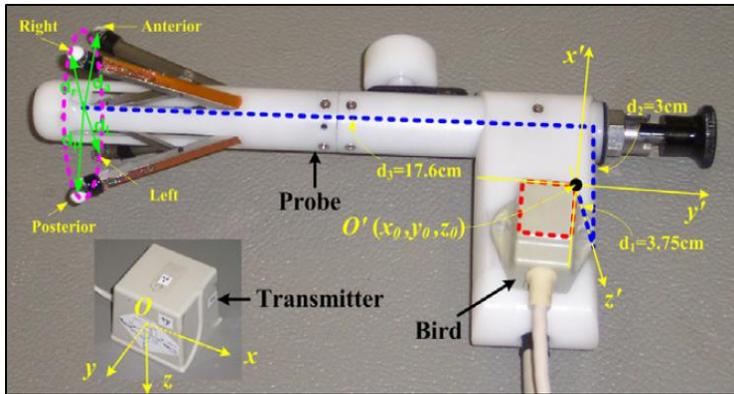


Figure 7: The probe of the Force/Displacement Leaf Spring, copied from Shishido *et al.* 2008.

has been used to measure vaginal closing force: both relaxed and during pelvic floor contractions. Pressure values reported for healthy women are 37.5 ± 4.8 kPa at rest and 48.2 ± 5.0 kPa during pelvic floor contraction [44]. Although

displacement is precisely measured by the Hall Effect transducers, it cannot be actively actuated and is only responsive. This makes it impossible to calculate elastic parameters from the data.

Vaginal Tactile Imaging

The most elaborate approach measuring vaginal tissue properties is vaginal tactile imaging. This instrument consists of a vaginal probe equipped with a pressure sensor array and a motion tracking system [45-49]. The hand operated probe, illustrated in Figure 8, measures the 2D pressure pattern on the measuring surface of

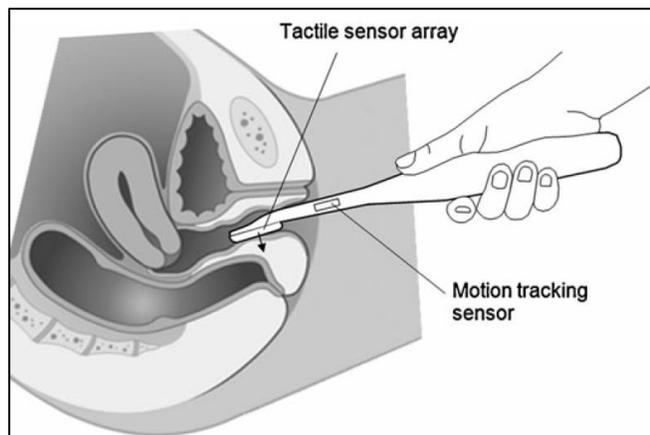


Figure 8: Vaginal Tactile Imaging probe illustration copied from Egorov *et al.* 2012.

the probe while the motion tracking system keeps track of the probe position to within 1 mm and 0.25 degree. The only values for vaginal elasticity using Vaginal Tactile Imaging on healthy women reports Young's modulus as 7.4 ± 4.3 kPa [45]. Since the probe is hand operated, it can offer quick position changes, but tissue displacement cannot be precisely controlled. This means that the device could generate elastic properties for vaginal closing force, but would not be able

to calculate viscoelastic properties in the future. In addition, since the test subject is not also motion-tracked, the system has no way to measure or account for movement other than that of the probe itself, invalidating the measurements if the subject were to move. Additionally, since the probe is only pushing on one side of the vaginal canal, the force could be displacing the entire vagina. If that is the case, the measurement would be measuring forces that are not relevant to squeezing flow models.

Summary

Although there are many devices in the available literature that can provide some measure of one or more component of vaginal closing force, none can provide an appropriate elastic boundary condition for our models to represent vaginal closing force. Table 1 summarizes each method’s strengths and weaknesses in the areas of interest for measuring vaginal closing force.

Table 1: Strengths and Weaknesses of Reviewed Devices

| Method | Constant Contact Area | Discrete and Directional Measurement | Measures Entire Structure In Vivo | Displacement Measurement | Displacement Control |
|---------------------------------|-----------------------|--------------------------------------|-----------------------------------|--------------------------|----------------------|
| Ex Vivo Tensile Testing | Y | N | N | Y | Y |
| Skin Probe | Y | Y | N | Y | N |
| Balloon Manometry | N | N | Y | N | N |
| Rigid Manometry | Y | Y | Y | N | N |
| Dynamometric Speculums | Y | N | Y | Y | N |
| Force/Displacement Leaf Springs | Y | Y | Y | Y | N |
| Vaginal Tactile Imaging | Y | Y | Y | Y | N |

These instruments do provide data that can inform the design of future instruments.

Specifically, the Vaginal Tactile Imaging studies report elasticity arising from vaginal closing force of 7.4 kPa [45]; and the force/displacement leaf springs report pressure measurements of 37.5 kPa [44].

Chapter 2) Instrument Design Process

Design Requirements

There have been many approaches to measuring vaginal closing force. Each of the previously developed instruments investigated gives valuable data, but isn't an ideal instrument for our needs. After reviewing the available literature, I began designing an instrument better suited to our needs and developed the following goals. An ideal measurement device to measure all aspects of vaginal closing force would be controllable, operate in a variety of modes, have a constant contact area, be able to measure at different places along the vaginal axis and in different directions, be modular and upgradable, be convenient and easy to operate in a clinical environment, and, above all else, be safe to operate for both the technician and the test subject.

Measure Force and Displacement

It is important to measure both vaginal closing force and displacement in order to determine appropriate elasticity parameters for our future models.

Controllable

The instrument must have precise and quick displacement control. Precise and quick control will allow the instrument to determine if there is frequency dependence for any component of the vaginal closing force.

Constant Contact Area

Having a constant contact area for the probe will allow the instrument to produce results that can be more easily incorporated into mathematical tissue models.

Discrete and Directional

Having the contact area constant and small will allow the instrument to make measurements along the vaginal axis and in a variety of different orientations. This will allow

the instrument to be used to make a map of the vaginal closing elasticity for more complex 3D models of delivery vehicle spread.

Modular and Upgradable

The device design should be modular to allow the quick upgrade or replacement of individual systems. It should also easily allow for future modifications for viscoelastic measurements and frequency sweeps, and to operate in a controlled force mode, rather than just a controlled displacement mode.

Convenience

The instrument should have an easy user interface so that it can be easily operated by healthcare professionals without engineering training. It is also important to keep the probe size at a minimum and eliminate or conceal the wiring and driving motors to make the device as subject-friendly as possible.

Safety

The safety of the instrument is extremely important. Any leaking hydraulic oil could greatly impact the vaginal flora; so, although not ideal mechanically, any hydraulics should be run with purified water as the fluid. The probe must also be designed with cleaning in mind, using materials and part geometries that can be easily sterilized. Also, there should be no electrical components in the probe.

Mechanical Design

Initial Instrument Design

The initial mechanical design of EVE (Elevated-surface Vaginal Elastometer) consisted of two main parts: the driving end and the probe end. The driving end includes a base, the motor, the encoder, the load cell, the parent bellows, and various support pieces. The driving end is used to drive and monitor the force and displacement of a water filled parent bellows which is hydraulically linked to a daughter bellows on the probe end through tubing. Water forced out of the driving end flows through the tubing and into the bellows housing at the probe end. This influx of water collapses the probe end daughter bellows and extends the measuring surface, as illustrated in Figure 9. Because the two bellows are hydraulically linked, the force and displacement experienced on the probe end should be calculable from the force and displacement measured at the driving end, with proper calibration.

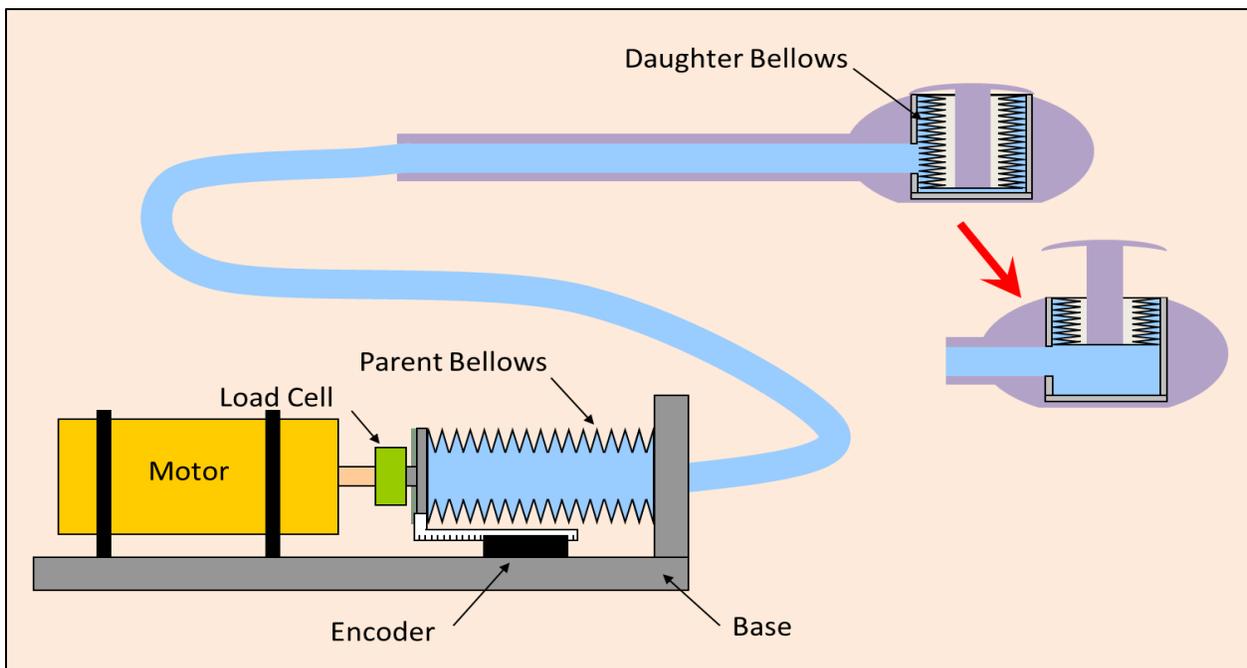


Figure 9: Early schematic of EVE design and actuation.

Driving End

The modular design of the driving end, shown in Figure 10, begins with a 27.5” long aluminum base with three T-slot mounting tracks (1545, 80/20 Inc.). This base provides a solid mounting surface for the individual modules of the driving end. It also allows the modules to be easily changed and ensures that they are aligned when mounting. The custom machined aluminum mounts for each module are allowed to slide back and forth along the base before being tightened into place. This ensures that proper distances between each module can be maintained.

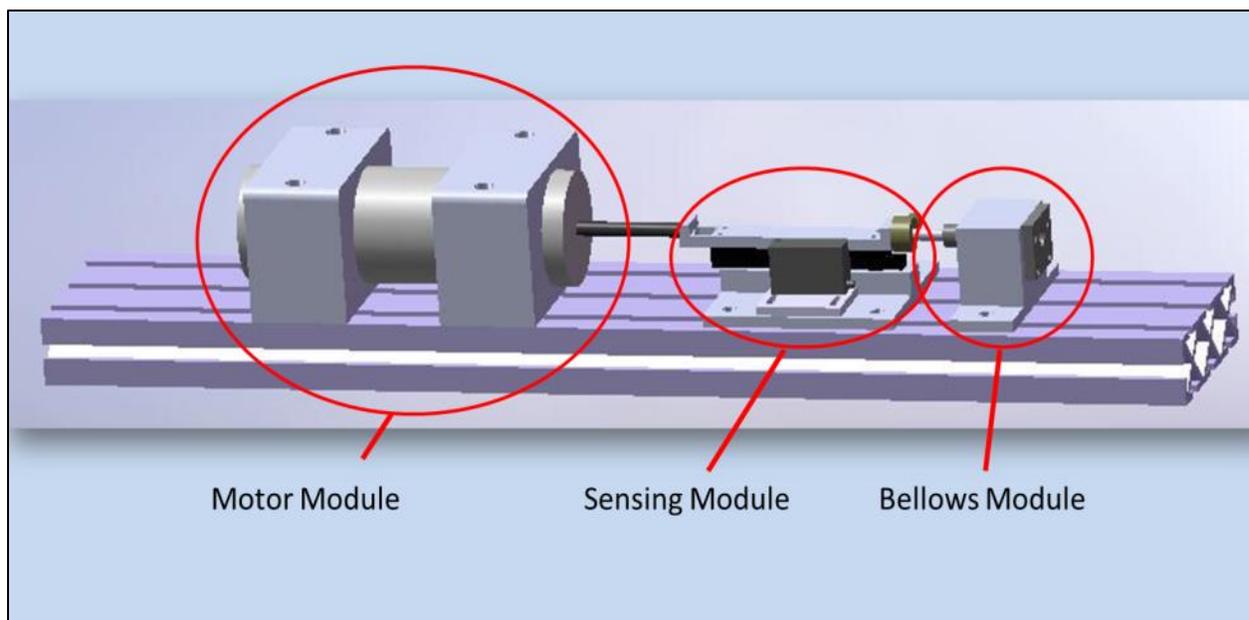


Figure 10: CAD model of the initial driving end design.

To drive the system, a moving magnet DC voice coil linear actuator (NCM30-25-090-2LB, H2W Technologies) was chosen to be the primary component of the motor module. Voice coil actuators have advantages over other linear actuators because they have fewer moving parts while still being quick and controllable. In general mechanical actuators operate at slower speeds, and have screws and threads that can wear and jam. Hydraulic actuators are also more

complex than necessary, and take up much more space due to the required pumps and reservoirs. Pneumatic actuation was not considered because of the bulk of most air compressors, and the loud noise would have been inappropriate in a clinical environment. Voice coil actuators offer a large force-to-size ratio and high accelerations that are required for the application. The selected motor offers a peak continuous force of 40 N and a peak force of 120 N at 10% duty.

The second module of the driving end, the sensing module, incorporates both of the sensors for the device. First, an encoder system (RGH22, Renishaw) measures the displacement of the linear actuator. The RGH22 is an optical encoder that measures displacement with a precision of 50 nm. The system works at high speed without adding any friction to the system, making it ideal for this application. The second sensor, which measures the driving end force, is a sealed load cell (WMC-10, Interface). This was chosen for its small size, because it works in both tension and compression, and, at a capacity of 44 N (10 lbf), matches the peak continuous force of the motor. The load cell and the encoder ribbon are both mounted to a ball slide linear bearing (E-4, Del-Tron Precision), which keeps the travel of the EVE driving end constrained to a precise linear path in order to allow the encoder to operate correctly.

The third module of the initial driving end design houses the water-filled bellows that drives the probe end. The bellows chosen was an edge-welded stainless steel bellows (WB-816, MDC Engineered Process Solutions). This bellows was chosen to match the probe bellows at 0.5” diameter; but, at 1.69” in length, it is much longer. This has the effect of reducing the force required from the motor to displace the bellows by decreasing the bellows spring constant.

Probe End

Connected to the driving end through tube fittings and nylon tubing, the probe end consists of a Delrin body surrounding a stainless steel bellows assembly.

Delrin was selected for the probe body because of its ease of machining, and ability to be easily sanitized by immersing it in a sterilizing solution (CIDEX OPA, Advanced Sterilization Products). The custom machined body consists of three parts: the two part head and the handle. The

head is divided into two parts to allow easy removal of the bellows casing; and the two parts are held together by the handle, which screws over both pieces. The probe body, when assembled, is 19.5 cm long with smooth transitions between the 5 cm long measuring area, 8.75 cm long shaft, and 5.75 cm long handle. The end of the probe containing the bellows casing is 2.5 cm square with rounded corners and a protruding 9.6 mm radius of curvature measuring surface, which tapers down to the 1.5 cm diameter shaft, before becoming the 2.5 cm diameter grip. The maximum collapsed height of the probe is 3.25 cm at the apex of the measuring surface.

The bellows casing consists of several parts which are held together by silver solder (Stay-Brite, Harris Products Group), and biocompatible epoxy (EP21LV, Master Bond).

Because bellows are more stable in compression, the housing is designed to have water surround

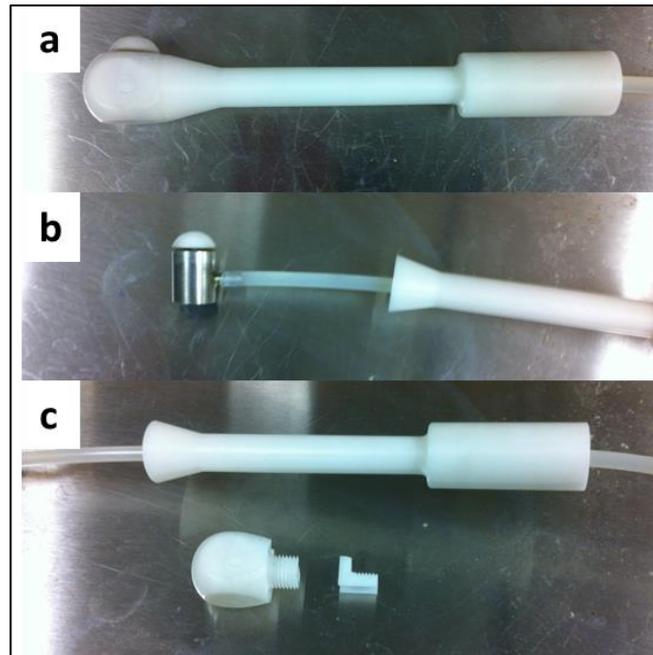


Figure 11: EVE probe end.

a) Assembled probe

b) Bellows casing

c) Disassembled probe end

the bellows. When water is forced into the housing by the driving end, the bellows collapses to accommodate the additional volume. This in turn extends the measuring surface against the material to be measured.

Mechanical Design Revisions

As with any project, unforeseen issues have necessitated some changes in the design. The modular design made many of the changes easier, but significant changes were needed in order to make EVE operational.

Bellows Sealing

The first problem encountered, which necessitated a design change, was difficulty in getting a watertight seal of the probe bellows casing assembly. Initially the assembly was done using only silver solder, which provided a strong bond; but it was difficult to obtain and maintain a

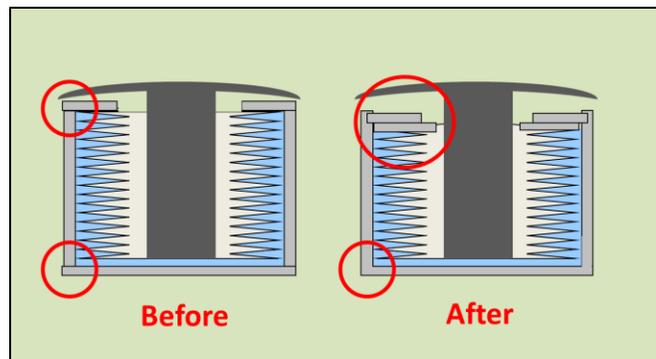


Figure 12: Illustration of the initial and final bellows casing.

watertight seal. Pinhole leaks developed frequently, and the entire assembly would need to be rebuilt. A second solution was attempted with biocompatible epoxy (EP21LV, Master Bond). With the epoxy, it was easy to create and maintain a watertight seal. However, the epoxy lacked the necessary strength and was prone to catastrophic failure, especially in any joint undergoing tensile stress. A solution was found by changing the design to eliminate the joints where tensile stress occurred. The bottom cap was incorporated into the casing wall in order to eliminate one problem joint, and the top cap was modified to incorporate a retaining ring, as shown in Figure 12. These changes removed the tensile stress on the epoxy joints, allowing the epoxy to be only responsible for making the joints watertight.

Bellows Sizing

Both bellows in the initial bellows set had matching diameters of 0.50". Since water is incompressible at the operational pressures of EVE (under 30 kPa), equal bellows diameters were used with the anticipation that they would have a displacement ratio of 1:1 between the driving and probe ends. Initial testing showed that, not only was the displacement not a 1:1 ratio, the long 1.69" length of the driving bellows combined with the narrow 0.50" diameter caused a significant buckling issue. Slight misalignments would cause the bellows to buckle easily when compressed, which was a problem for two reasons. First, the difference in shape of the unbuckled vs buckled bellows changed the volume of water displaced for the same motor position. Second, the buckled bellows would rub on the support piece adding friction to the force measurements. It was evident very early that a new bellows was necessary. A new bellows was ordered with a 1.07" diameter, and 1.38" free length (WB-801, MDC Engineered Process Solutions). This new bellows, shown in Figure 13, required that some parts, like the bellows mount, be modified, while others, like the bellows mounting plate, were redesigned to fit. Being both wider and shorter than the previous bellows the replacement bellows does not have the buckling issues of the original bellows.



Figure 13: Size comparison of old and new driving bellows.

Motor Sizing

Changing the driving bellows produced consequences beyond eliminating the buckling issues. Increasing the bellows diameter by a factor of two increased the hydraulic area that the motor is now acting on by a factor of four. This increased area means that, in order to develop the same system pressure for extending the measuring surface, the motor must produce four times as much force as previously, assuming no change in bellows stiffness. This necessitated a switch to a much larger voice coil motor (NCM-30-40-350-2LB, H2W Technologies) capable of a maximum continuous force of 156 N, compared to the 40 N maximum of the old motor. This larger motor generates forces well beyond the capacity of the old load cell; so a new matched load cell (WMC-50, Interface force), which has a capacity of 222 N (50 lbf), was also selected and incorporated into the design. The new motor and load cell combination is a scaled up version of the previous pair; so very little adjustment to the programming needed to be done to accommodate the change. The new motor can now easily drive the new bellows system.

Air Within the Hydraulic System

Any air that finds its way into the hydraulic system greatly changes the compressibility of the system, and makes accurately driving the probe bellows more difficult. Air in the system comes primarily from two sources: clinging to crevices during initial assembly and through air-permeable joints when the system is under negative relative pressure. Bleeding air from the system initially involved disassembly of barbed tube fittings underwater to release the air bubbles. This process would deform the tubing and worsen air leakage under negative pressure.

Three design changes were made to the hydraulic system because of air bubbles: two to prevent as much air entry as possible, and the other to enable easier bleeding of the system. The first, and most simple of the changes, was replacing, wherever possible, barbed tube fittings in favor of compression tube fittings. Compression fittings are more airtight, but are larger, so the fitting at the probe end bellows assembly was unable to be changed and remains a barbed fitting. Although the remaining barbed fitting can still let some air into the system, the amount is small enough that regular bleeding is sufficient to maintain reliable operation. The second change was adding a bleed point in the middle of the tubing length. This bleed point is simply a “T” junction with two tube fittings and a male pipe fitting closed with a threaded end cap. Now bleeding consists of removing the end cap under water and allowing the air to escape. This minimizes the damage to the tubing, and simplifies the bleed process.

The third hydraulic system change allows an initial pressure to be applied to the system so that the system is never under negative relative pressure, preventing much of the air from entering the system. A second “T” junction was added, identical to the bleed point junction. The pipe fitting on this junction has a one-way check valve and a modified syringe that can add water to the hydraulic system; this is shown in Figure 14. After assembly and just before testing, up to one additional milliliter of water is added to the system to ensure constant positive pressure. The check valve



Figure 14: The pre-pressure junction, check valve, and syringe.

prevents backflow; and the additional water raises the system pressure to keep air from entering the system from joints that are watertight, but not airtight.

Final Design

The final design, taking the initial design and incorporating the design revisions described previously, can be seen in Figure 15; and technical part drawings for the custom-machined parts are available in Appendix A.

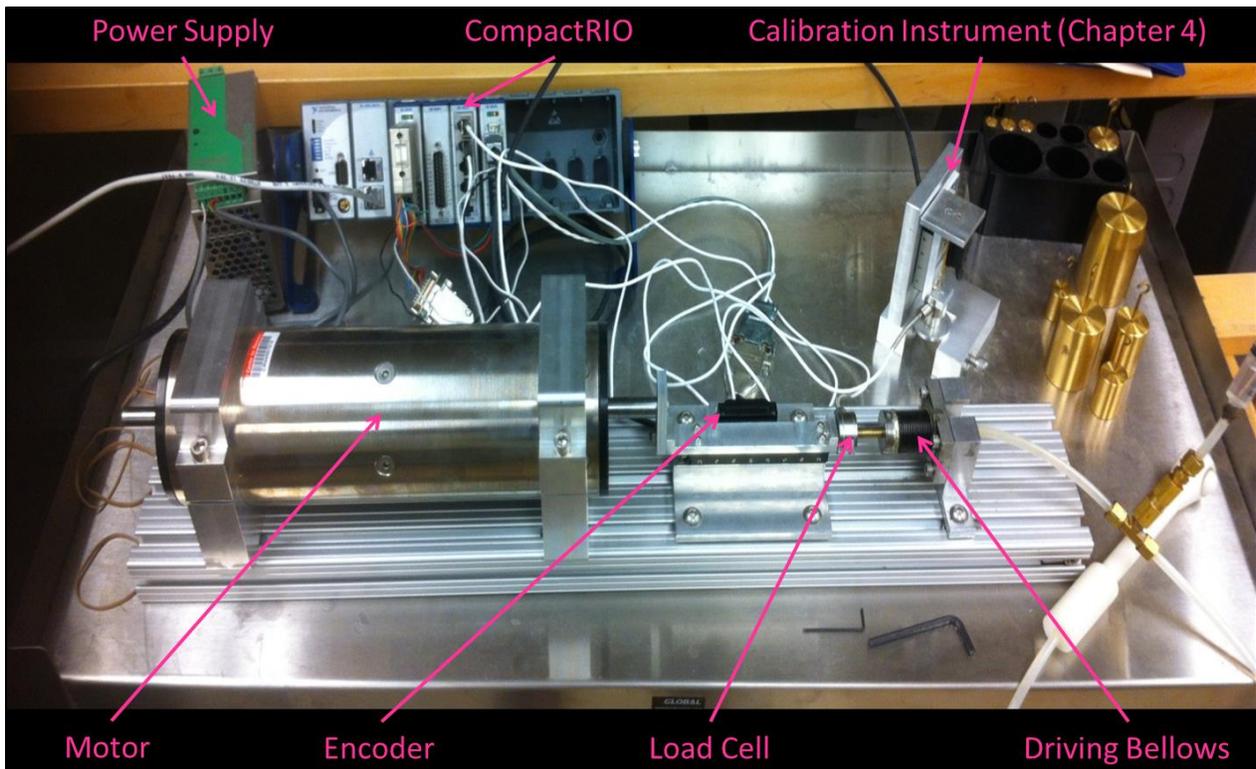


Figure 15: EVE final design and build.

Software Design

The programming for EVE was completed in National Instruments LabVIEW to run on the National Instruments CompactRIO configurable control and monitoring system



Figure 16: The National Instruments CompactRIO.

shown in Figure 16. The CompactRIO allows up to eight swappable modules to customize the platform for a specific application; and EVE utilizes three of these slots. A 9237 module was used to collect load cell data from both the driving end and the calibration instrument. Two 9505 modules were used: one to read the driving end encoder and drive the motor, and the other to read the encoder of the calibration instrument which is discussed in Chapter 4. The code executes on three different computers (FPGA, Real-Time Computer, and Host Computer) simultaneously utilizing each computer's strengths to control the instrument and collect data reliably. The interaction between the computers is summarized in Figure 17.

FPGA

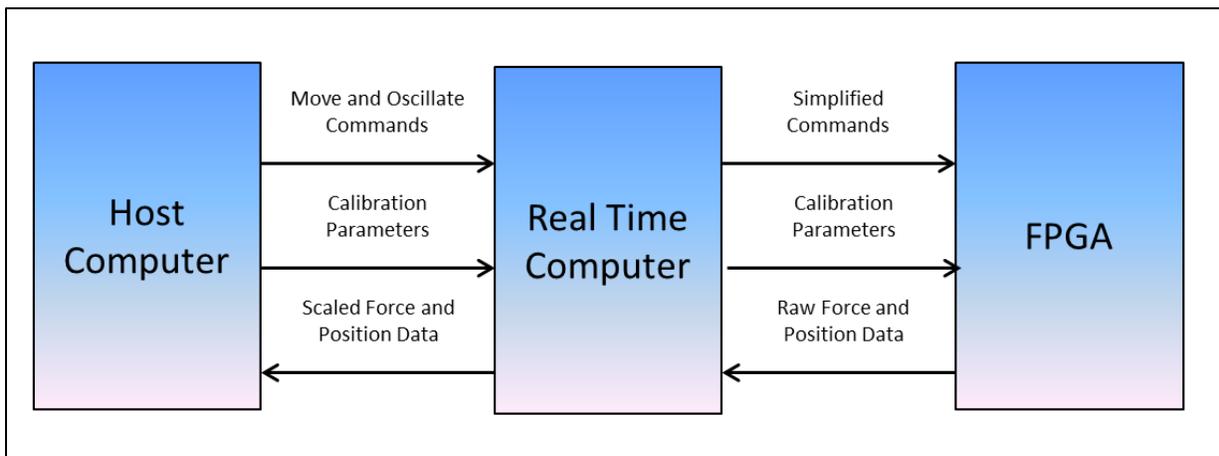


Figure 17: Interactions between the three EVE computers.

The most basic computer is the FPGA, or Field Programmable Gate Array, which is housed on the CompactRIO. The FPGA is the primary processor of signals for EVE. As a programmable gate array the FPGA is essentially an easily customizable logic chip that can process numerous tasks at once in parallel. Currently the FPGA runs 14 loops in parallel, which can all run simultaneously at whatever speed is appropriate for the loop. Several of the loops are in constant communication with each other and the other two computers. Surface level loops communicate with the higher level computers, while several process loops quickly accomplish their continuous lower level tasks.

One of the most important surface level loops is the Position Set Loop; it is the heart of the motor control process diagramed in Figure 18. The Position Set Loop takes commands from the Real-Time Computer and calculates what the driving end encoder position should be.

Driving end control is accomplished by sending the Position Set Loop either the velocity and

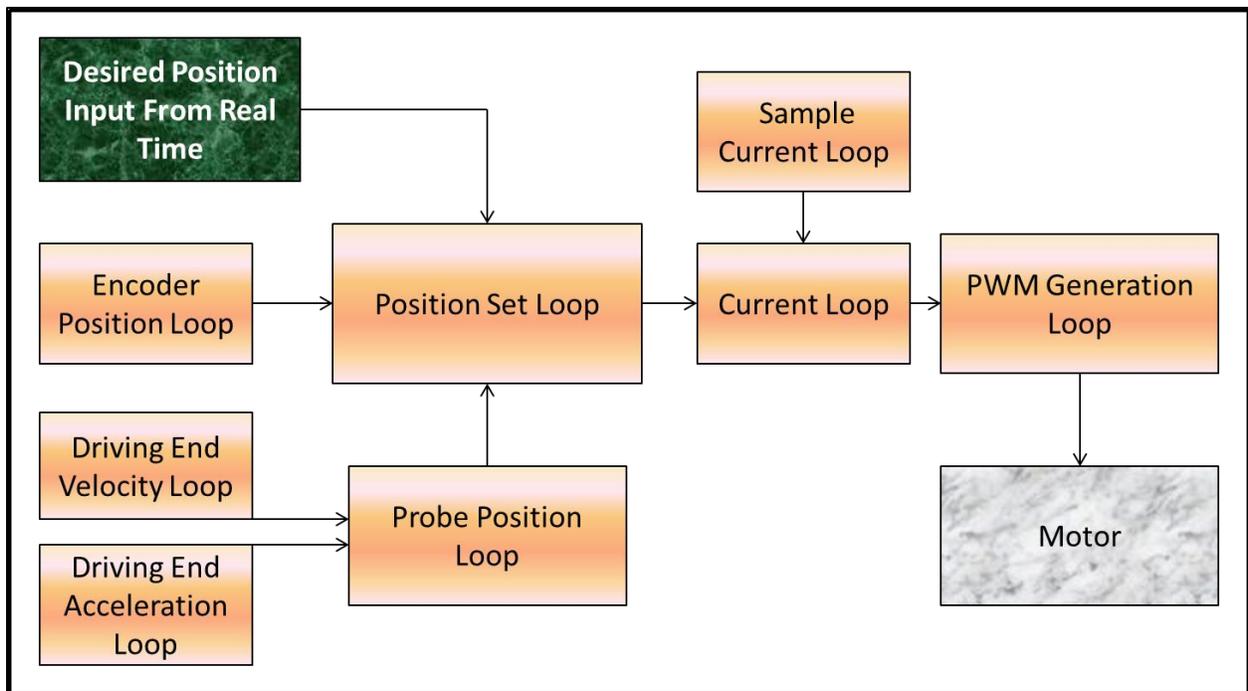


Figure 18: Schematic of FPGA loop interactions for motor control.

desired end position of a move or the frequency, amplitude, and number of cycles of the desired oscillation. The Position Set Loop then calculates the desired position of the driving end encoder and feeds that position, along with the latest driving end position reading, to a PID controller. The PID controller then outputs the value of the electrical current to the motor needed to achieve the desired encoder position. In probe-control mode, a step is added utilizing the Probe Position Loop, a process loop which takes in data from other process loops that calculate the driving end position, velocity, acceleration, and force. Within the Probe Position Loop, the appropriate driving end position is then calculated using the calibration equation determined through the calibration process which is discussed in Chapter 4. This desired driving end position undergoes the same process as driving end control, resulting in the proper probe displacement. The desired electrical current is taken as an input of the Current Loop. The Current Loop is a process loop that evaluates the desired current and makes sure it is safe before comparing it to the current feedback, which is sampled in another process loop (Sample Current Loop), and then sends those values to an internal PI controller. This output is sent to another independent process loop, the PWM Generation Loop, in which a pulse width signal is generated and sent to the motor.

The other main surface level loop is the Data Acquisition Loop. This loop samples important values from other parts of the FPGA program and collects them into an output packet for the Real-Time Computer. This packet is constantly updated to provide the most recent sample of data for the Real-Time Computer.

Real-Time Computer

The second computer is also housed within the CompactRIO, and it operates in real-time. Real-time refers to the deterministic way which this computer processes information. Most computers do not run in real-time. If you tell a standard personal computer to complete a task every 500 cycles it will be completed on average that often, but the task may be completed at

496 clock cycles for one instance of the task and at 504 during another. A real-time computer will accomplish the task at 500 cycles every time. This makes the Real-Time Computer the ideal place to capture the data from the FPGA for saving.

The main tasks of the Real-Time Computer for EVE are to capture the data from the FPGA in a deterministic manner, sending that data to the Host Computer for saving, and coordinating the communication and commands between the Host and FPGA. Since the FPGA does not process higher level mathematical operations, the Real-Time Computer is used to take commands from the Host Computer and reformat them into signals and cues that the FPGA can process. This can be breaking down a velocity for a move into which loop iterations to increment the position set point, or simply getting the commands from the Host Computer to scale correctly from the double precision floating-point structure of the Host Computer to the fixed-point architecture of the FPGA.

Host Computer

The Host Computer is a standard laptop which runs LabVIEW in order to facilitate the human interaction with EVE and to serve as a hard drive to save the relevant data. Data are received from the Real-Time Computer and sent to waveform charts so that the user can monitor the operation of EVE. With the flip of a virtual switch, data can be captured by the user into a .tdms file to be processed later. The HostGUI.vi program uses a user-provided base file name and appends to it the date and time in order to differentiate files and allow the user to capture many files without overwriting the file each time.

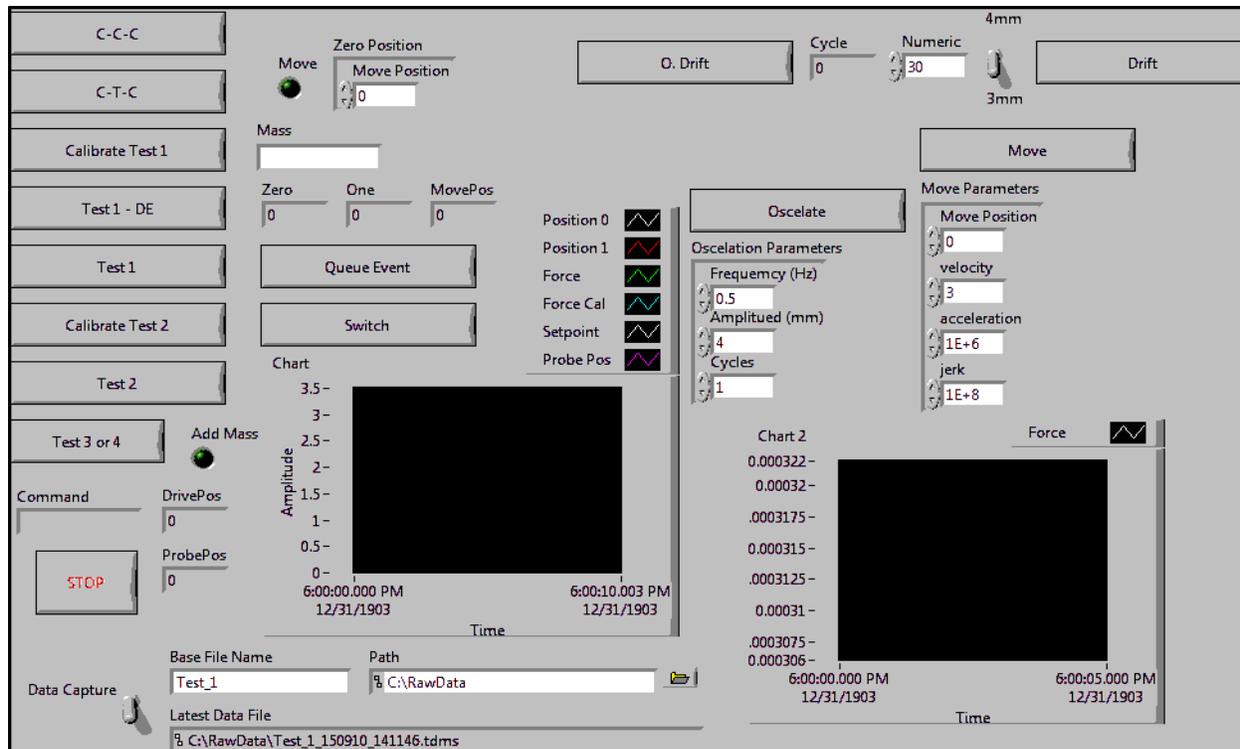


Figure 19: Current host computer user interface, where buttons on the top and right are programmed automatic protocols, data capture is controlled in the bottom left corner, the “Oscillate” and “Move” buttons control the instrument’s two basic movements with their respective inputs below, and two charts which display the latest values from the sensors.

In the most basic operation, the user can send EVE to a given position at a given velocity or prescribe an oscillation frequency, amplitude, and number of cycles to complete. The user is also able to designate a base file name and stop or start data capture at any point. I have also programmed several custom process buttons, which can be seen in Figure 19, that automatically perform the protocol for a given test, including changing base file names and precisely timed movement commands and data capture periods. Several of these test procedures are described later.

Chapter 3) Tissue Phantom Validation Design Process

Tissue phantoms can be tuned to mimic human tissue elasticity and have been used to validate many methods of measuring elasticity of different tissues [50-53]. Gelatin-based and agar-based phantoms can be used to validate EVE, characterize its operation, finalize the human subject protocol, and ensure its reliable operation before human subject testing begins. Although all of these tests have not been completed, the framework of the test design is still valuable for future validation of EVE.

Selection and Manufacture of Tissue Phantoms

The six phantoms, five gelatin (Ballistic Gelatin Lot#00535, Gelatin Innovations) and one agar (A360-500, Fisher Chemical), shown in Table 2, were selected and produced using a protocol modified from Hall *et al.* [50] described later in this section. The phantoms selected have an expected Young's modulus covering a range from the 7.4 kPa reported from vaginal tactile imaging [45] to higher values that EVE may encounter during contractions or from underlying tissues. The agar phantom is included because it can show nonlinear behavior [50], and data from this study may be used in the future to show that the EVE can detect nonlinearity.

Table 2: Phantom Formulations.

| Number | Type | Gel (g) | Water (mL) | Formaldehyde (mL of 37% solution) | Expected E (kPa) |
|--------|---------|---------|------------|-----------------------------------|------------------|
| 1 | Gelatin | 40 | 996 | 4 | 7.6 |
| 2 | Gelatin | 60 | 996 | 4 | 17.7 |
| 3 | Gelatin | 80 | 996 | 4 | 32.3 |
| 4 | Gelatin | 100 | 996 | 4 | 51.5 |
| 5 | Gelatin | 120 | 996 | 4 | 75.3 |
| 6 | Agar | 11.4 | 1000 | 0 | 32.2 |

Formaldehyde is added to the gelatin phantoms as a hardener. The formaldehyde increases crosslinking in the gelatin which increases the stiffness and melting point [54]. The

formaldehyde also continues acting for several weeks after the phantom is manufactured, so it will be important to test each phantom at the same time post-manufacture. Hall *et al.* used n-propanol in order to manage the speed of sound within the phantom [50] because their phantoms were used for ultrasound testing. For these tests, the n-propanol was removed as unnecessary and replaced with an equivalent volume of water.

Hall *et al.* also reported that an expected Young's modulus could be estimated from the concentration of gel by the relationship $E_{gelatin} = 0.0034C^{2.09}$ and $E_{agar} = 0.34C^{1.87}$, where E is the Young's modulus in kPa and C is the concentration of the gel in g/L [50]. These formulas were used to find a set of gelatin phantoms which represented the range of interest. The concentration of the agar phantom was determined in order to match the expected Young's modulus of Phantom 3, the 80 g gelatin phantom.

The phantoms were manufactured using the following procedure adapted from Hall *et al.* [50] and the formulations in Table 2:

1. Heat the water to 80° C and add gel slowly to prevent clumping
2. Stir for 10 minutes using mechanical stirrer to allow gel to dissolve
3. Add formaldehyde (if applicable) and continue stirring for 30 seconds
4. Pour into mold in waiting ice bath and let the solution cool for 3 minutes
5. Remove mold from ice bath, cover and put in refrigerator
6. Remove from mold 8-24 hours later, after hardening
7. Store in airtight bag in refrigerator
8. Let sit for one week from manufacture to allow formaldehyde to crosslink gelatin

Tissue Phantom Mold Design

A special mold, shown in Figure 20, was made for the phantoms to set in, technical drawings of which can be found in Appendix A. The mold creates a cube of phantom which is four inches per side, with a one inch diameter cylindrical cavity through the phantom in the center of two opposing faces. These dimensions were chosen with the cavity matching the approximate size of the probe and the sides to

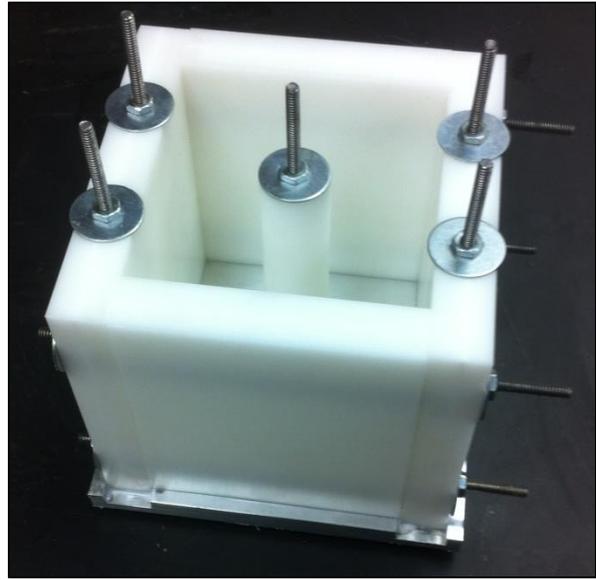


Figure 20: Assembled phantom mold.

allow the finished phantom to be approximately a cube with a volume of one liter to match the volume of the phantom recipe. The mold was designed to easily disassemble for easy release of the phantom and easy cleaning. Because of this, the mold has several joints which are made temporarily water tight through the use of washable glue. The glue holds a watertight seal long enough for the phantom to set, while still being easy to clean. Soybean oil-based spray is also used on the interior surfaces of the mold to prevent phantom damage by facilitating a clean release of the phantom from the mold.

Phantom Test Design

Phantom Data Collection Protocol

Prior to testing, the phantom will be removed from the refrigerator and allowed to sit for two hours in order to warm up to room temperature. The phantom will then be placed on its side, and a female condom may be placed into the cavity. After initializing EVE, the probe will be calibrated

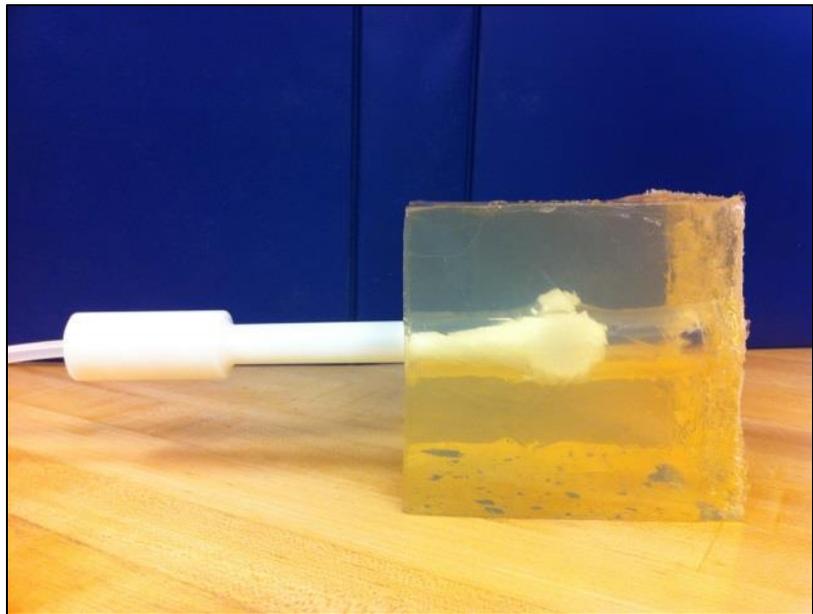


Figure 21: Tissue phantom with probe inserted ready for test procedure.

following the procedures outlined in Chapter 4 for the target frequency; and then the probe can be inserted approximately six centimeters with the rear supported to keep the probe approximately level, as shown in Figure 21 (support out of frame). Once the probe is inserted, the EVE control software will perform the desired test. At the end of each test the measuring surface will be retracted to zero displacement, and the probe will be removed and recalibrated for the next test.

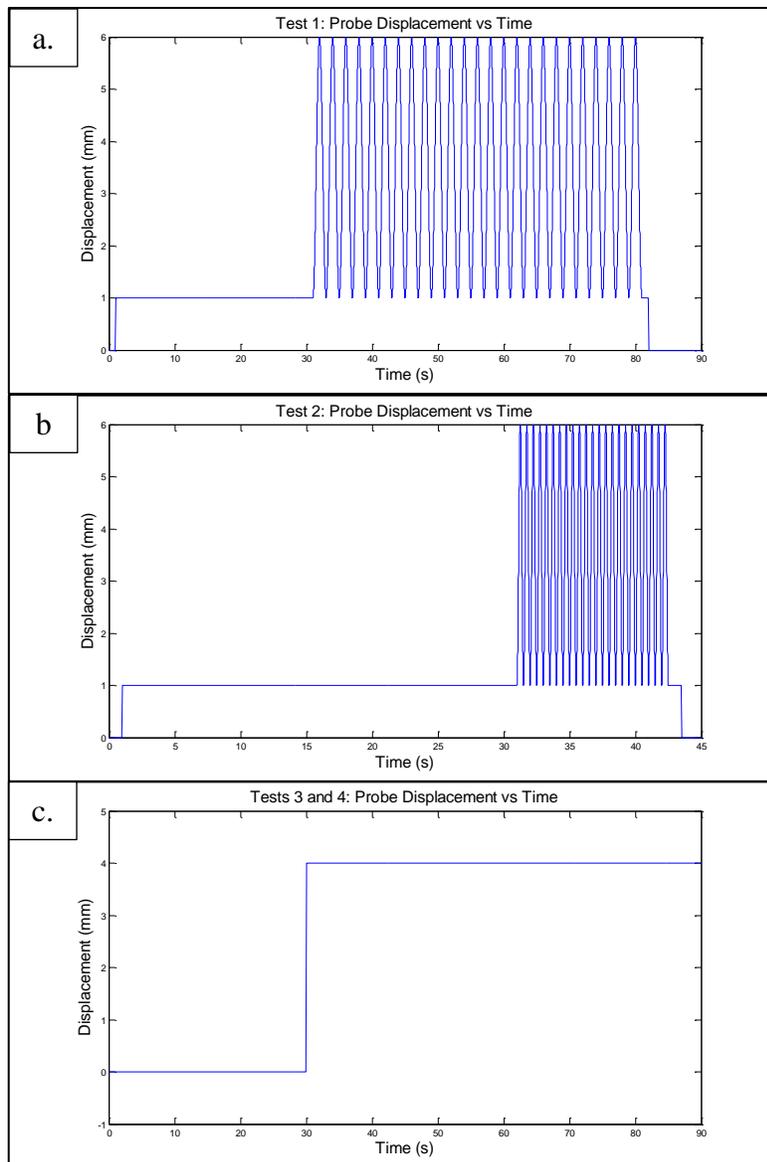


Figure 22: Probe displacement over time for each of the planned tests.

will then be held for one minute while recording the force and displacement measured at the driving end and the calculated force and position at the measuring surface (Figure 22c). The fourth test will follow the same procedure as the third, but approximately 20 seconds after the step displacement, a 500 mg mass will be gently placed on the top surface of the phantom.

Elasticity will be estimated by looking at the 20th loading cycle of each frequency from Tests 1 and 2. We will estimate stress from the instrument force over the area of the measuring

The first test will apply a 1 mm initial displacement which will be held for 30 seconds followed by a 0.5 Hz oscillating displacement with a magnitude of 5 mm for 25 cycles while recording the force and displacement measured at the driving end and the calculated force and position at the measuring surface (Figure 22a). The second test will follow the same procedure as the first, but the frequency of oscillation will be changed to 2 Hz (Figure 22b). For the third test, EVE will apply a step displacement of 4 mm which

surface (265 mm²) and strain from the instrument's displacement over the thickness of the phantom from the cavity edge to the outside edge of the phantom (3.8 cm).

Plans for Pilot Phantom Study 1

The first pilot study was designed to test for phantom damage from the EVE procedure and repeatability of the combined calibration and testing process. Even though tissue damage in human subject testing would be very unlikely, the phantoms were selected in order to match the expected stiffness component of the vaginal closing force and are much more susceptible to damage than the tissue they mimic. It will be important to confirm that testing will not damage the phantoms, and that each phantom can be used for multiple tests.

Phantom 1 will be run through the testing procedure ten times and examined for any damage to the phantom. Special care will be taken to look for tearing of the gelatin and for cracks extending from the measurement site.

In addition to direct observation of phantom damage, a comparison of the elasticity estimates for each frequency will be made over time to check for phantom damage. Additionally, a student t-test will be performed on the elasticity estimates at each frequency to test for repeatability. If the t-test reveals a significant difference among the measurements, steps will need to be taken to ensure that no phantom damage is occurring and to ensure that EVE is operating repeatably.

If damage is found to be more than minimal, the phantom data collection protocol will be modified to decrease total displacement and/or the oscillation frequency. Additionally, this pilot study may be repeated with Phantom 2 Phantom 1 proves to be too delicate for the testing procedure. If Phantom 1 is too fragile to stand up to repeated testing, it may be removed from the future studies, or the number of repeated tests on it may be greatly reduced.

Plans for Pilot Phantom Study 2

The second pilot study was designed to determine the effect of a female condom on the elasticity estimate. Using a female condom will increase patient safety and facilitate easier cleaning of EVE; however, the female condom may affect the elasticity measurement. This study will be used to determine if there is a significant change in the elasticity measurement from using a female condom, and will be used to evaluate the necessity of using female condoms in the main phantom study as well as future *in vivo* studies.

Phantom 3 will be run through the testing procedure ten times, five without a female condom in place and five with the female condom in place alternating between the two cases. The elasticity estimate from the loading portion of the 20th cycle for each condition at each frequency will be compared by using a student t-test. If the t-test reveals a significant difference between the measurements, the use of the female condom may be removed from future *in vivo* studies, and a more thorough probe cleaning process may be required.

Plans for the Main Phantom Study

The main phantom study is designed to demonstrate the reliability and repeatability of EVE. It will involve all six phantoms, and each single phantom will be run through the phantom data collection protocol five times, as shown in Table 3. Data analysis for this study will look at the elasticity estimate at each frequency on the loading portion of the 20th cycle. For each phantom, a standard deviation will be calculated for each frequency to evaluate repeatability. A two factor ANOVA will also be performed on the EVE data, using the two factors of phantom and frequency, in order to verify a significant ability to detect a change in elasticity or a frequency dependence in the phantom or EVE.

Table 3: Data to be Collected in the Phantom Study.

| Phantom | Test 1 (0.5 Hz) | Test 2 (2 Hz) |
|---------|-----------------|---------------|
| 1 | E ± SD (n=5) | E ± SD (n=5) |
| 2 | E ± SD (n=5) | E ± SD (n=5) |
| 3 | E ± SD (n=5) | E ± SD (n=5) |
| 4 | E ± SD (n=5) | E ± SD (n=5) |
| 5 | E ± SD (n=5) | E ± SD (n=5) |
| 6 | E ± SD (n=5) | E ± SD (n=5) |

Tests three and four from the protocol will be performed and the data will be archived for possible later use, with no statistical analysis performed at that time. Their inclusion in this procedure is to evaluate possible human subject protocols and monitor the device for proper operation.

Chapter 4) Design Process for Calibration Instrument and Procedure

Calibration Instrument

A second instrument was also developed to be used to calibrate EVE. The calibration instrument, shown in Figure 23, measures the force and displacement of the measuring surface of the EVE probe. These measurements are then used to make the calibration equations, which relate force and displacement at the driving end to the force and displacement of the measuring surface. To simplify programming, the calibration instrument uses the same initial load cell

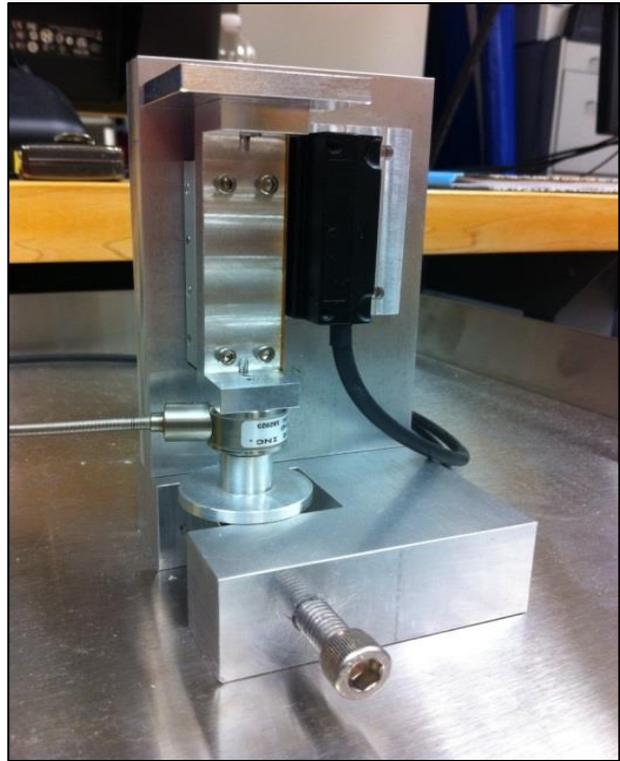


Figure 23: The calibration instrument. (WMC-10, Interface) and encoder (RGH22, Renishaw) as the driving end of EVE. The calibration instrument features a set screw to keep the probe head in position during the calibration process, as well as a platform for calibration masses. The ability to add elastic bands gives the operator the option to vary the load during the calibration process to calibrate the instrument under more physiologically relevant loads.

Technical drawings of the calibration instrument machined parts are available in Appendix A.

Force and Position Calibration Process

In the initial design, with both bellows of matching diameter, the expectation was that the displacement at the probe end would be identical to the displacement at the driving end. Even

when the driving bellows had to be replaced; it was hoped, due to the incompressibility of water, that the probe end position would still be a simple ratio of the driving end position.

Similarly, because the two bellows are linearly elastic, determining the force at the probe end was initially thought to be easily calculated through a linear function of the driving end force and position such as: $F_P = c_1F + c_2P$, where F_P is probe end force, F is the driving end force, P is the driving end position and c_1 and c_2 are the two constants to be determined through calibration. The c_1F term represents the relationship between the force at the probe end and the force at the driving end and the c_2P term acting to account for the effect of the elastic bellows.

These models, however, were extremely optimistic as illustrated by Figure 24, which shows that calculating the probe end position requires at least the inclusion of the driving end force, and not simply a ratio of the bellows' dimensions. This began a search for a new calibration equation, with the goal of finding an equation that would allow accurate calculating

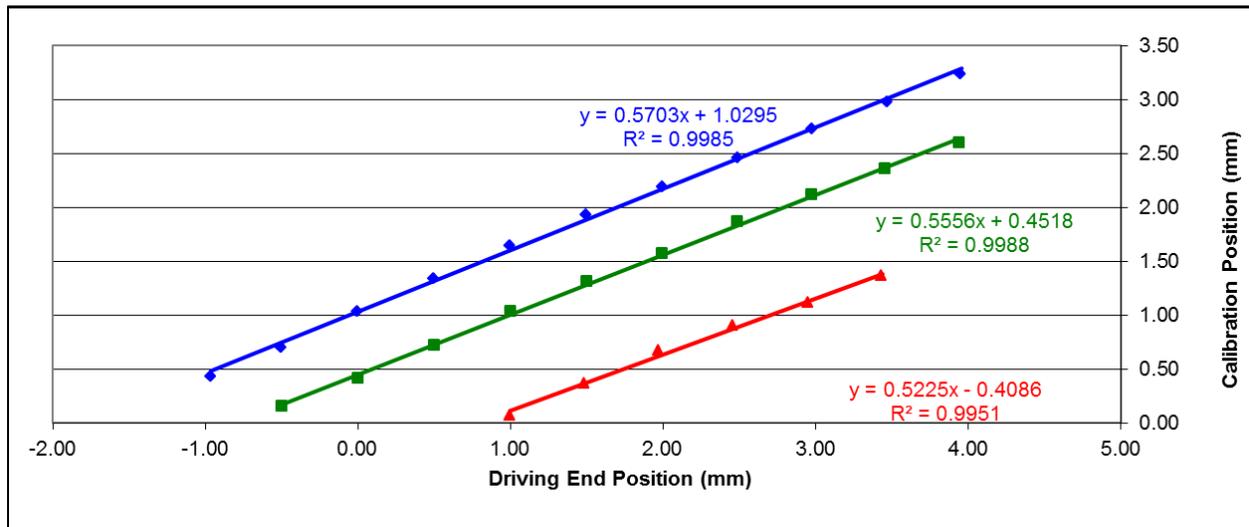


Figure 24: Early position calibration data. Each line represents a different calibration mass. the probe end position and force from the displacement and force measured at the driving end.

Eight Parameter Calibration Process

Several factors may contribute to the necessity for a more complex model, including non-rigid tubing, and air clinging to internal bellows folds. To identify relevant variables for this more complex calibration process, additional parameters were tested by stepwise regression. Stepwise regression showed that eight calibration parameters were important to include in the calibration equation. Probe force and position were determined to be best calculated with the following calibration equations:

$$F_p = c_0 + c_1F + c_2P + c_3F^2 + c_4P^2 + c_5FP + c_6\frac{dP}{dt} + c_7F\frac{dP}{dt}$$

$$P_p = d_0 + d_1F + d_2P + d_3F^2 + d_4P^2 + d_5FP + d_6\frac{dP}{dt} + d_7F\frac{dP}{dt}$$

Probe force (F_p) and position (P_p) are both calculated as functions of the measured driving end force (F) and position (P), squared terms of both force and position (F^2 and P^2) to account for the nonlinear compliance of the system, a term for system work (FP), the driving end velocity ($\frac{dP}{dt}$), and a power term ($F\frac{dP}{dt}$).

When the probe position was calculated as a simple function of the driving end position, moving the probe end to a specified position could be done easily on the Host Computer without monitoring any sensor values. Because the probe position is now also a function of the driving end force and velocity, sensors must be actively monitored and calibration variables calculated in order to control the probe displacement. Calculating probe position and updating the appropriate driving end position to attain the desired probe position would be too slow and cause significant delay if it was still done on the Host Computer. So it became necessary to calculate the probe end displacement using the FPGA in order to have accurate probe position control.

The eight parameter calibration process was designed to match the oscillatory tests run by

EVE. The procedure is as follows:

1. Insert the probe into calibration instrument with rubber band in place, as shown in Figure 25
2. Check initial system pressure, and add up to 1 mL of water to the system if necessary to maintain a positive system pressure



Figure 25: The calibration instrument in use.

3. Add 1 kg mass to the calibration instrument platform to push the probe down to zero displacement for encoder initialization
4. Slightly disturb driving end by manually moving the motor approximately 3 mm and releasing to ensure that the system begins in equilibrium
5. Start program to initialize zero position and begin motor control
6. Remove the 1 kg mass from calibration instrument
7. Start data collection
8. Oscillate from 0 to 4 mm at the target frequency for 40 seconds, changing masses every 10 seconds through the sequence of unloaded, 100 g, 200 g, and 500 g
9. Stop data collection
10. Fit to eight parameter model using a least-squared fit to obtain calibration constants
11. Switch the instrument to probe control mode

Figures 26 and 27 show sample data from the eight parameter calibration process, which consistently yields R^2 values greater than 0.95 for both force and position fits.

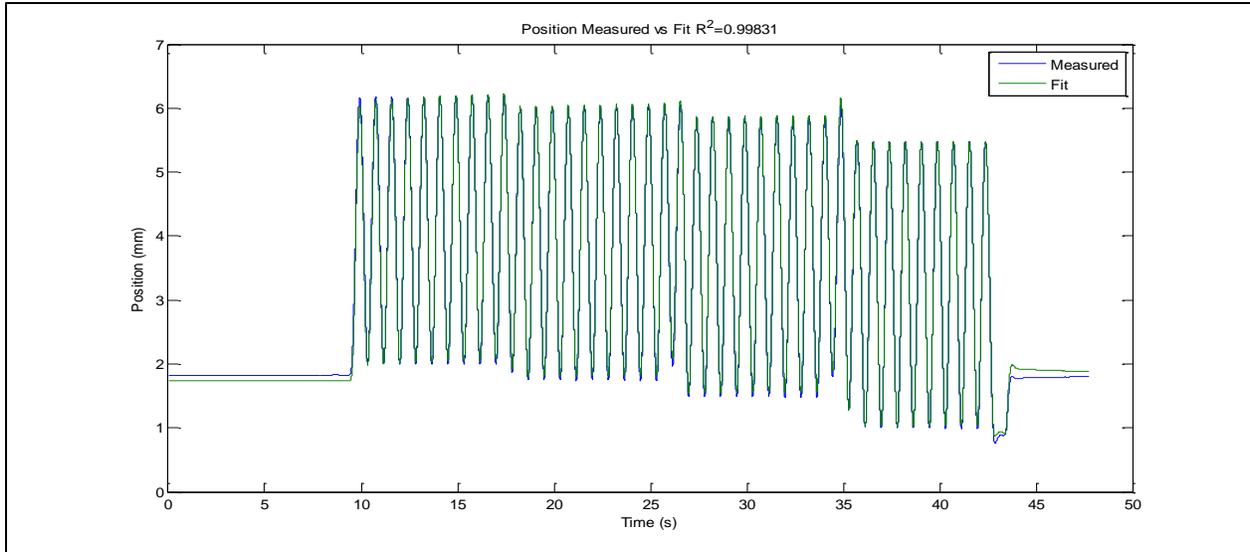


Figure 26: Eight parameter position calibration data. With the measured data vs fit has an $R^2=0.998$.

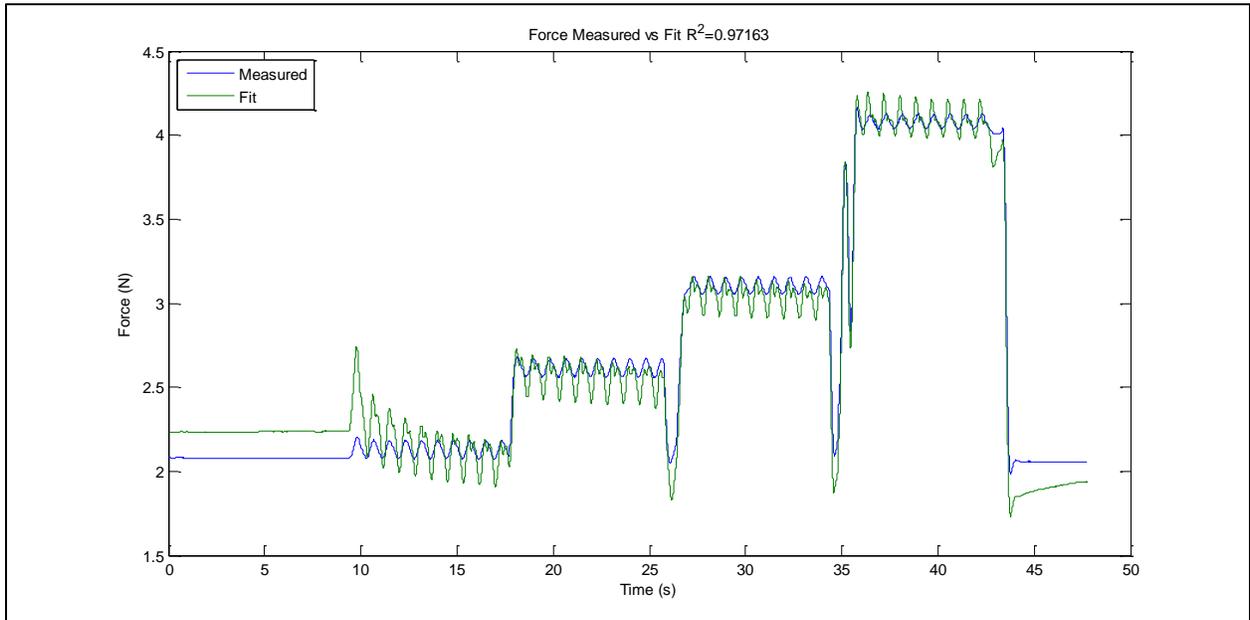


Figure 27: Eight parameter force calibration data. With the measured data vs fit has an $R^2=0.972$.

The eight parameter model breaks down when actually used for probe control. Although there are good R^2 values matching the measured calibration data to the estimate; it is still not good enough for accurate control. This is especially evident when taking a closer look at the force data in Figure 27. Although the calculated force does follow the bulk moves of the measured force, the actual fit is not close enough to the data to make an accurate elasticity measurement. Looking at the oscillation at 20 seconds in Figure 27, one can see that, although the measured force is only oscillating with a magnitude of approximately 0.1 N, the calculated force is oscillating with a magnitude of approximately double that. This will give elasticity estimates that could be double the actual even though the R^2 value for the fit is very good.

Comparative Elasticity Calibration Process

The previous section shows that finding a fit which can precisely match the displacement and resultant force at the probe end from the values measured at the driving end have proven to be very difficult to find through a calibration equation. Ultimately, since we are interested in finding an approximation of Young's modulus for the tissue, it was determined that it might be possible to get an estimate from measuring the elasticity for the entire system at the driving end and correlating that with a measured calibration Young's modulus.

With that in mind, a new calibration process was created that would rely entirely on calibrating the instrument against varying elastic loads. The new process is as follows:

1. Insert the probe into the calibration instrument making sure that the set screw is tight on the probe head
2. Check initial system pressure, and add up to 1mL of water to the system if necessary to maintain a positive system pressure
3. Add seven elastic resistance bands to the calibration instrument

4. Add 1 kg mass to the calibration instrument platform to push the probe down to zero displacement for encoder initialization
5. Slightly disturb the driving end by manually moving the motor approximately 3 mm and releasing to ensure that the system begins in equilibrium
6. Start program to initialize zero position and begin motor control
7. Remove 1 kg mass from calibration instrument
8. Start data collection
9. Move the driving end from a zero position to a 1 mm displacement
10. Oscillate from 1 mm to 2 mm driving end displacement at a frequency of 0.5 Hz for 3 cycles
11. Hold position at 1 mm driving end displacement for 4 seconds while an elastic resistance band is removed from the calibration instrument
12. Repeat steps 9-11 seven times
13. Move the driving end back to a zero position
14. Stop data collection

A graph of the driving end position over time for this new calibration process can be seen in Figure 28.

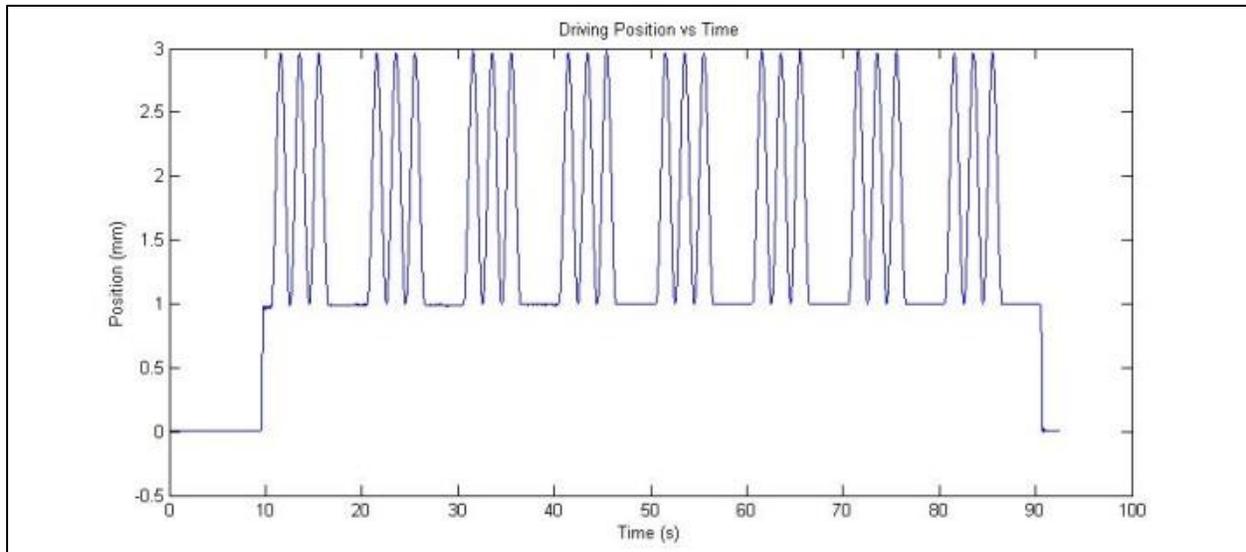
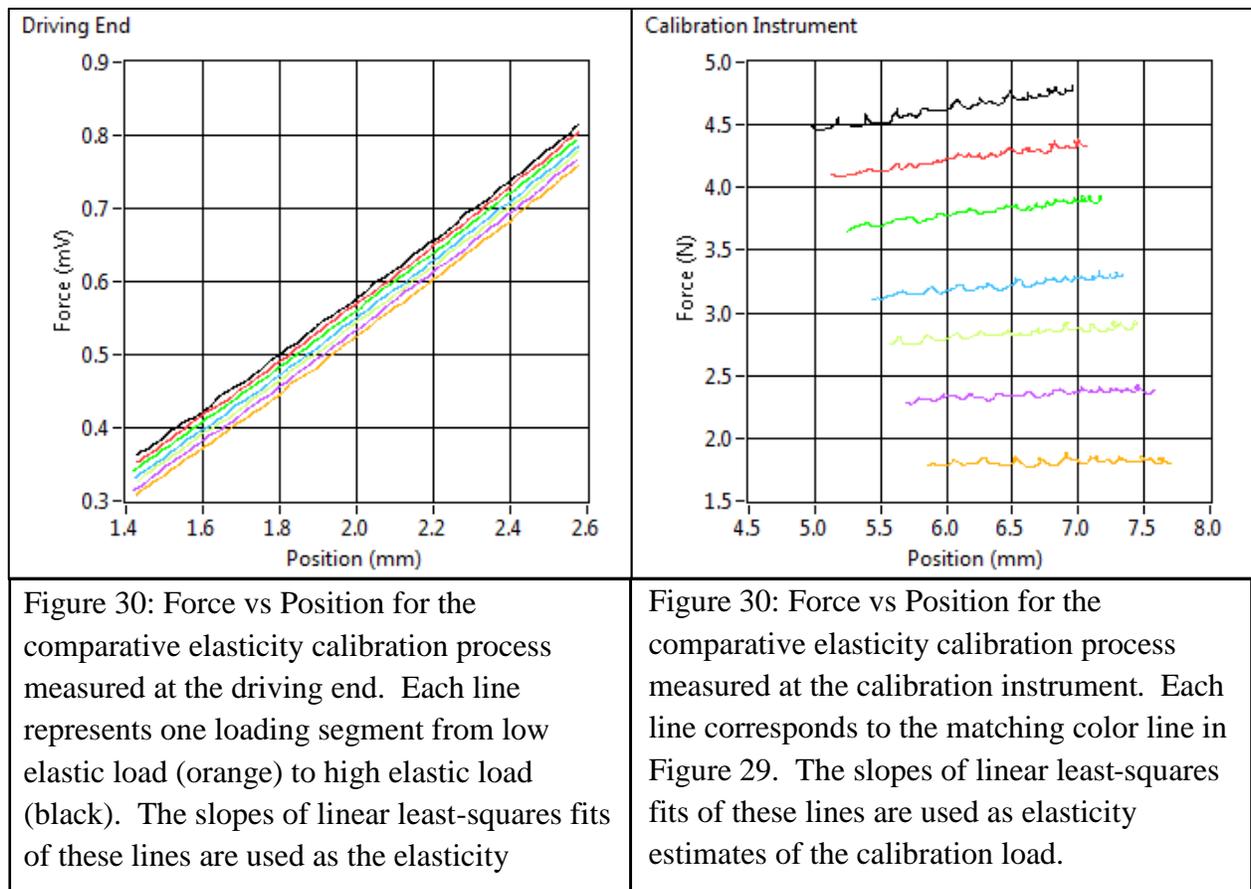


Figure 28: Driving Position vs Time for the comparative elasticity calibration process.

This new calibration process is not sufficient to enable the instrument to enter probe end control. In fact, probe force and position are never calculated. The ability to detect nonlinearity is also sacrificed. However, since we are looking at the change in the whole system's response to varied calibration loads, we are only interested in moving the driving end reliably, which EVE does very well. Looking at the whole system response might negatively affect the instrument's ability to measure viscoelasticity, but allowing for estimation of Young's modulus is a significant beginning.

After the calibration process is complete, the data is processed in the Slopes2.vi data processing program which can be found in Appendix B. The Slopes2.vi code automatically imports the saved data from the trial and plots the driving and calibration positions and forces to allow for a visual inspection of the data to ensure it was taken correctly. Next, the program searches for the second loading phase for each elastic resistance. The indexes of these phases are then used to generate plots of force vs position for both the driving end and the calibration instrument for each of these ranges, examples of which can be seen in Figures 29 and 30. With each loading segment isolated, the slope of each line can be used to calculate elasticity for the entire system (E_{driving}) at each load and the Young's modulus of each calibration load (E_{cal}). Then a plot is generated of E_{cal} vs E_{driving} as seen in Figure 31. Using a least-squares fit equation



with these eight data points, an estimate of the calibration instrument's measured elasticity can be made from the system elasticity measured at the driving end.

After calibration, the entire calibration procedure can be repeated as a test procedure with the probe in the tissue phantom. This can generate the desired elasticity estimate for the tissue phantoms based on the measured system elasticity using the calibration curve generated in the comparative elasticity calibration process.

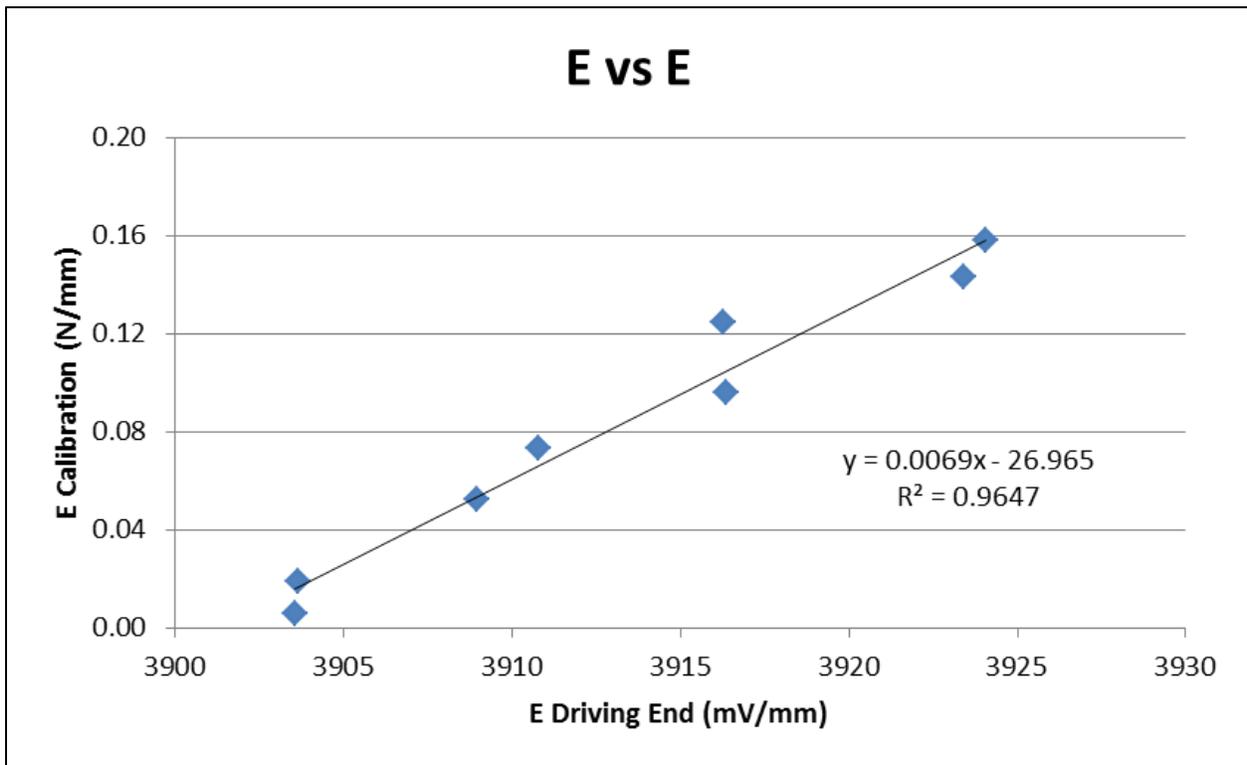


Figure 31: Example E_{cal} vs $E_{driving}$ plot and fit from the comparative elasticity calibration method.

Chapter 5) Design Evaluation

As an instrument, EVE is designed to accurately capture a very small signal embedded within a much larger signal. Looking at the measured driving end force from a sample calibration process in Figure 32, it can be seen how little the peak force transducer reading (in mV) reacts to the addition of a significant load on the probe end. Throughout the entire process,

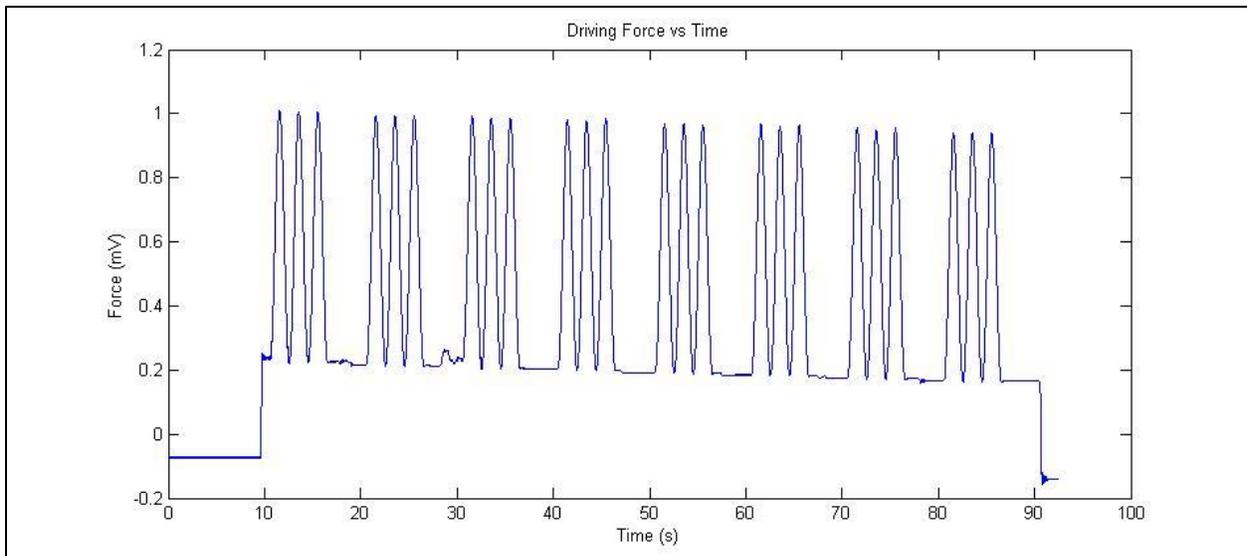


Figure 32: Example driving force transducer reading (in mV) over time for a calibration from the maximum load during the calibration to a negligible load at the probe end, the peak force measured at the driving end only decreases by approximately 5%. This is also just the change in maximum force; the difference in slope of the force-displacement curve is much more subtle. Up until this point, we have been confident that, whatever happened during the process, we would be able to mathematically determine what was happening at the probe end. Since we are looking for such a small part of a comparatively large signal, any small disruption of the system can have disastrous consequences for our ability to make meaningful measurements. Obvious sealing issues, buckling of bellows, and air within the system all caused major problems with the calibration of EVE, but were readily apparent and have been addressed. This new issue,

although more subtle in its detection, has nonetheless had a major effect on the viability of EVE as a clinical instrument.

Drift

During initial testing, it soon became apparent that there was another issue with the calibration process. Bench tests, with the probe still within the calibration instrument, were performed. Young's modulus values that were measured within calibration range by the

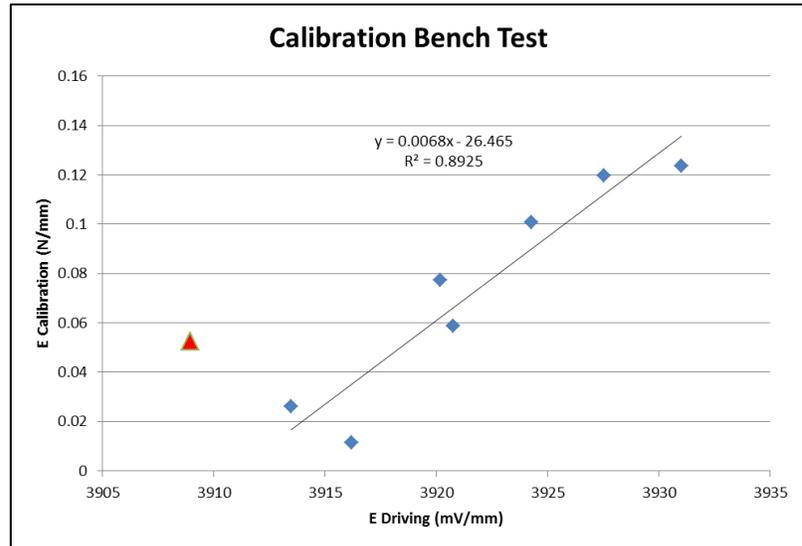


Figure 33: Example bench test of calibration process.

calibration instrument were calculated to be well outside of range from the comparative elasticity calibration equation. This can be seen in Figure 33, where the calculated elasticity of the test measurement of the red triangle would have a non-physical negative Young's modulus according to the comparative elasticity calibration equation, despite having a measured Young's modulus that is well within the calibration range. Bench tests were consistently underestimating the calibration force; so it seemed that there was an unaccounted for drift tending toward lower system elasticity.

Drift Tests

Test Procedure

In order to quantify this drift and to try to identify the source of the issue, a simple protocol was developed to view the system change over time. A new protocol, called Drift, was

programmed into the HostGUI.vi program. This protocol monitored the system through an approximately thirty-minute ramp and hold test displacement. If necessary, before the test, the system was prepped with a preload of up to 1 mL of water as in the calibration protocol. The 1 kg calibration mass was then placed on the calibration instrument to ensure the calibration encoder was initialized properly. The system was then initialized, after which the 1 kg mass was removed, and the 200 mg test mass was put in place before beginning the Drift Protocol. The Drift Protocol first began collecting data. The next command quickly stepped the driving end to the desired displacement, either three or four millimeters, which was determined by a user input switch. The displacement was held for thirty minutes before the driving end was moved back to zero displacement at the end of the test.

Because of the file size required to constantly record data at 2000 samples per second in six channels of double precision data for half an hour, the host computer would have had trouble processing the data from these tests if the data were collected in that way. To get around this limitation, the drift protocol on the HostGUI.vi was programmed to only collect data for thirty seconds at a time, after which, data was not recorded for thirty seconds before recording again. , Instead of one unmanageable file, this process yielded thirty smaller files that could be sequentially processed more easily by the host computer.

The host processing of the data analysis program (DriftAnalysis.vi shown in Appendix B) opened each file, then took an average of the measured driving end forces, driving end positions, calibration forces, and calibration positions over one second of the collected data. This average point was used as representative data for that file's time point, reducing over 21 million points to the representative 30 used to examine system drift.

Test Results

In order to quantify and look for the source of the system drift, several drift tests were conducted. Each test was run in triplicate to test for repeatability of the situation. First, to ensure that the load cells and encoders were functioning properly, the drift

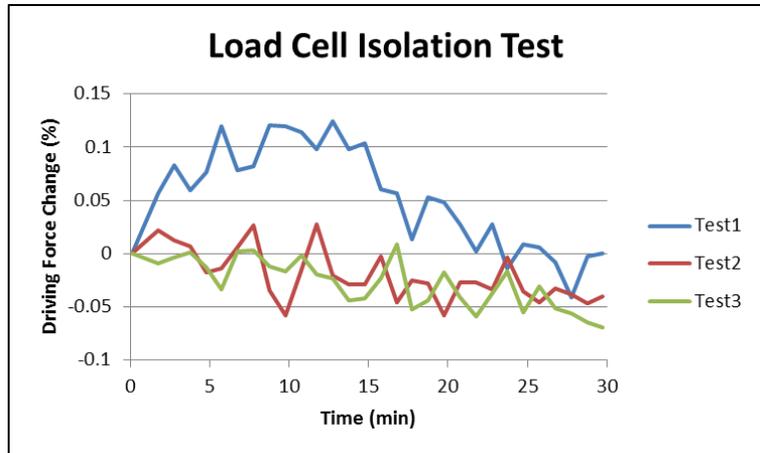


Figure 34: Isolated driving load cell percent force change with a constant load

protocol was run with the load cells removed and isolated under static loads, and with the encoders fixed. This test, as expected, showed no drift. A plot of the change in driving force over time can be seen in Figure 34, where the magnitude of force change always remained under 0.15%.

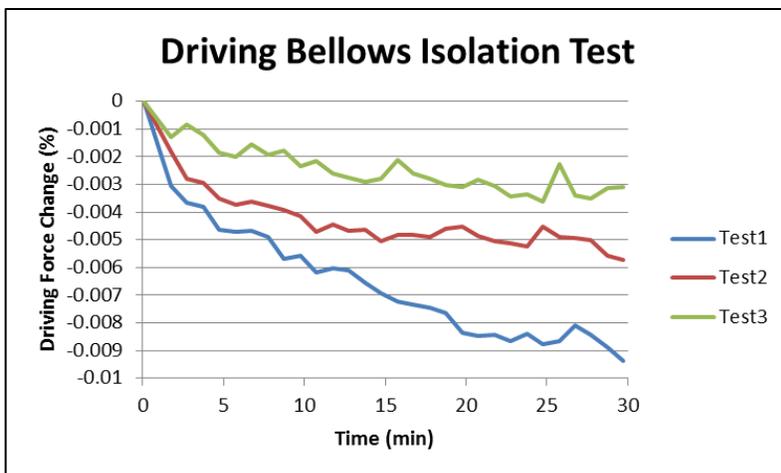


Figure 35: Isolated driving bellows force change with a constant displacement.

After confirming that the sensors were working properly, an additional variable was added to search for the source of the drift. The second drift test was conducted with the hydraulic components removed from the system, with the driving end

ramping and holding against the elastic resistance of a drained driving bellows. The driving

bellows was displaced by 4 mm and the resulting driving end force was tracked. This test was to determine if the bellows were showing signs of creep. The results of this test, presented in Figure 35, show that there is a slight relaxation of the bellows, but the force transducer measurement changes are very low, with the maximum change being less than 0.01%.

With this knowledge, the next area of investigation for the third set of tests was the tubing. EVE utilizes 0.25” outer diameter nylon tubing as the hydraulic link between the driving and probe bellows. It was thought that, given that there was no creep in the bellows, the additive creep of all elements of the hydraulic system could be causing the system to drift. If this was the case, then greatly lengthening the tubing would greatly increase the drift, and replacing the nylon tubing with rigid copper tubing, although unsuitable for human trials, would greatly decrease the drift. Three setups were selected for testing: the original short nylon tubing (approximately 0.7 meter of tubing) used in all previous measurements, long nylon tubing (approximately 2.6 meters of tubing), and copper tubing (approximately 0.5 meter of tubing). These tests were once again run in triplicate, and Figure 36 shows the average driving force change for each tubing setup. Interestingly, the force change was the greatest for the short nylon tubing. This could have been

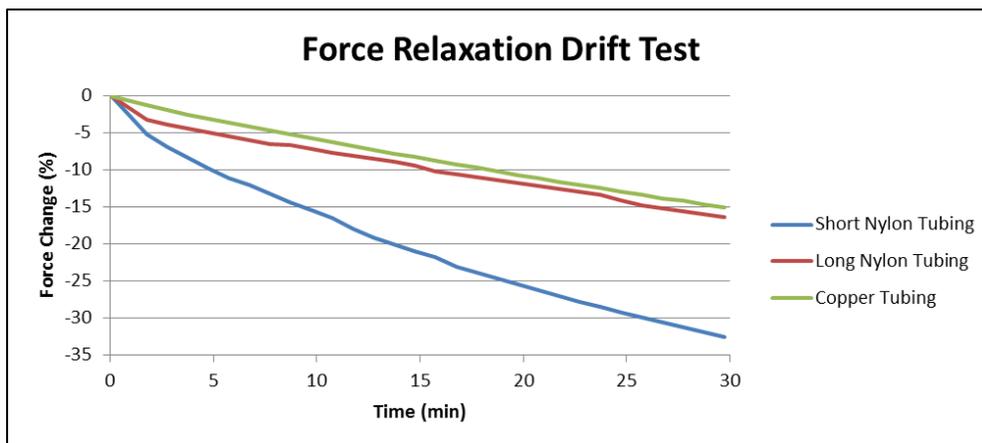


Figure 36: Average driving force reduction over time for three different tubing setups with a driving end displacement of 4 mm.

because the long nylon tubing setup used all new tubing, while the short nylon tubing setup was using tubing that had

been used on the instrument for several years. As predicted, the copper tubing showed the least force relaxation of the three. However, it still showed an unacceptable average drift of over 15% of the force reading in the 30 minute test. Thus, there is still a significant source of drift unrelated to the choice of tubing.

To attempt to isolate the effect of the system pressure on the drift issue, drift tests were conducted holding at 3 mm and 4 mm with both the long nylon tubing and copper tubing. Changing the system displacement is the easiest way to increase system pressure. Since the instrument force is of a much greater magnitude than that generated by a load, increasing the displacement of the system increases the system pressure far more than an additional load at the probe end would generate. If the system pressure was an important variable in determining the magnitude of drift, we could expect to see the drift decrease for the lower displacement. As can be seen in Figure 37, these tests had mixed results. For the nylon tubing, it was indeed the case that the drift was smaller for the lower displacement (3 mm compared to 4 mm displacement data). However, the average force change was lower in the 4 mm displacement copper tubing tests than in the 3 mm displacement tests. For both types of tubing, the averages for each displacement fall well within the measured range for the other displacement.

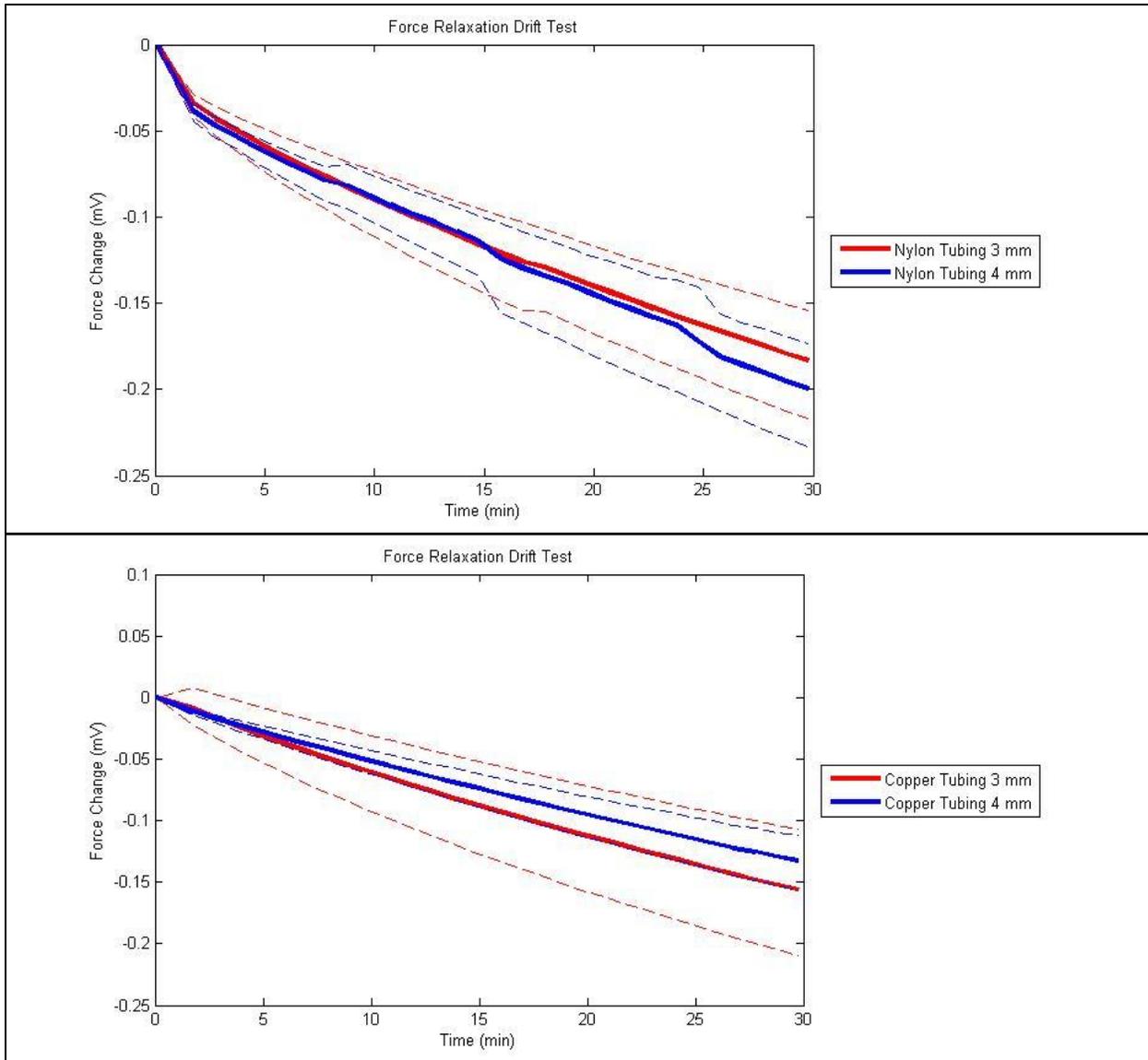


Figure 37: Average driving force reduction over time (solid line) with minimum and maximum measured (dashed lines) values, comparing 3 and 4 mm displacements in two types of tubing.

I believe that system pressure is still an important variable for the amount of drift in the system. However, there is another source of system pressure that was not controlled in these tests, the preload to ensure positive system pressure. The varying amount of preload from adding water to the system before the tests could have changed the system pressure enough to

explain the range of results seen here. In order to control this, a pressure gauge should be incorporated into the instrument in the future in order to ensure a consistent preload.

Although it is not apparent from our testing I believe that there are most likely one or several small leaks causing the drift issue. All of the readily accessible sites for possible leakage have been tested, but there are a few other sites which would be possible for undetected leakage to occur. Any internal joint within the probe bellows assembly is a likely site for concealed leakage. Water leaking from the hydraulic system into the interior of the bellows might evaporate before it could be detected. In addition, the check valve used in the system pre-pressure system may be allowing backflow into the syringe if it is not properly seating. Water leaking in this manner would also not be readily detectable. Although drift testing did not show a definitive link between system pressure and drift, which would strongly indicate a leak, the lack of proper control of the system pressure still leaves this a likely scenario for the origin of the drift issue.

Load-Order

Drift testing yielded no greater insight into what is causing the system drift, so options to minimize or account for the system drift were considered important. In order to be sure that our calibration is valid, and not just

measuring the drift within the system, the calibration process needed to be tested to see if the load-order for the calibration instrument mattered. To test this, the comparative elasticity calibration procedure was

modified to calibrate against increasing resistance rather than the decreasing resistance of the calibration process. The results, illustrated in Figures 38 and 39, show that changing the calibration process to an increasing load, although it still maintains a positive slope, changes the fit of the data dramatically. The decreasing elastic load test masks the drift

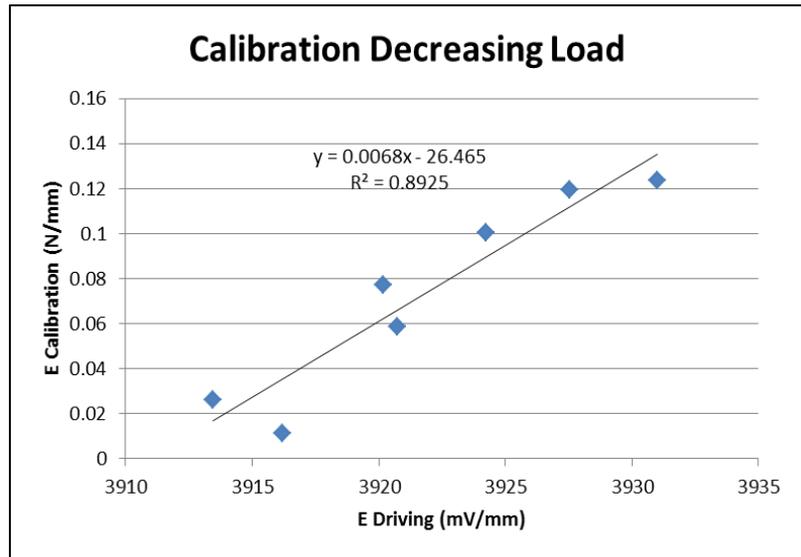


Figure 39: A sample calibration plot generated using a decreasing elastic load (uppermost first, with the drift tending to take points to the left).

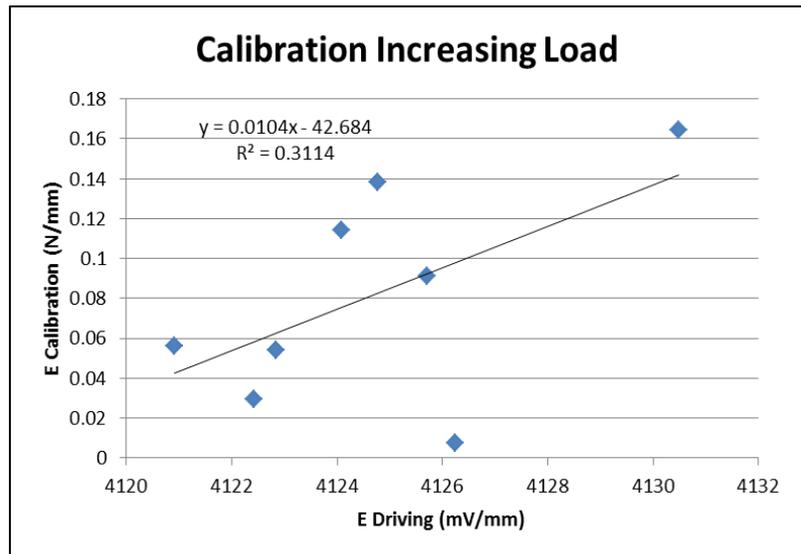


Figure 38: A sample calibration plot generated using an increasing elastic load (bottommost first, with the drift still taking points to the left).

within the expected results. Because the calibration elasticity decreased the driving end elasticity was also expected to decrease. We expect the new point to be to the left of the previous, higher elasticity, point; but this is also the direction that the drift takes the point. By switching to an increasing load calibration process, the next point should be to the right of the previous point, opposite to the drift. Large drift values can cause the next point to end up to the left of the previous point even though it should occur to the right of the previous point. This new loading order highlights the drift rather than masking it in the results. The results of these tests caused reevaluation of the comparative elasticity calibration process and change the procedure to one of increasing elastic loads to ensure that we are taking drift into account as much as possible when we are testing.

Calibrate-Test-Calibrate (C-T-C) Testing

In order to attempt to account for drift in the measurements, it was hoped that performing the calibration process as quickly as possible, both before and after a test, would allow us to average the calibration curves and data collected in between in order to get an estimate of

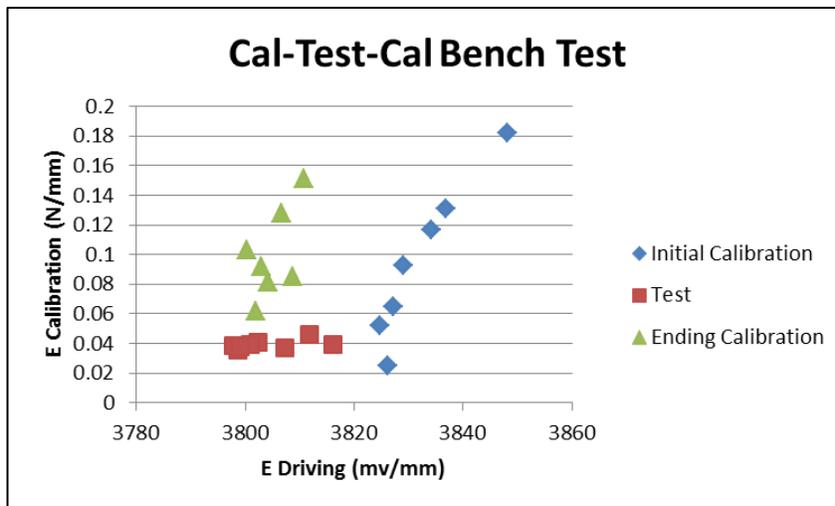


Figure 40: Sample Calibrate-Test-Calibrate bench test against a known elastic resistance.

elasticity. To accomplish this, another custom protocol button was added to the HostGUI.vi program that would run the calibration procedure three times sequentially with a standardized short delay between the three protocols

to allow the probe to be moved into a waiting phantom. This allows performing calibrations both before and after the middle test on a phantom. In order to test this process, bench tests were performed against a measured elastic resistance within the calibration instrument for the test known to be within the calibration range. The results, sample data from which are shown in Figure 40, only prove to illustrate the magnitude of effect that the drift issue has on generating meaningful results. The calibration curves, shown in blue and green, look serviceable enough, and appear to have a slight positive correlation between the elasticity at the driving end and elasticity at the calibration instrument, as hoped. However the test results, shown in red, illustrate how bad the drift is, with the span of the measured driving end elasticity covering almost the entire area between the two calibration curves. If not for them being plotted with the measured elasticity at the calibration instrument, it would be impossible to recognize what the probe end elasticity might be.

Repeated Calibration

To assess the calibration process, tests were run where the calibration process was

completed ten times

sequentially. Figure 41

shows sample data from the

first of three repeated

calibration tests. The drift

between the individual

calibration curves is observed

by the calibration curves

shifting to the left with

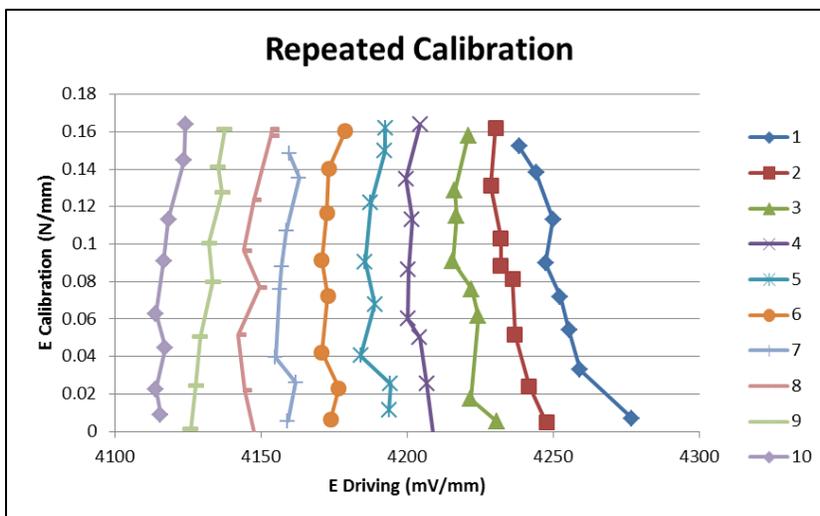


Figure 41: Sample repeated calibration plot.

not discern a difference between these two phantoms, then a new calibration process or a major re-design of the instrument would be necessary. However, the results from these tests, sample data of which can be found in Figure 42 for Phantom 1 and Figure 43 for Phantom 5, are very intriguing.

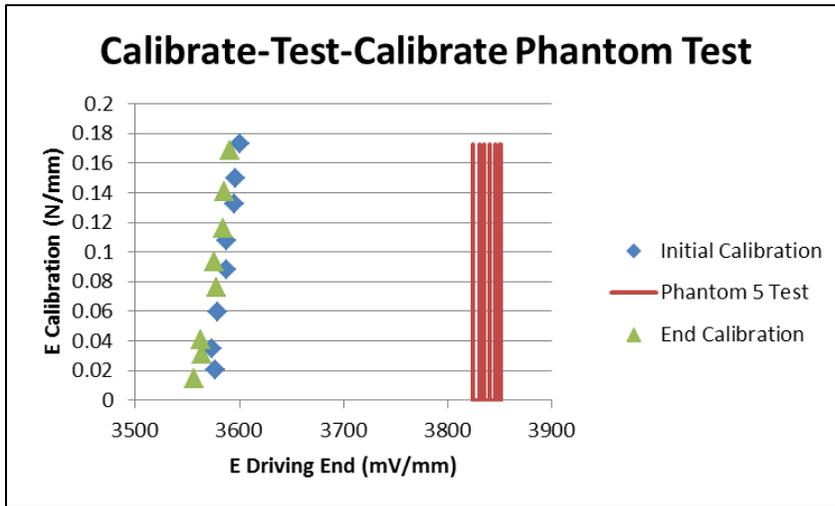


Figure 43: Sample Calibrate-Test-Calibrate test on Phantom 5. The blue and green data points represent the initial and end calibration data points, while the red lines are the driving end elasticity measured during the phantom test.

The much stiffer phantom's (5) driving end elasticity estimate is over 200 mV/mm away from the calibration curves, while Phantom 1's driving end elasticity estimate intersects the initial calibration curve.

This ability to discern between the two phantoms exposed an error in the design of the comparative elasticity calibration process. In choosing the elastic resistance elements for the calibration process, the maximum load was the main consideration. It was assumed that calibrating from a zero load to the maximum load of the calibration instrument would be sufficient to cover the elasticity of all proposed phantoms. However, because of the attachment methods for the elastic resistance elements, the elements were placed on the instrument already under great strain. Because of this, the maximum force of the calibration instrument was reached

The results show that, even though the calibration curves are often drifting too badly to be useful, the difference between Phantom 1 and Phantom 5 can be discerned from their distance away from the calibration curves.

before an appropriate range of elasticity was covered. The calibration range used was lower than the measurements we are expecting to make on phantoms and eventually *in vivo*. If a modification to the calibration instrument to accept resistance elements that are not already under such high strains could be made, then retesting with an appropriate elasticity calibration range might increase the signal that we are trying to measure within the much larger measurement of the system elasticity.

Chapter 6) Instrument Validation

The design evaluation of EVE exposed a weakness in the calibration process. Even though the calibration was performed over a large range of elastic loads, because each elastic element was already experiencing a high strain, the process was not done over as large a range of elasticities as possible. If the elastic elements were under lower initial strains the calibration process could utilize higher elasticity elements and still stay under the maximum instrument load.

Calibration Instrument Modification

In order to accept resistance elements that are not already under high strain, a slight modification to the calibration instrument was made. An ordinary hardware store corner brace was cut to fit under the calibration load platform. It is held in place by the same bolts that hold the platform in place. The

other arm of the corner brace has a long bolt attached to it with two nuts. This modification, shown in Figure 44, allows the elastic elements to be attached 3.75 cm lower than before, and over a much narrower surface. Instead of being already highly strained at zero probe displacement, the

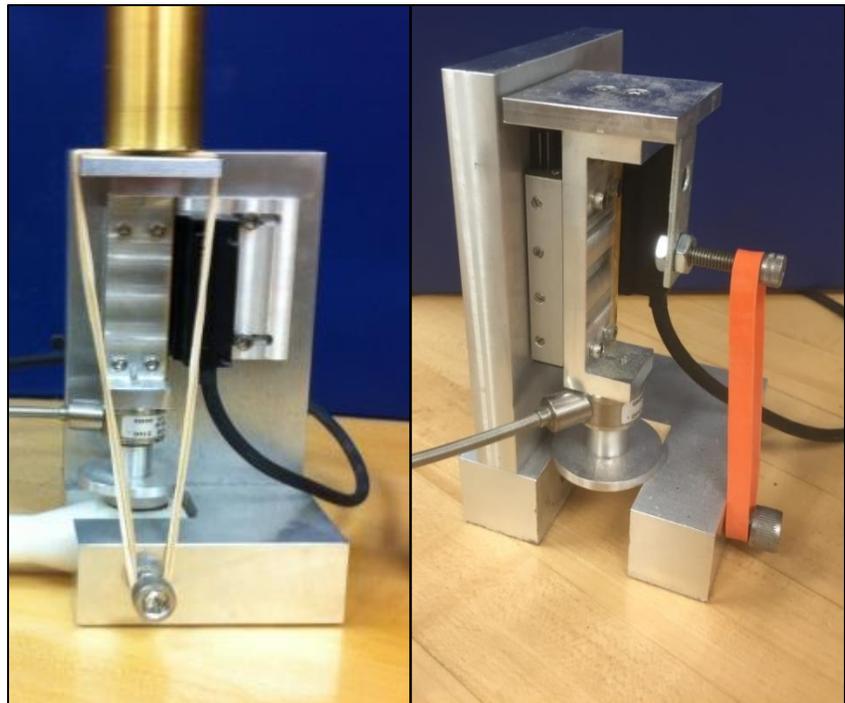


Figure 44: The calibration instrument, pre-modification (left) and modified to accept higher resistance elastic elements (right).

elements are now lightly strained, just enough to ensure that they are taut at zero probe displacement so as to ensure that they never go slack.

The new resistance elements are stiffer, and have a spring constant of 0.097 N/mm, while the old elements were only 0.011 N/mm. This calibration instrument modification allows us to use resistance elements with about nine times the elastic resistance as before and still stay under the instrument's maximum load, and enables us to do testing over a much larger elastic range.

Higher Elasticity Calibrate-Test-Calibrate Bench Testing

The modification of the calibration instrument and new elastic elements should have an effect on the calibration curves generated in the calibration process. In order to evaluate these effects the Calibrate-Test-Calibrate procedure was repeated. The instrument was calibrated using the comparative elasticity calibration procedure detailed in Chapter 4 with the low to high elasticity loading order and from one to eight elastic elements. Then, the test segment of the C-T-C process was performed in the calibration instrument against measured elasticity, either the 2-band or 5-band load of the same elements used during the calibration. Last, it was calibrated again using the same procedure as the initial calibration. This was all done in quick succession (using the same C-T-C computer protocol described in Chapter 5). The process was completed three times for each test load (2-band and 5-band), with each test generating eight data points. Sample results, shown in Figure 45 for two bands and Figure 46 for five bands, show a great improvement over the tests with the old bands. The drift, although still present, is no longer the dominant signal the system. Now the test results lie on the calibration curve. The points from the before and after calibrations of an individual C-T-C test can now be used as one data set and generate a least-squares fit. This new fit uses data from both before and after the test, so the fit

equation is an average fit over the whole time. Because of this the drift issue is further mitigated, and we can relate the driving end elasticity to the calibration instrument measurements.

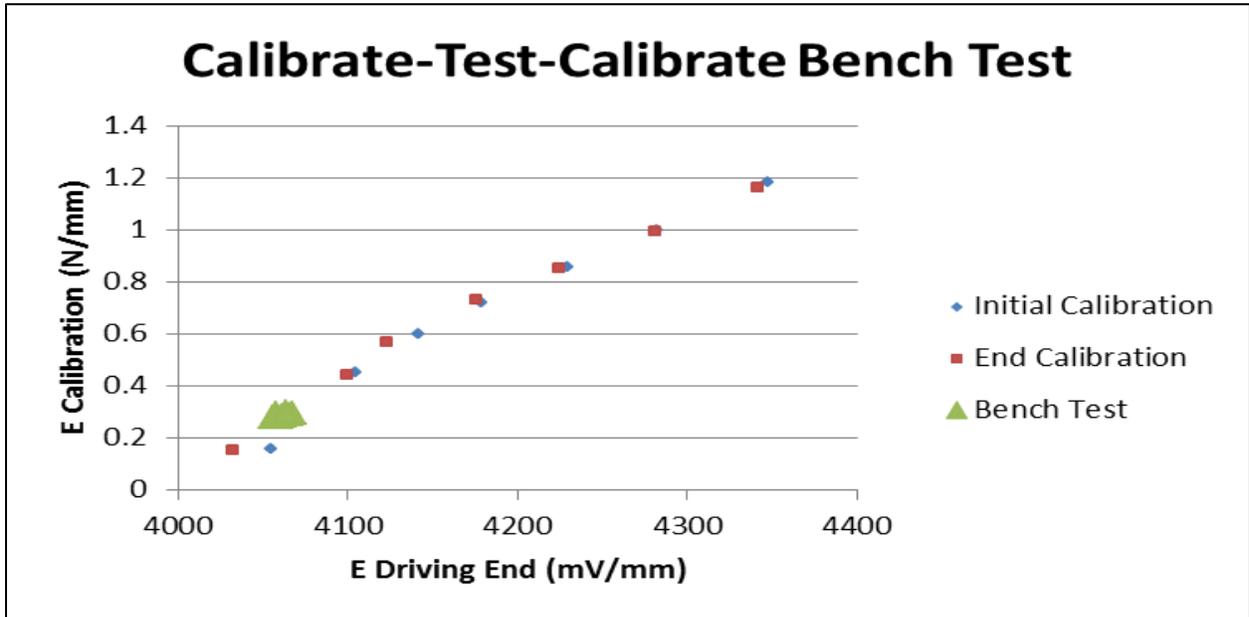


Figure 45: Sample Test-Calibrate-Test bench test data with two elastic resistance elements. The initial and final calibrations are represented by the small red and blue dots, while the bench test performed between the two is represented by larger green triangles.

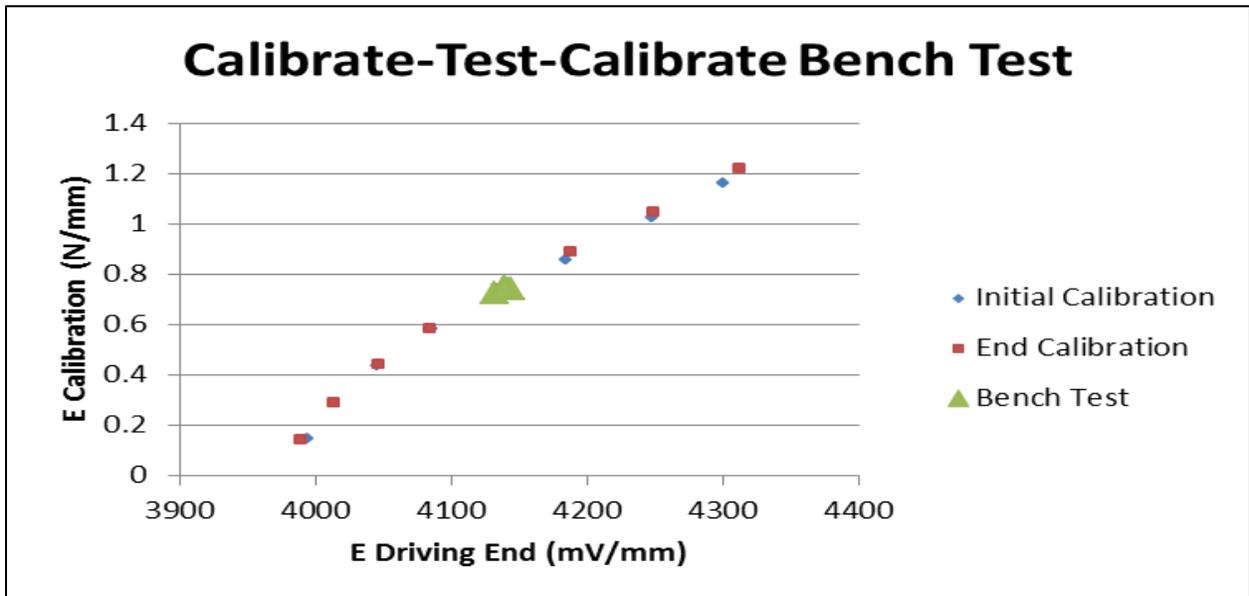


Figure 46: Sample Test-Calibrate-Test bench test data with five elastic resistance elements. The initial and final calibrations are represented by the small red and blue dots, while the bench test performed between the two is represented by larger green triangles.

Results from the tests are shown in Table 4. The results from these tests show that the instrument is now measuring elasticity quite well. For each of the three tests, the total elasticity of the test elements was measured at the calibration instrument eight times and reported as a mean and a standard deviation. The mean calculated elasticity, using the calibration equation, are also reported for those same loading segments with the corresponding standard deviations. As can be seen in Table 4, EVE is calculating elasticity very consistently, with standard deviations within an order of magnitude of the calibration instrument elasticity measurements.

Table 4: C-T-C Bench Testing Results

| 2-Band | Measured Elasticity (N/mm) | Standard Deviation (N/mm) | Calculated Elasticity (N/mm) | Standard Deviation (N/mm) | Relative Error |
|--------|----------------------------|---------------------------|------------------------------|---------------------------|----------------|
| 1 | 0.2891 | 0.0075 | 0.2941 | 0.0130 | 1.72% |
| 2 | 0.3008 | 0.0066 | 0.2988 | 0.0128 | 0.67% |
| 3 | 0.2981 | 0.0057 | 0.2973 | 0.0082 | 0.26% |
| 5-Band | | | | | |
| 1 | 0.7424 | 0.0074 | 0.7000 | 0.0116 | 5.72% |
| 2 | 0.7485 | 0.0038 | 0.7312 | 0.0075 | 2.30% |
| 3 | 0.7546 | 0.0062 | 0.7286 | 0.0108 | 3.45% |

Relative error is also small, always under 6%, but as low as 0.26% for one test. The relative error for the 5-band test is slightly higher. This is likely caused by the linear least-squares fit. Each of the comparative elasticity calibration curves has a slight parabolic curve to it, as can be seen in Figures 45 and 46. The linear fit of these curves, although still very good, is less accurate in the middle and calibration range, where the 5-band test operates. Switching to a higher order least-squares fit would reduce this error; but for these initial proof of concept trials, a linear fit is sufficient. With bench testing successful, we can move forward into phantom testing, confident that we will generate meaningful results.

Phantom Calibrate-Test-Calibrate Testing

The new calibration process, which calibrates over a wider range of elasticities, allows us to test phantoms with the likelihood that their elasticities are encompassed within the calibration range. To show this, and validate the instrument's ability to measure phantom elasticity, Calibrate-Test-Calibrate testing was performed on all five test phantoms discussed in Chapter 3. With the new elastic bands, measurements could be made of the phantom elasticity. Sample data for Phantom 1 can be seen in Figure 47, while sample data for Phantom 5 is presented in Figure 48. Each figure shows a single C-T-C test, but the C-T-C protocol was run on each of the test phantoms three times. For each C-T-C, test the protocol collects eight measures of driving elasticity that are averaged before being put into the calibration equation to give a measurement of phantom elasticity.

As in the bench testing that was detailed in the previous section, for each test a calibration equation was determined using the a linear least-squares fit on the calibration data together as a single set. The driving end elasticity was then found for the second loading segment for each of the eight sets of oscillations performed during the test phase. The mean of these measurements was then put in to the calibration equation to determine one measurement of elasticity for the C-T-C test.

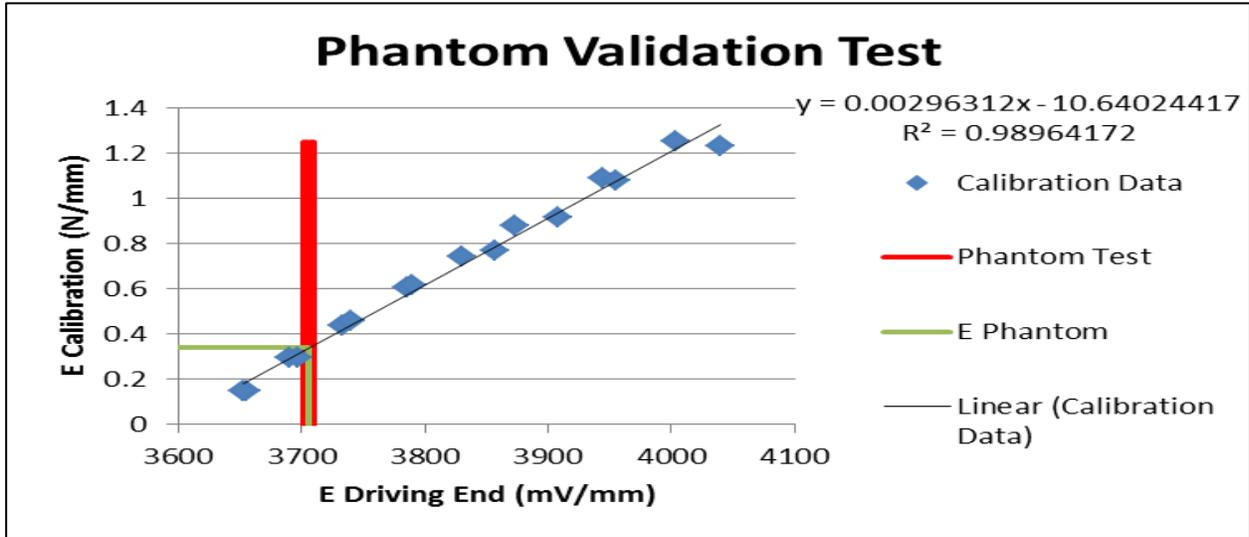


Figure 48: Sample Calibrate-Test-Calibrate phantom test data from Phantom 1. The initial and final calibrations are represented together by the blue dots, with a black least squares fit line. The equation for the fit line is shown on the top right. The red lines are the driving end elasticity values from the phantom test. The green line vertical segment is located at the average driving end elasticity for the eight phantom tests, while the horizontal segment is the calculated phantom elasticity from the least squares fit equation of the calibration data and the average driving end elasticity from the phantom tests.

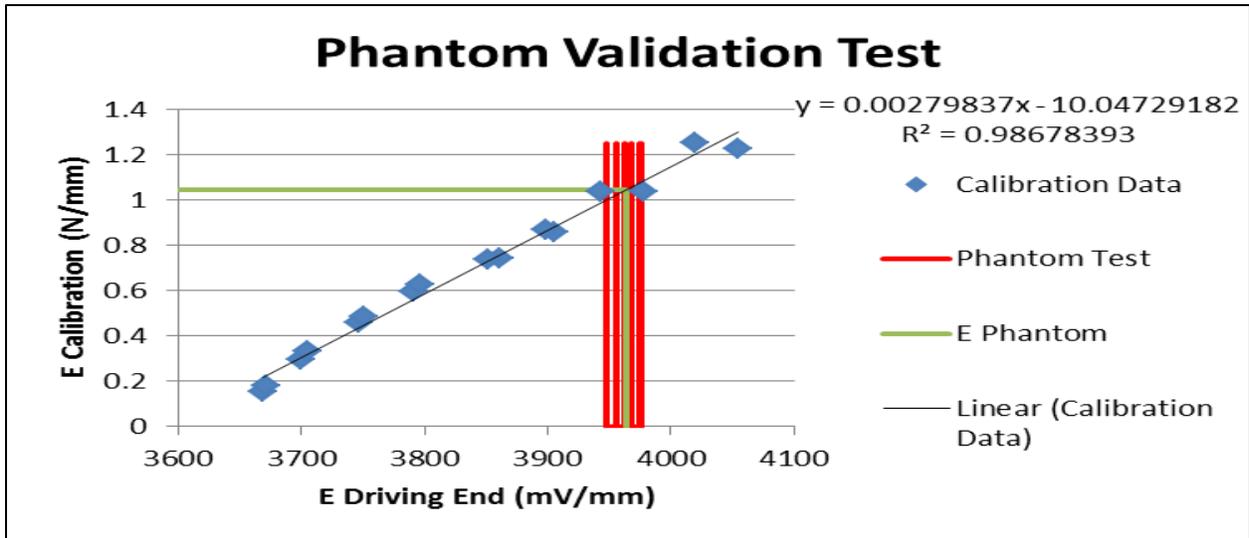


Figure 47: Sample Calibrate-Test-Calibrate phantom test data from Phantom 5. The initial and final calibrations are represented together by the blue dots, with a black least squares fit line. The equation for the fit line is shown on the top right. The red lines are the driving end elasticity values from the phantom test. The green line vertical segment is located at the average driving end elasticity for the eight phantom tests, while the horizontal segment is the calculated phantom elasticity from the least squares fit equation of the calibration data and the average driving end elasticity from the phantom tests.

These tests show that EVE has the ability to distinguish between the each of the test phantoms. Based on these tests, the average measured elasticity of Phantom 1 is 0.3376 N/mm, and the average measured elasticity of Phantom 5 is 1.0923 N/mm. To convert this to a Young's modulus, we estimate the stress by assuming that the force is acting over the area of the measuring surface (265 mm²). We estimate the strain by assuming that the original length of the phantom is the distance from the central cavity to the edge of the phantom (3.8 cm). This gives an average Young's modulus of 33.03±0.61 kPa for Phantom 1 and 156.63±9.15 kPa for Phantom 5. Calculated Young's modulus for each trial can be seen in Table 5.

Table 5: C-T-C Phantom Validation Elasticities

| Test | E Phantom 1 (kPa) | E Phantom 2 (kPa) | E Phantom 3 (kPa) | E Phantom 4 (kPa) | E Phantom 5 (kPa) |
|----------|-------------------|-------------------|-------------------|-------------------|-------------------|
| 1 | 33.73 | 45.56 | 69.30 | 81.56 | 149.68 |
| 2 | 32.68 | 43.79 | 67.43 | 84.33 | 166.99 |
| 3 | 32.66 | 46.65 | 70.17 | 77.20 | 153.22 |
| Average | 33.03 | 45.33 | 68.97 | 81.03 | 156.63 |
| St Dev | 0.61 | 1.44 | 1.40 | 3.60 | 9.15 |
| Expected | 7.6 | 17.7 | 32.3 | 51.5 | 75.3 |

These values can be compared to the expected Young's modulus obtained through the equation from Hall *et al.* [50] presented in Chapter 3. Although our values are higher than the estimated values, we did not expect to precisely match and our values are still within reason. This quick estimate of elasticity neglects much of the geometry of the phantom.

Converting the elasticity estimate from the measured N/mm into a Young's modulus in kPa makes several massive approximations to simplify the

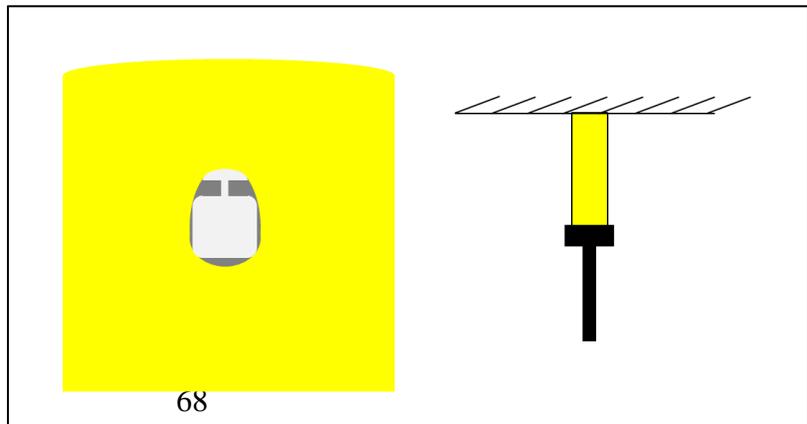


Figure 49: Illustration of the actual (left) vs assumed (right) geometry of phantom tests for translating calculated stiffness into Young's modulus.

geometry. First, for area we assume that the area being compressed is the same as the area of the measurement surface, but there is much more phantom volume around the measurement surface that is being affected by the displacement. Second, the original length being used to calculate strain is just the length from the cavity of the phantom to the surface and the change in length is the displacement of the instrument. These are also not the best measures, because the phantom is not constrained on its outer edges. The displacement of the instrument can move the entire phantom surface up without straining the interior very much. To determine Young's modulus, we have essentially assumed that the probe is acting on a column of phantom the diameter of the measuring surface and height of the length between the phantom cavity and the edge of the phantom which is constrained on the other side. This can be seen in the Figure 49, illustrating the difference between the actual geometry and the geometry assumed in our calculations. Other work, already under way in our lab, to use three-dimensional finite element models to process the data from EVE [55] can be used to refine the Young's modulus obtained by using more physical geometric assumptions.

Additional differences in the measurement may also arise from the changes in manufacturing processes between our procedure and the Hall *et al.* process. For the tests used to generate the equation for expected Young's modulus Hall *et al.* held the gelatin solution at high temperatures for one to two hours. This can cause the gelatin to degrade and may result in up to a 20% loss in stiffness [50]. Additionally, Hall *et al.* did not report how long after manufacture their phantoms were tested, and within the first week of manufacture Young's modulus can increase by 10% due to increased crosslinking over time [50].

More relevant to the current validation of EVE is ensuring that we can statistically show that we are differentiating between these phantoms of different elasticities. A student t-test

confirms that these measures of phantom Young's modulus are statistically different with a 95% confidence interval. All of the phantoms measured did order in their expected rank, increasing in measured stiffness when gelatin concentration increased. Future studies paired with DMA measurements on other gelatin phantoms will be able to determine the ability of the instrument to discern between more similar elasticities.

Chapter 7) Alternate Approaches and Conclusions

Although EVE is currently working in its present configuration to estimate elasticity, it is not working as was hoped at the beginning of the project. Most notably, any measure of viscoelasticity will require an overhaul of the EVE system. Currently we can get a simple elasticity measurement, and discern between some physiologically relevant tissue phantoms, while meeting all of the original design requirements outlined in Chapter 2. We cannot, however, use the current setup and calibration process to measure viscoelasticity, switch to probe displacement control, or easily adapt to probe force control. The comparative elasticity calibration procedure works very well in order to measure elasticity, however, since it skips the intermediate step of finding the probe force and displacement, we cannot use it to switch EVE into probe control.

The lessons learned so far in the creation of EVE can be used to inform a next iteration in a major overhaul of the device. One of two main areas of approach should be chosen in order to advance the design: incorporating a force sensor in the probe end, or the replacement of the hydraulic driving system with a mechanical linkage system. Either of these two improvements might allow us to obtain full force and displacement measurements at the probe end. These measurements could be useful in refining our elasticity estimate, as well as for investigating other avenues, such as viscoelasticity, or allow for other modes of testing, such as ramp-and-hold testing.

Force Sensing at the Probe End

Integrating a force sensor in the probe end would be counter to one of the initial design requirements. However, it would still allow the device to be safe and could greatly increase the accuracy of the force measurement and permit using a calibration process similar to the eight

parameter calibration model again which enables viscoelastic measurements and probe control. A submersible miniature compression load button might be placed under the bellows casing, between it and the probe body. The button's output cable could be run through the handle along with the hydraulic tubing and be read by the 9237 CompactRIO module which is currently only using two of its four inputs. This modification would allow a much more accurate and precise measurement of force at the probe end. This force could also be combined with the parameters from the eight parameter model in order to increase the accuracy of the calculation of the probe end displacement.

Replacing the Hydraulic System

Alternatively the entire hydraulic driving system could be replaced. The hydraulic system adds significant complexity to the instrument and the data processing. Switching to a mechanical linkage would eliminate the problems of air within the system, pre-pressurization variation, and system sealing. A mechanical linkage would also replace the complex bellows spring constant and tubing elasticity with a much more linear spring constant. Switching to a mechanical linkage, however, would require a complete redesign of the probe end, but, unlike implementing a force sensor within the probe, this would allow us to meet all of the initial design requirements. In this proposed design, an illustration of which is shown in Figure 50, the driving end would remain relatively unchanged; but, instead of applying compressive force to the driving bellows, the motor would be used to keep tension on the inner cable of a Bowden cable. Bowden cables, which are used frequently in bicycles brakes, are flexible cables which transmit displacement over a distance by moving an inner cable relative to the outer cable housing. The flexibility of the driving end setup would allow this change to minimally affect the driving end

because all of the sensing and driving components are made to drive and sense in either tension or compression.

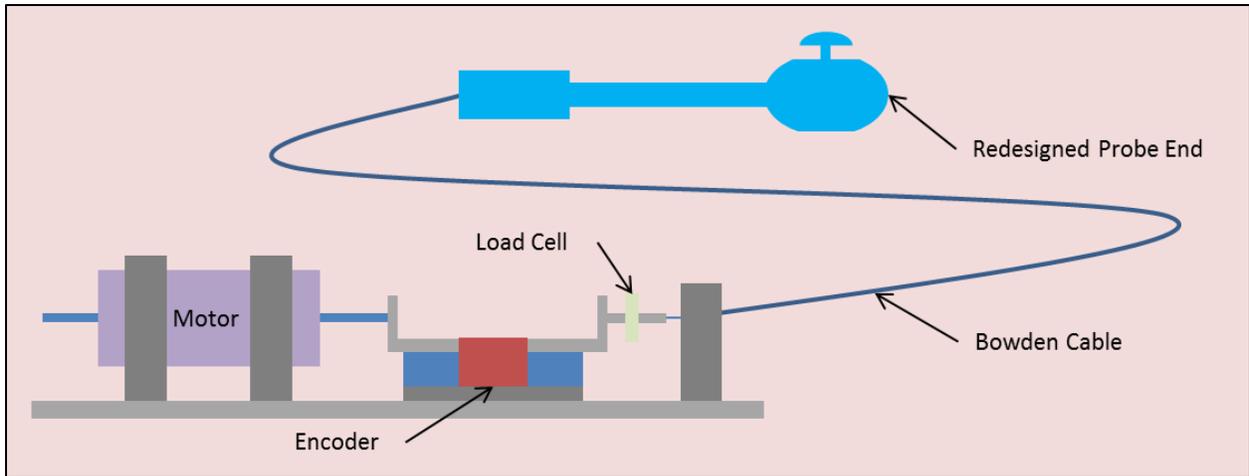


Figure 50: Design exterior schematic of a redesigned EVE utilizing mechanical linkages instead of hydraulics.

The redesigned probe end would need to be entirely remade. In the proposed schematic cutaway, seen in Figure 51, a proposed mechanical linkage would transmit the displacement from the Bowden cable to the measurement surface. Within the probe head would be a mechanical linkage, similar to a car jack or a scissor lift. Tension within the Bowden cable would pull on the forward linkage arm joint. This motion would cause the linkage to become smaller in the lateral direction and expand in the vertical direction, extending the measuring surface. Although we could rely on the tissue to return the measuring surface to rest, a low stiffness spring would ensure that the measuring surface retracts when tension is relaxed in the Bowen cable. The spring constant of the return spring could be removed from the measurement through calibration.

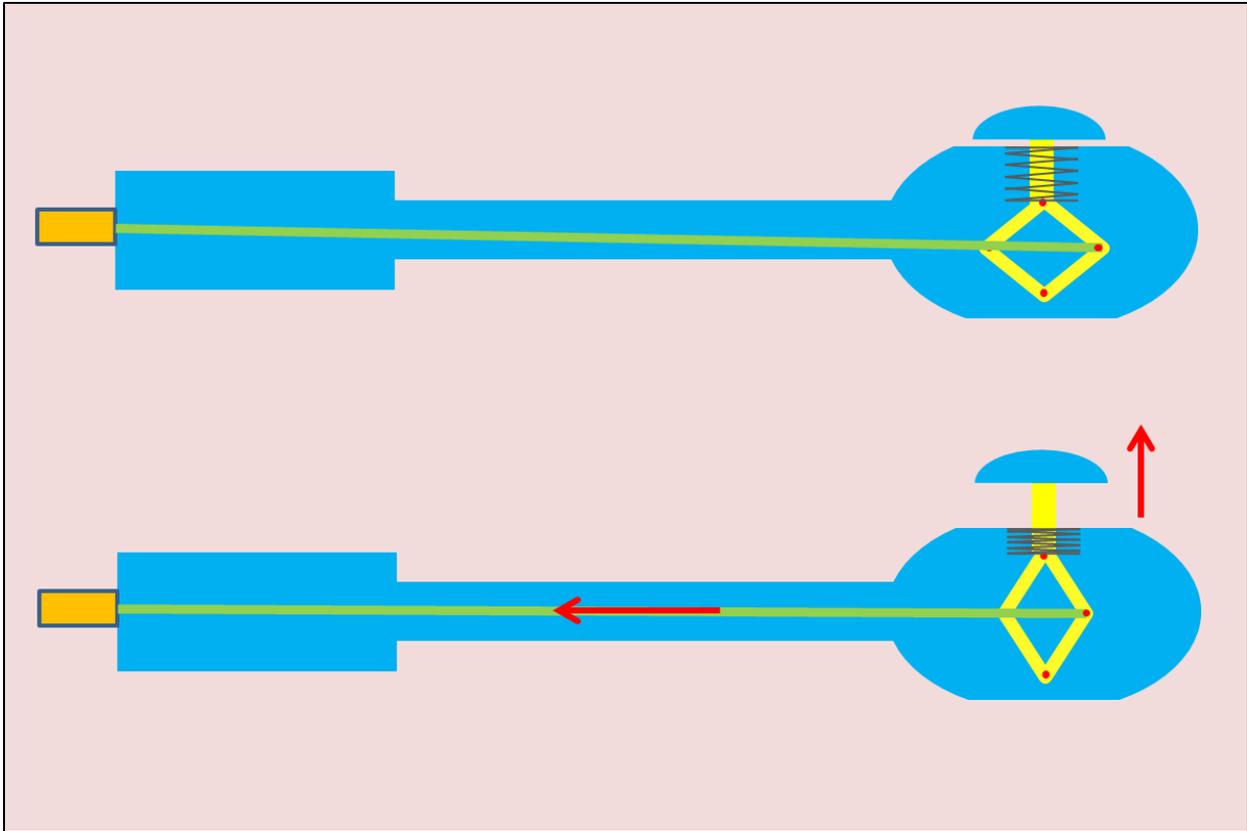


Figure 51: Schematic of a proposed probe design utilizing mechanical linkages. Tension within the Bowden cable pulls on the forward linkage arm joint. This motion causes the linkage to become smaller in the lateral direction and expand in the vertical direction, which extends the measuring surface. A low stiffness spring ensures that the measuring surface retracts when tension is relaxed in the Bowen cable.

This design would have several advantages over the hydraulic system, but come with a few drawbacks as well. Advantages of this system over hydraulics include an expected simplification of the calibration equations that would be needed in order to calculate force and displacement at the probe end. The stainless steel inner cable of the Bowden cable should behave much less elastically than the water with nylon tubing of the current setup. Additionally, all of the complications involving system pressure and air within the system would be gone. This setup also eliminates the variable of the initial system pressure. This might even allow us to calibrate the system much less frequently than the hydraulic setup currently requires. Some

disadvantages might also present themselves. Friction might play a much more significant role in this setup which will have frictional losses along the Bowden cable as well as at all of the proposed linkage joints. Hopefully these friction losses would be on the scale of their hydraulic counterparts, such as head loss, which have been negligible in the current iteration of EVE. Additionally, the probe body for this design might require significantly more pieces, which would increase the difficulty of machining a new probe and have more joints where clinical sterilization might become more difficult.

Future Work

Even without a new design, more work is needed to get EVE ready for *in vivo* studies. In order to fully validate EVE, more phantoms which are closer in elasticity should be measured in order to determine the precision of the elasticity estimates. These tests should also be compared to an independent measure, such as DMA testing, of the phantom elasticities to see if we can discern differences as well as standard measurement devices. With these tests complete, EVE could be ready for *in vivo* testing in the near future.

In tandem with *in vivo* testing, additional 3-D finite element analysis of phantom and vaginal geometry should be run in order to refine our Young's modulus measurement. Decreasing the number of geometric assumptions will greatly enhance the accuracy of our measurements for future applications.

After *in vivo* studies, or in tandem with them, the alternate approaches described earlier in this chapter can be investigated. These instrument refinements have the potential to improve the EVE measurements, as well enable other modes of operation that have had to be sacrificed in the present configuration such as probe control and viscoelastic measurement.

Conclusions

As a whole the EVE instrument is a successful step forward in the ability to properly measure vaginal tissue closing force for the application of mathematical models of delivery vehicle spread. Many of the initial design challenges have been overcome, and a majority of the necessary programming has been completed. Tissue phantoms have been selected and manufactured which will allow for full validation of the instrument. Measurement of phantom tissue elasticity is now possible; and the drift problem has been investigated and mitigated. EVE is nearly ready for *in vivo* testing. During this process, it was necessary to abandon the measurement of viscoelastic properties; however, a redesign of some of the components could allow for their reimplementation into the data collection process. Although EVE is not currently working up to our initial ambitions, we are now able to collect valuable data; and there is a path forward for refining the instrument to collect all of the data envisioned at the start of this project.

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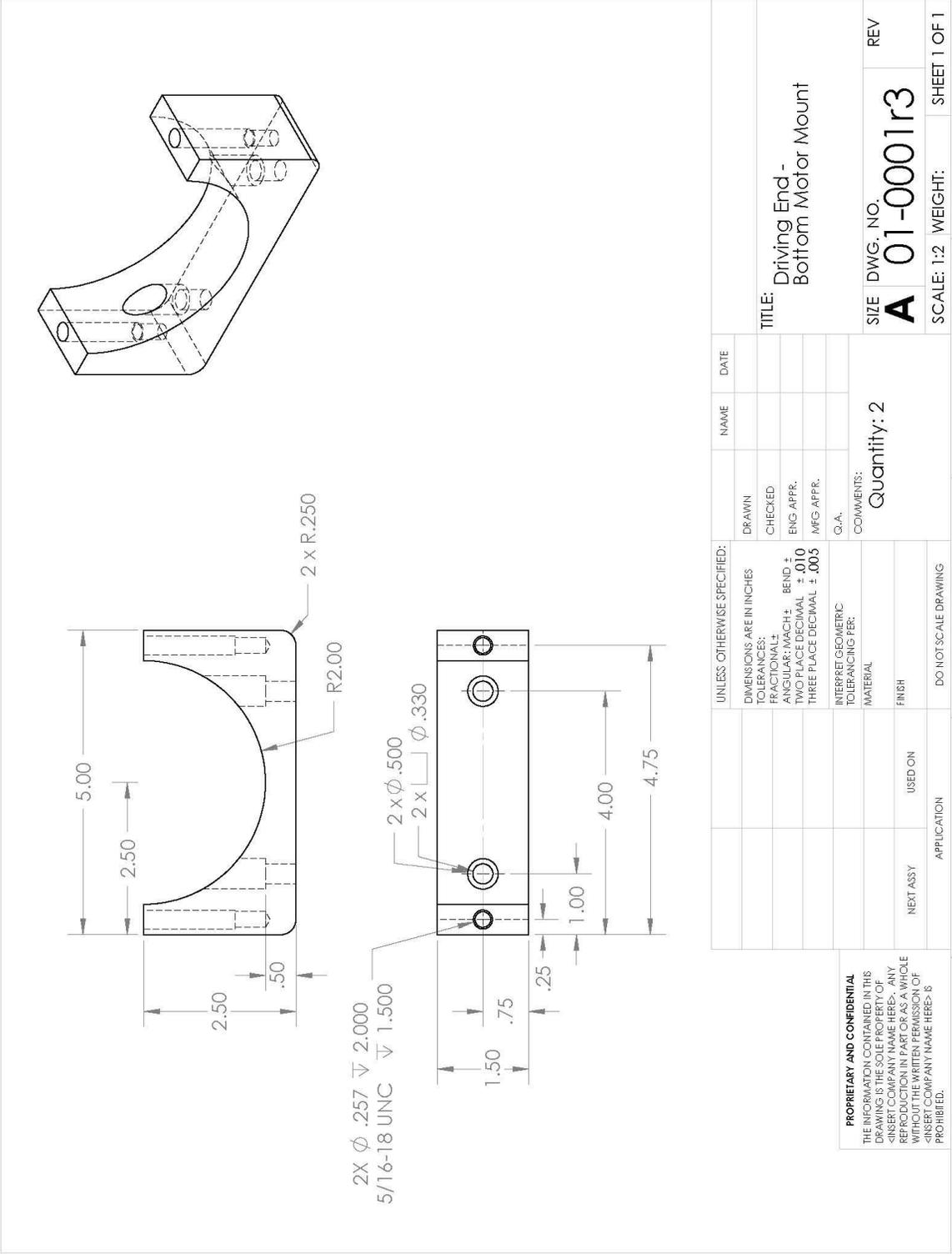
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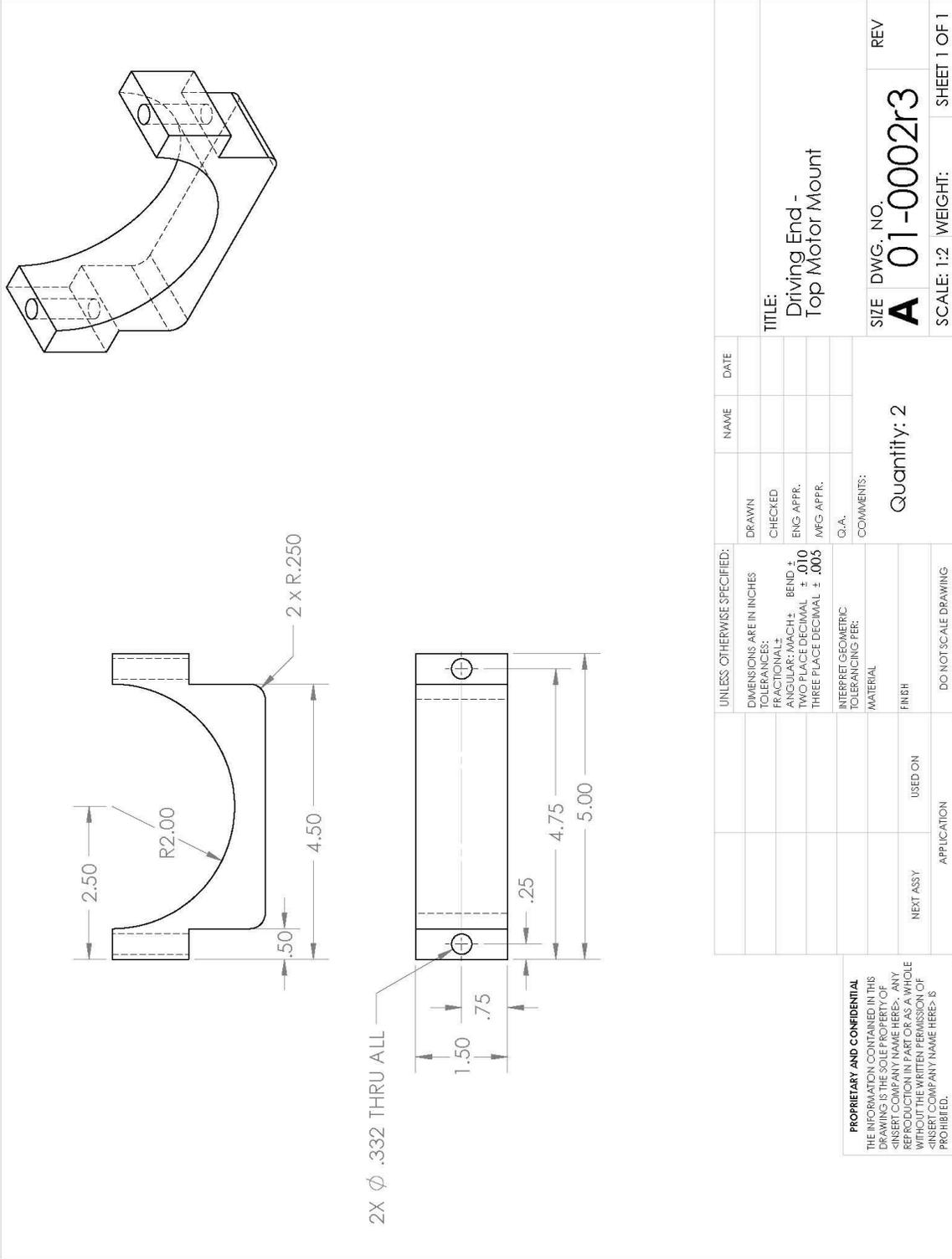
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Appendix A) Mechanical Design Drawings

Driving End

Technical drawings of the custom machined pieces of the driving end referred to in Chapter 2)
Instrument Design Process





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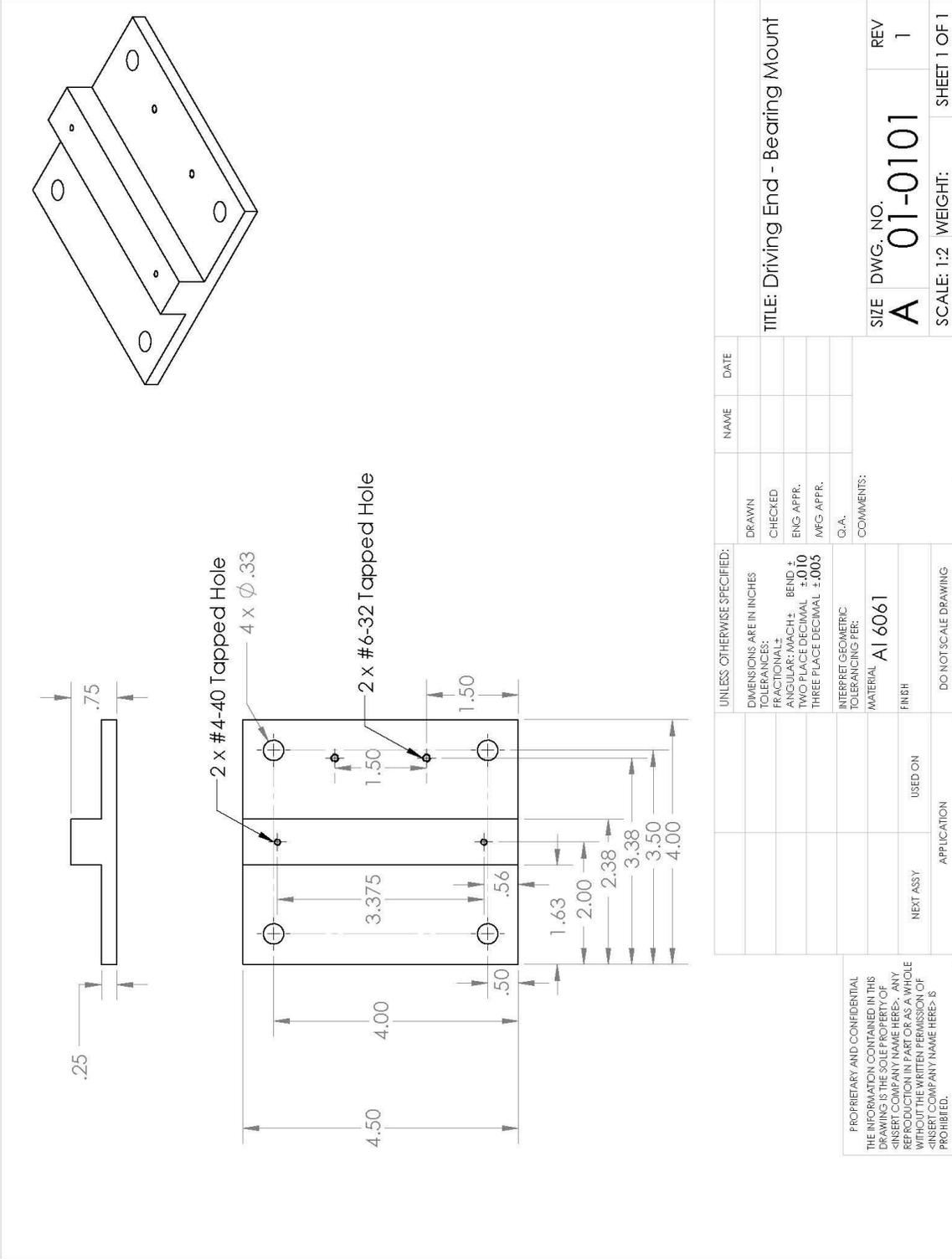
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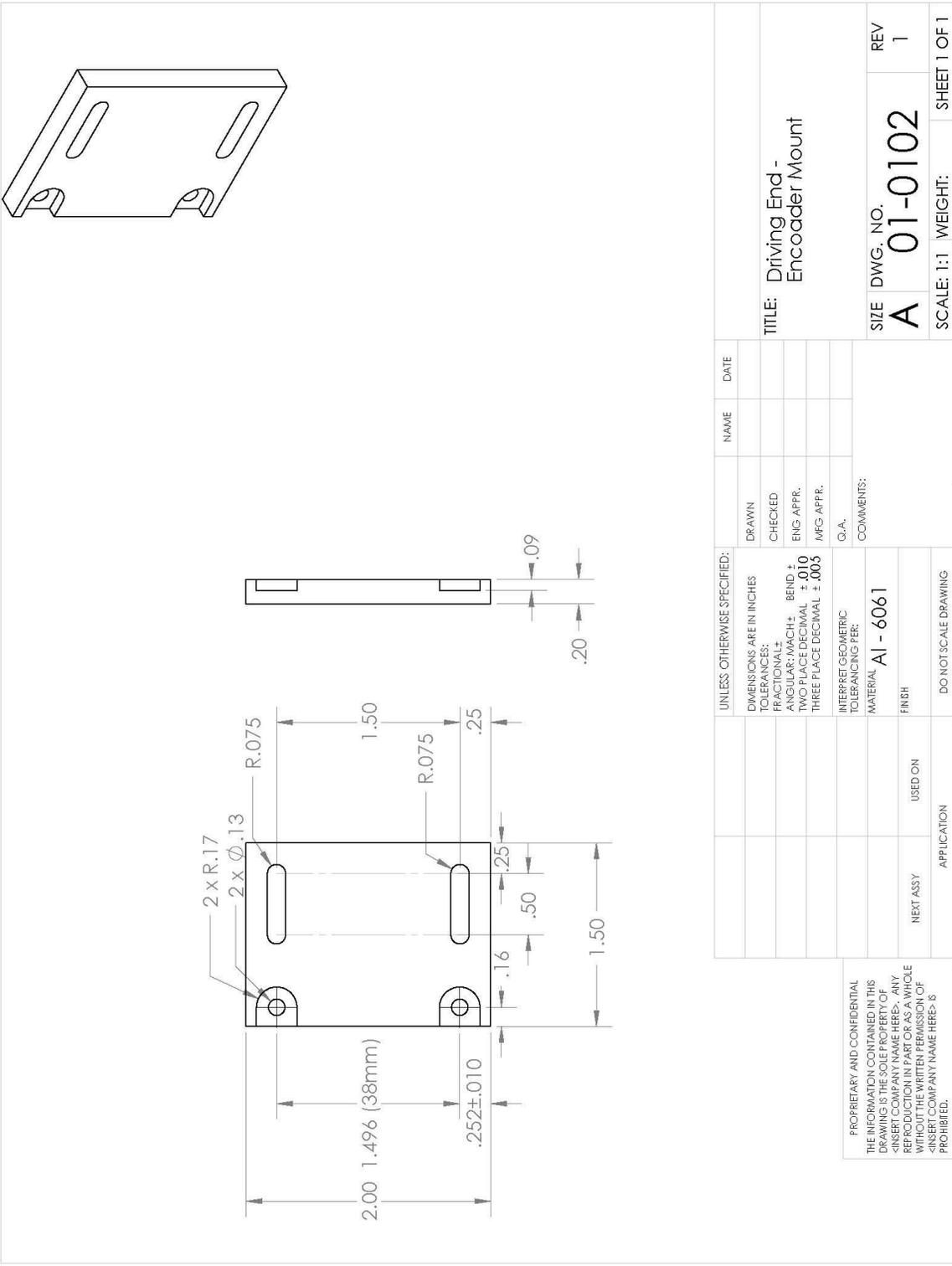
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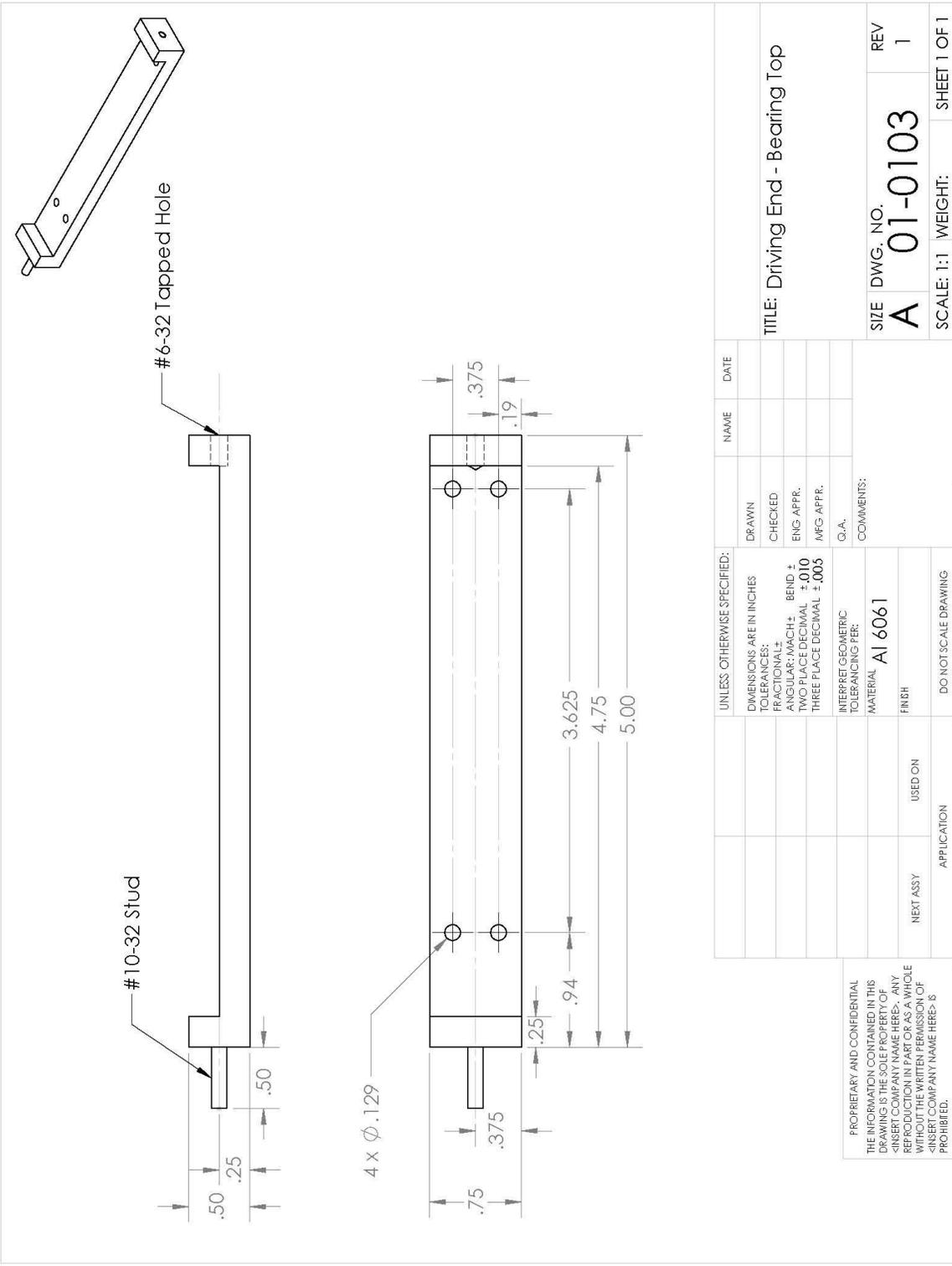
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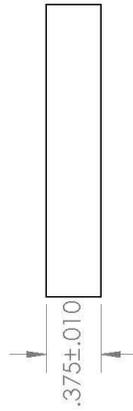
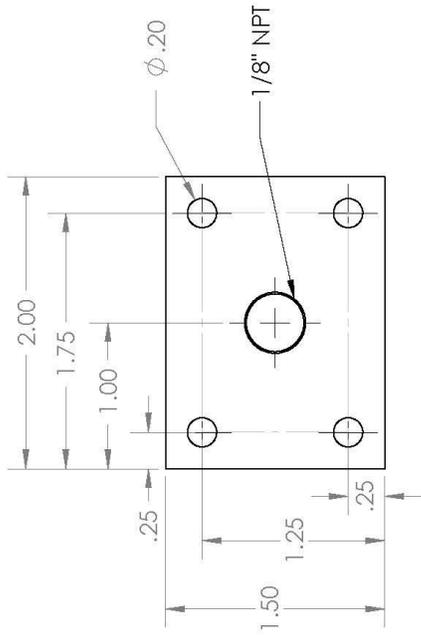
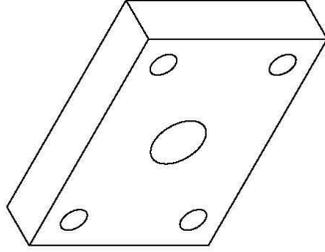
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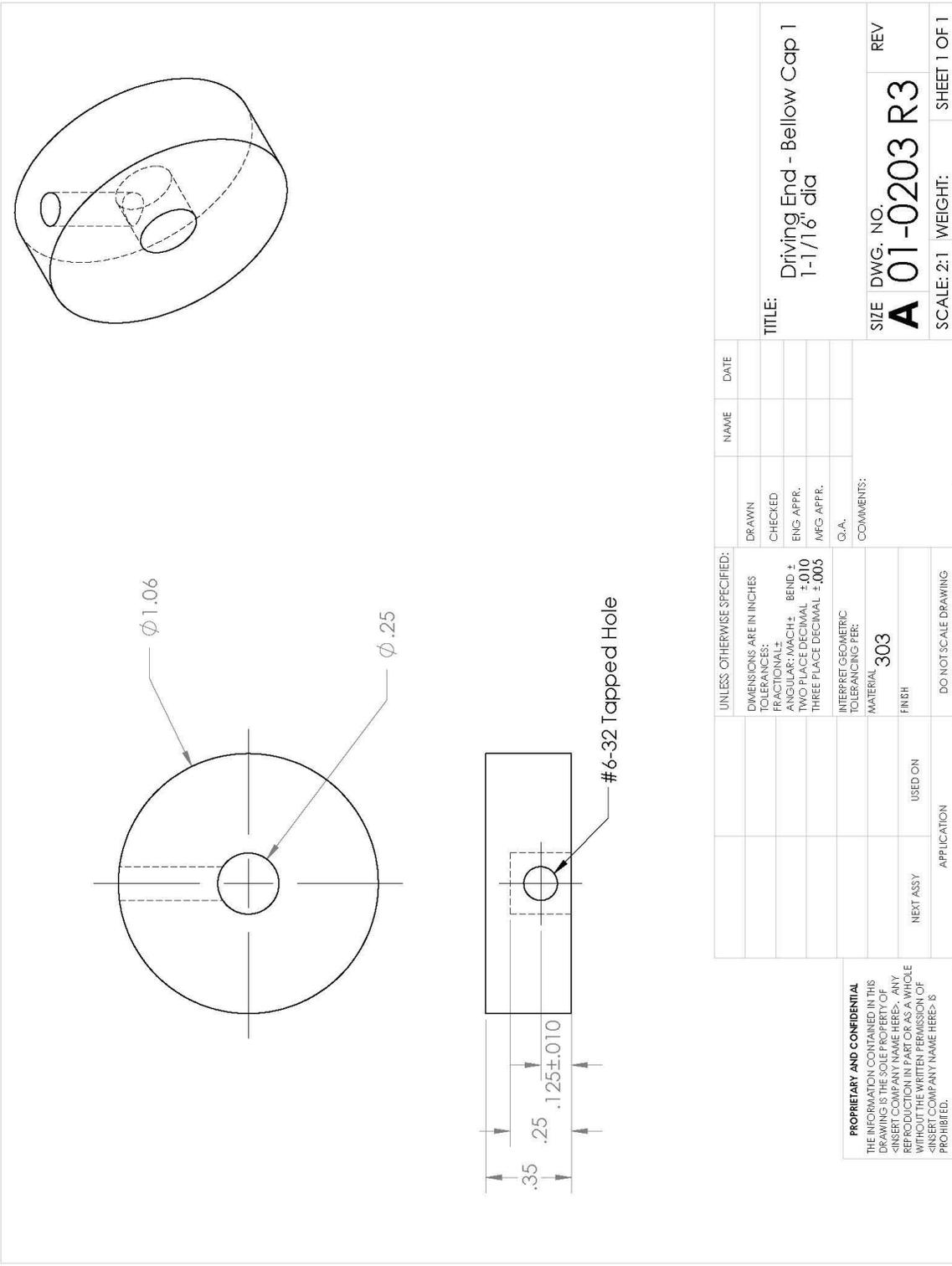


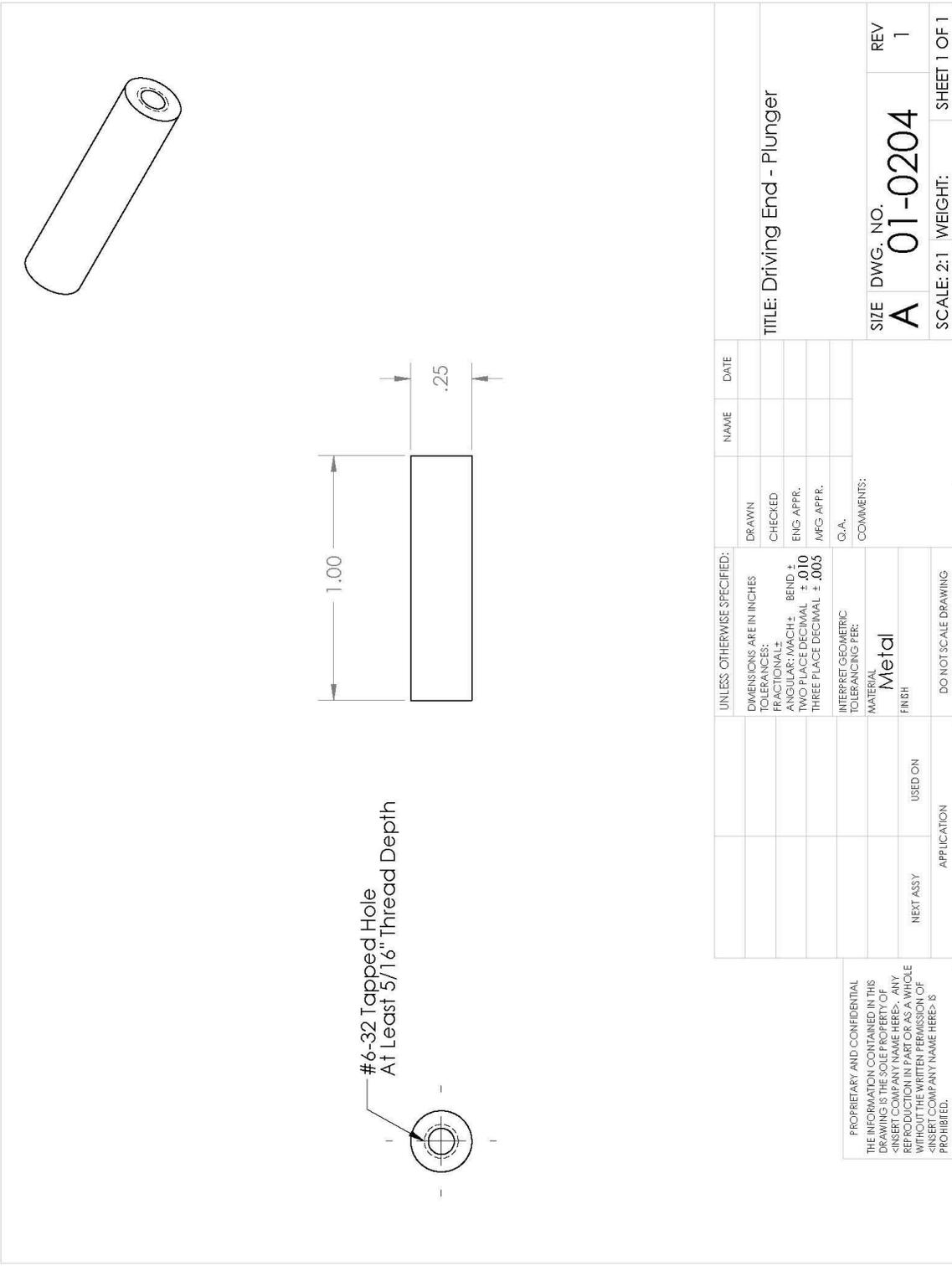






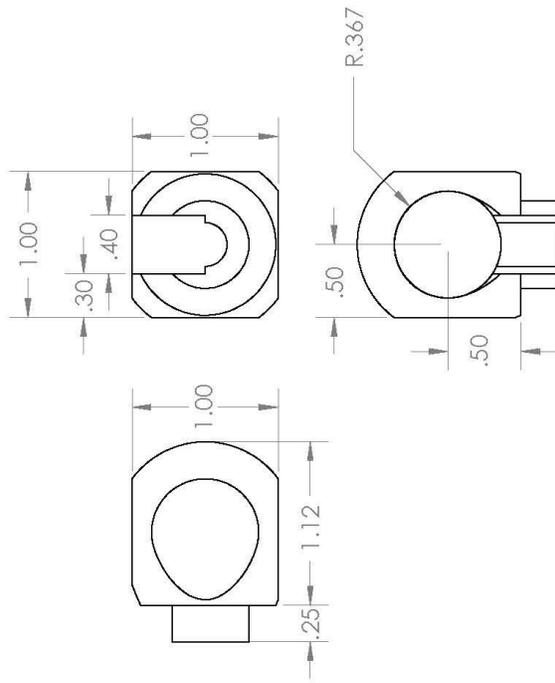
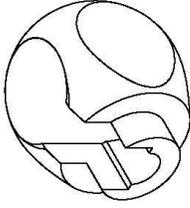
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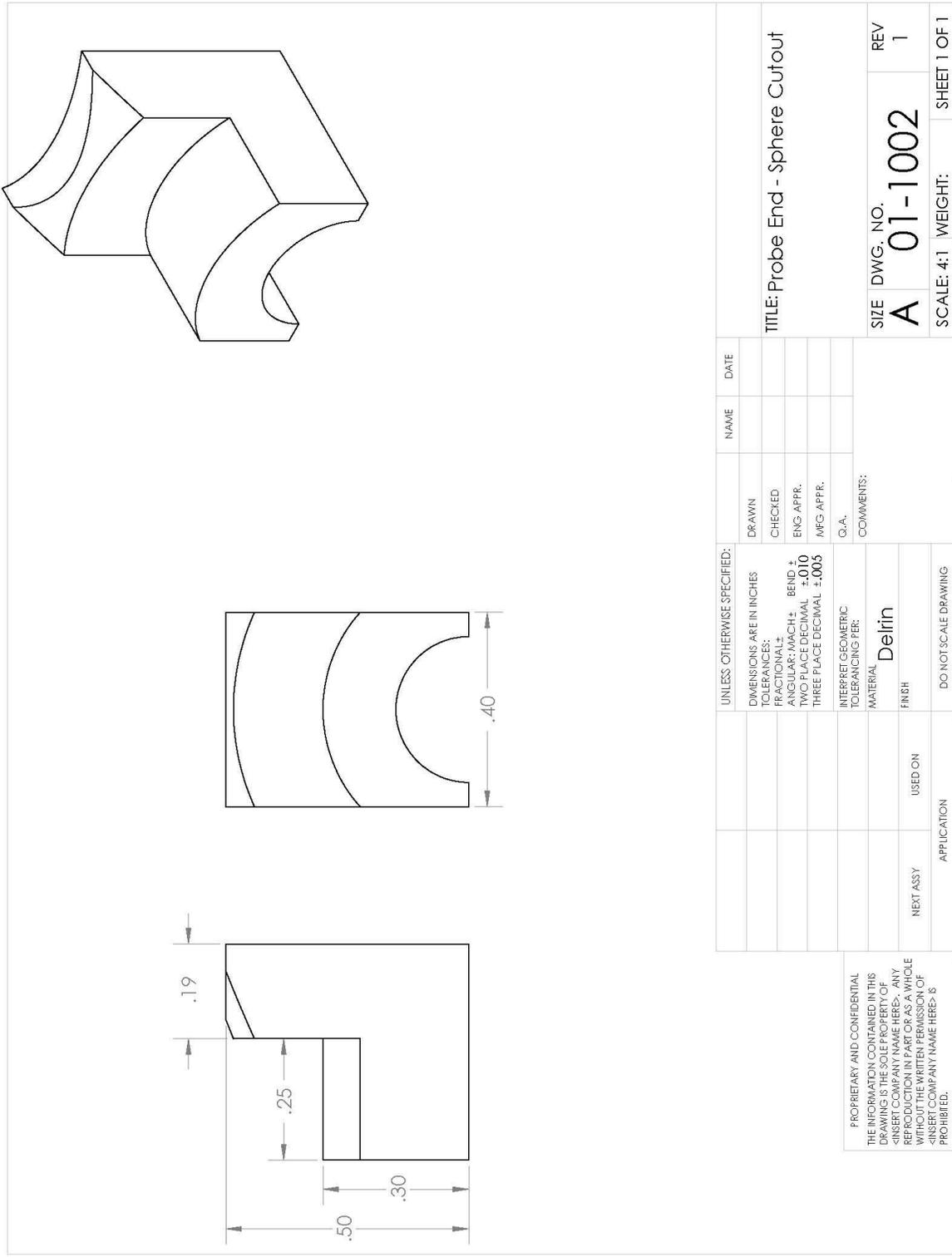


Probe End

Technical drawings of the custom machined pieces of the probe end referred to in Chapter 2)
Instrument Design Process



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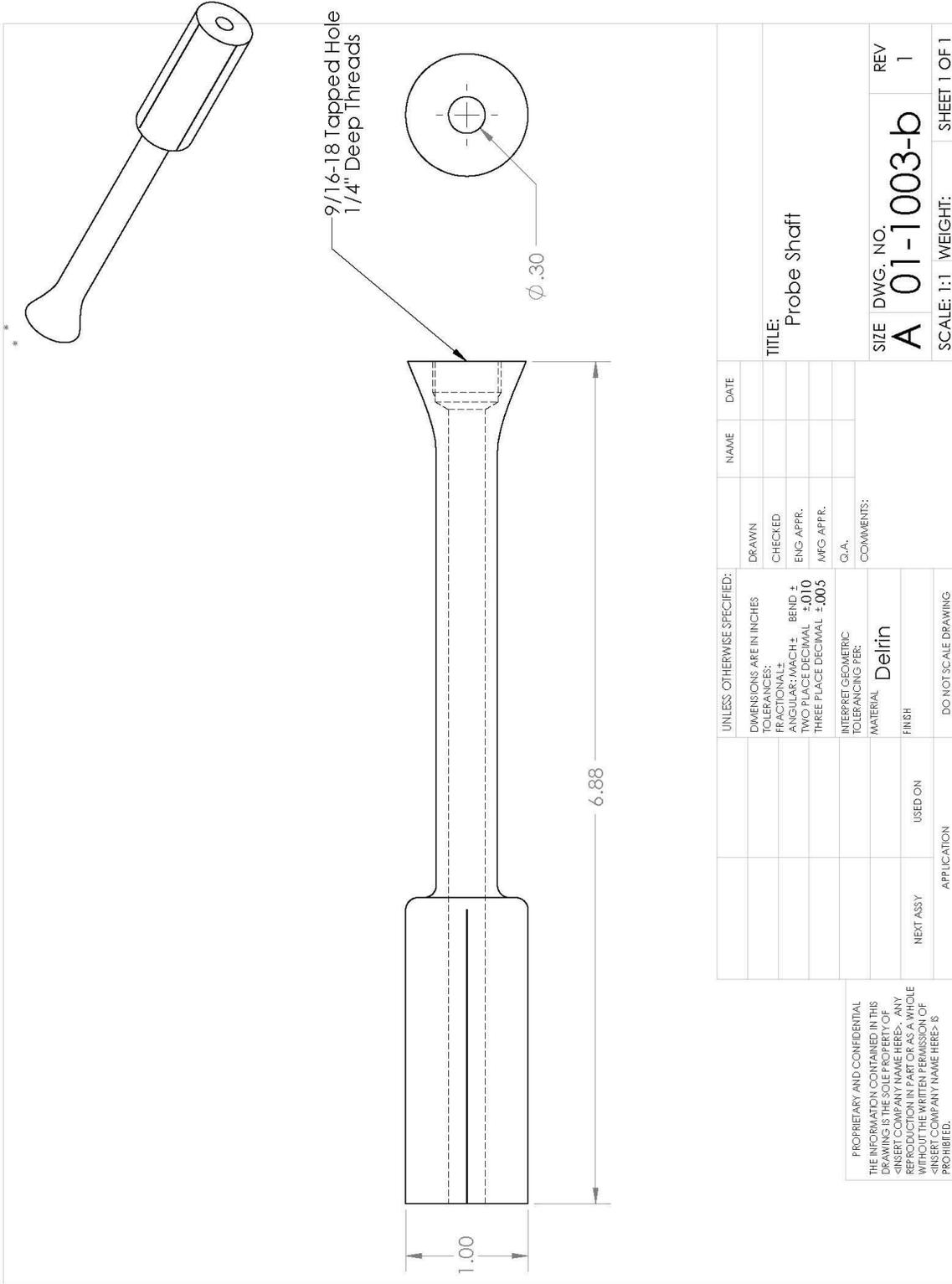


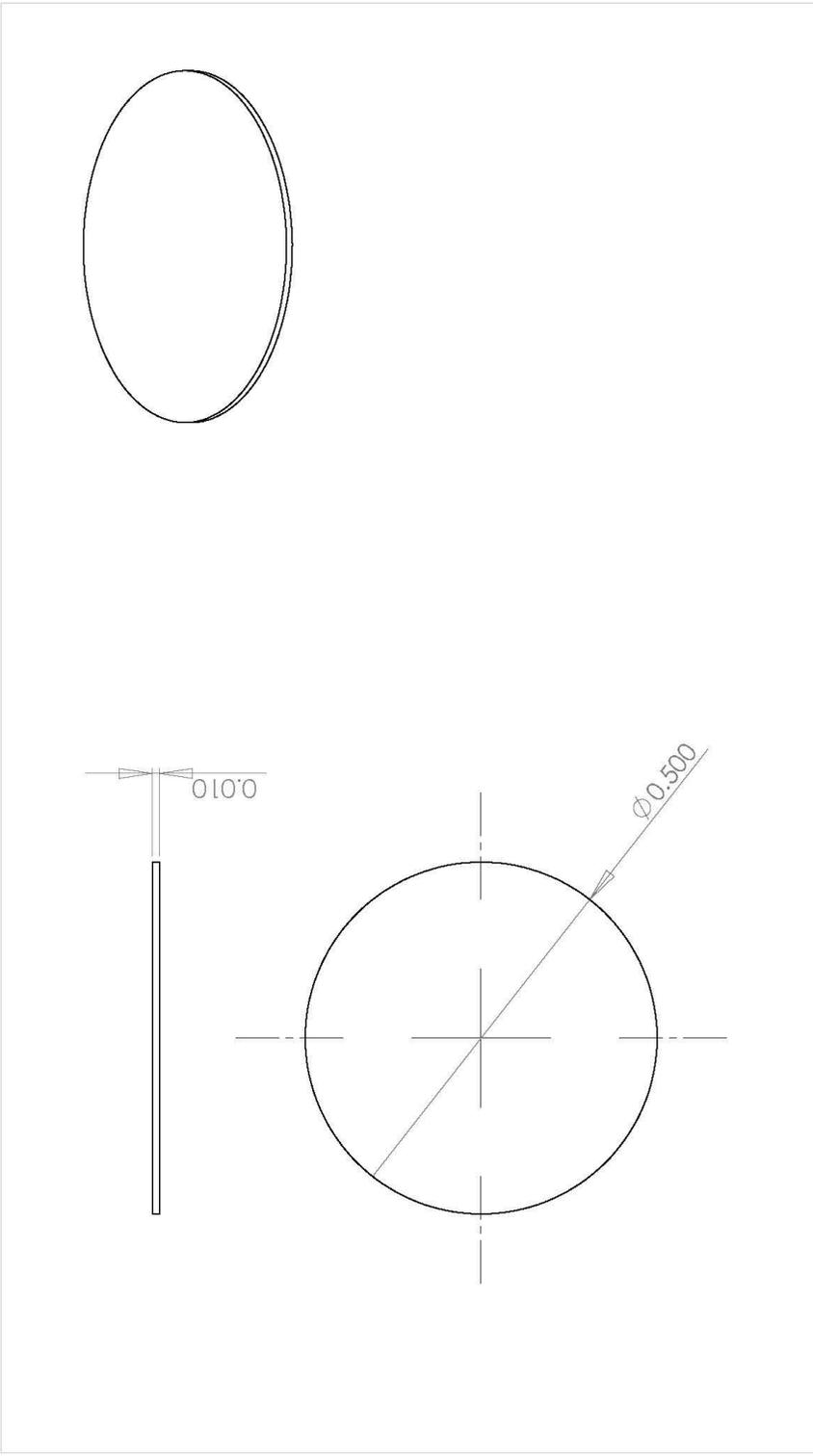
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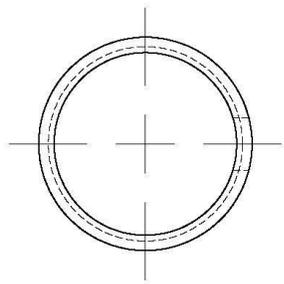
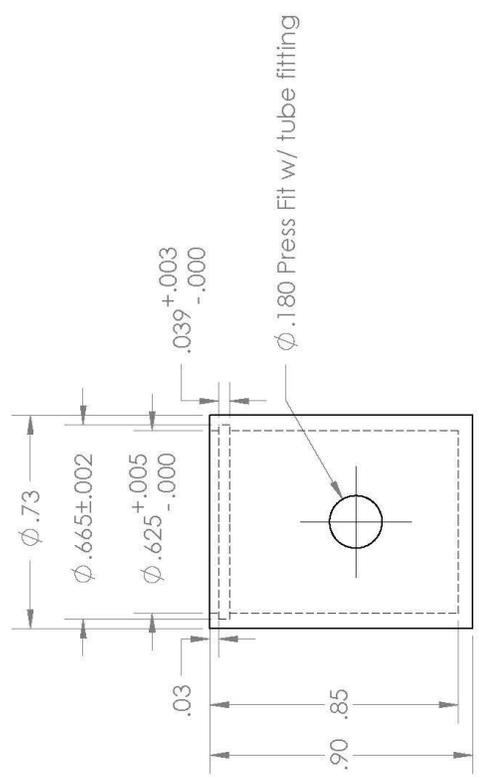
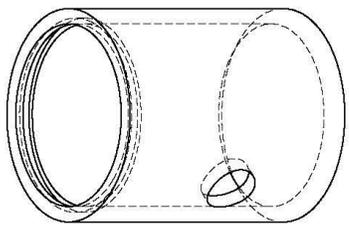
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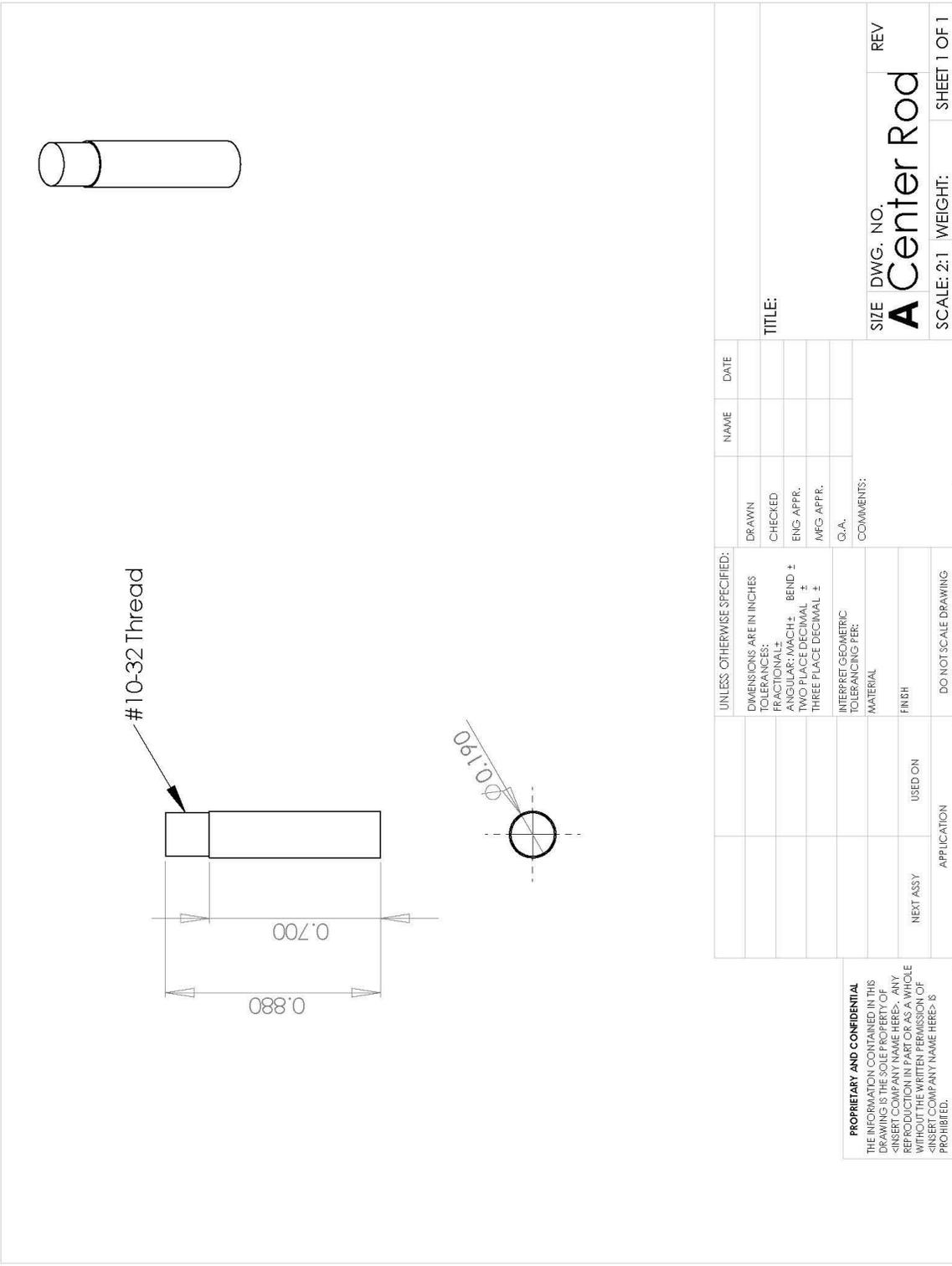


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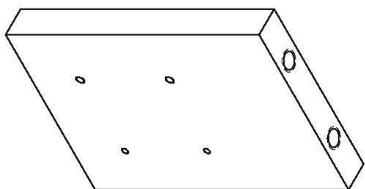
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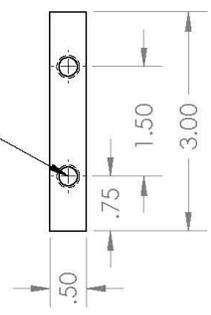
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Calibration Instrument

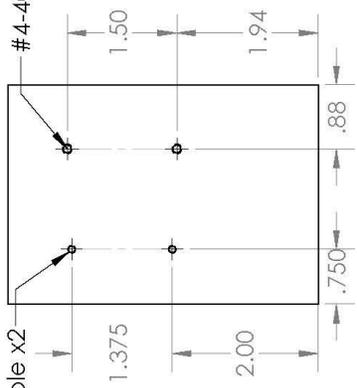
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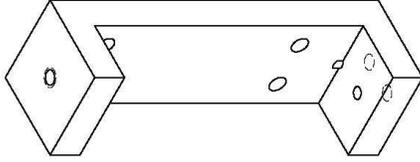
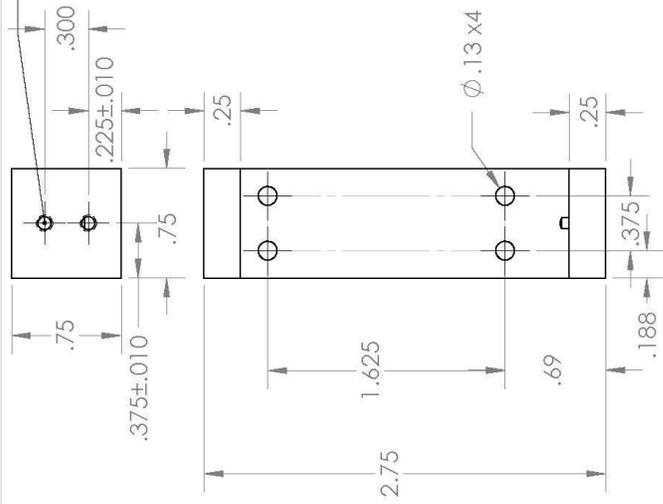


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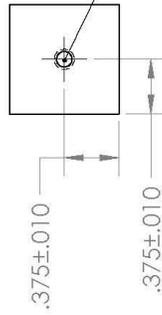
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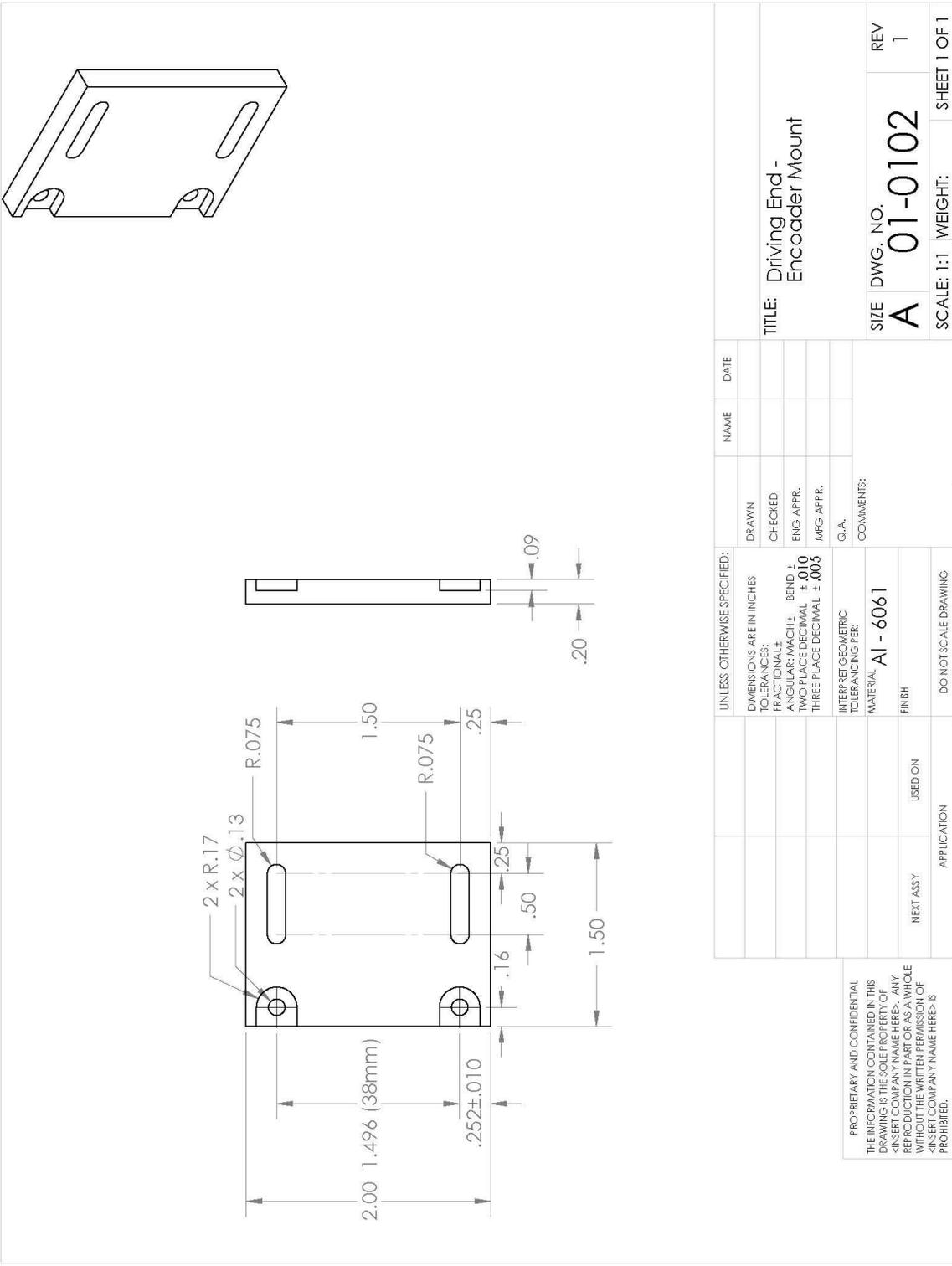


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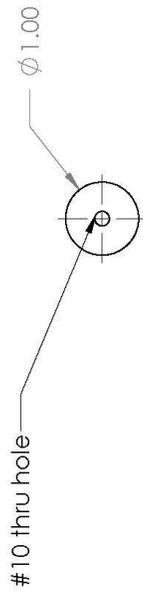
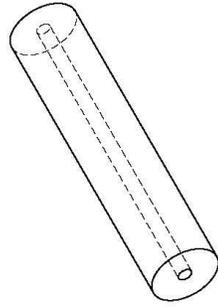
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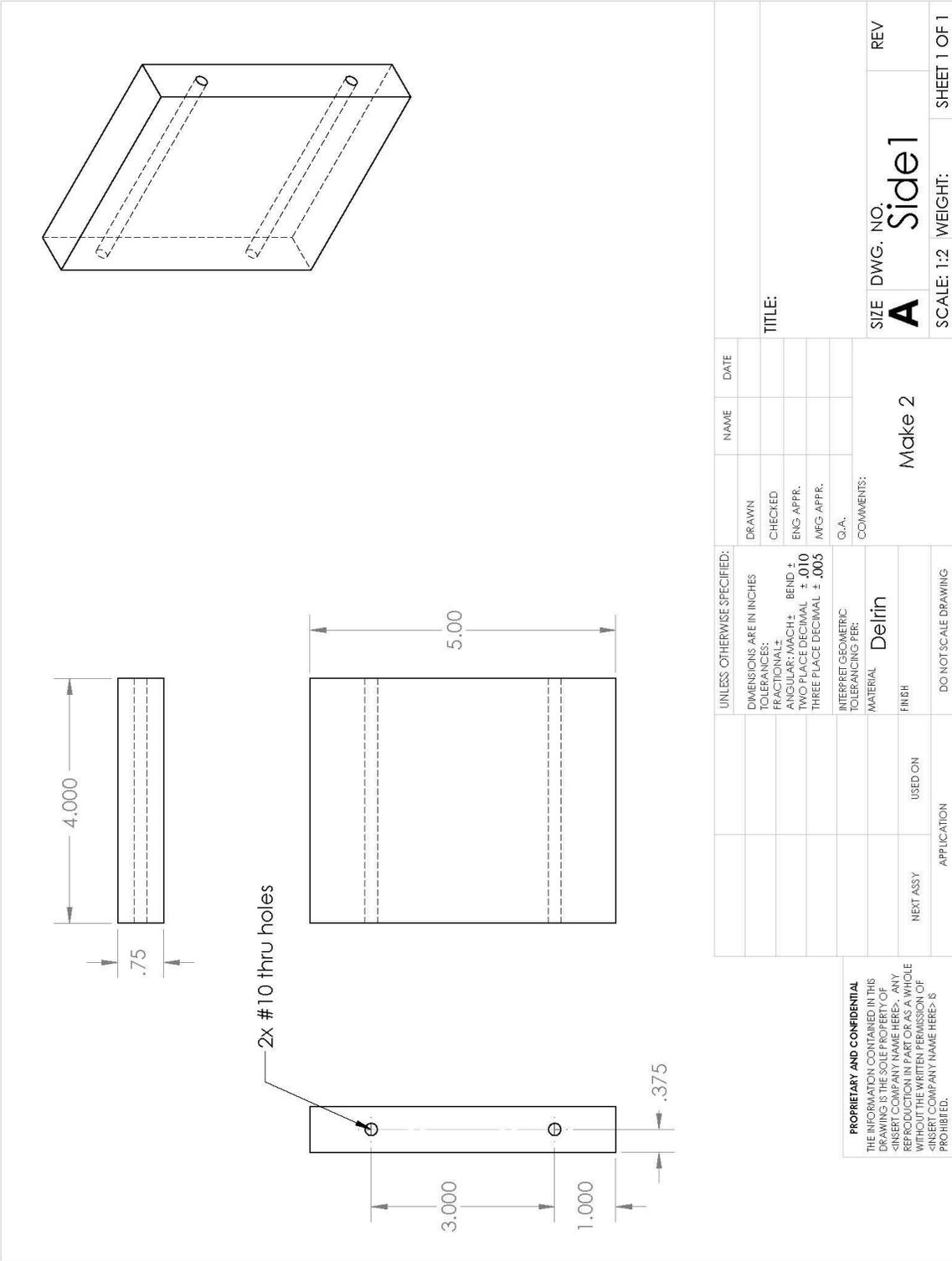


Phantom Mold

Technical drawings of the custom machined pieces of the driving end referred to in Chapter 3)
Tissue Phantom Validation Design Process

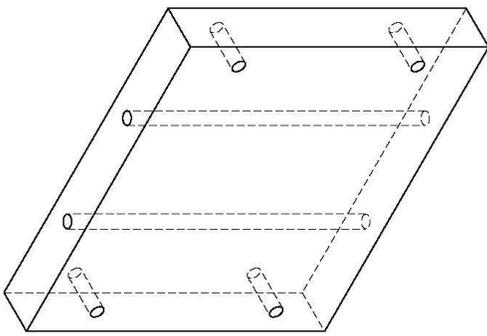
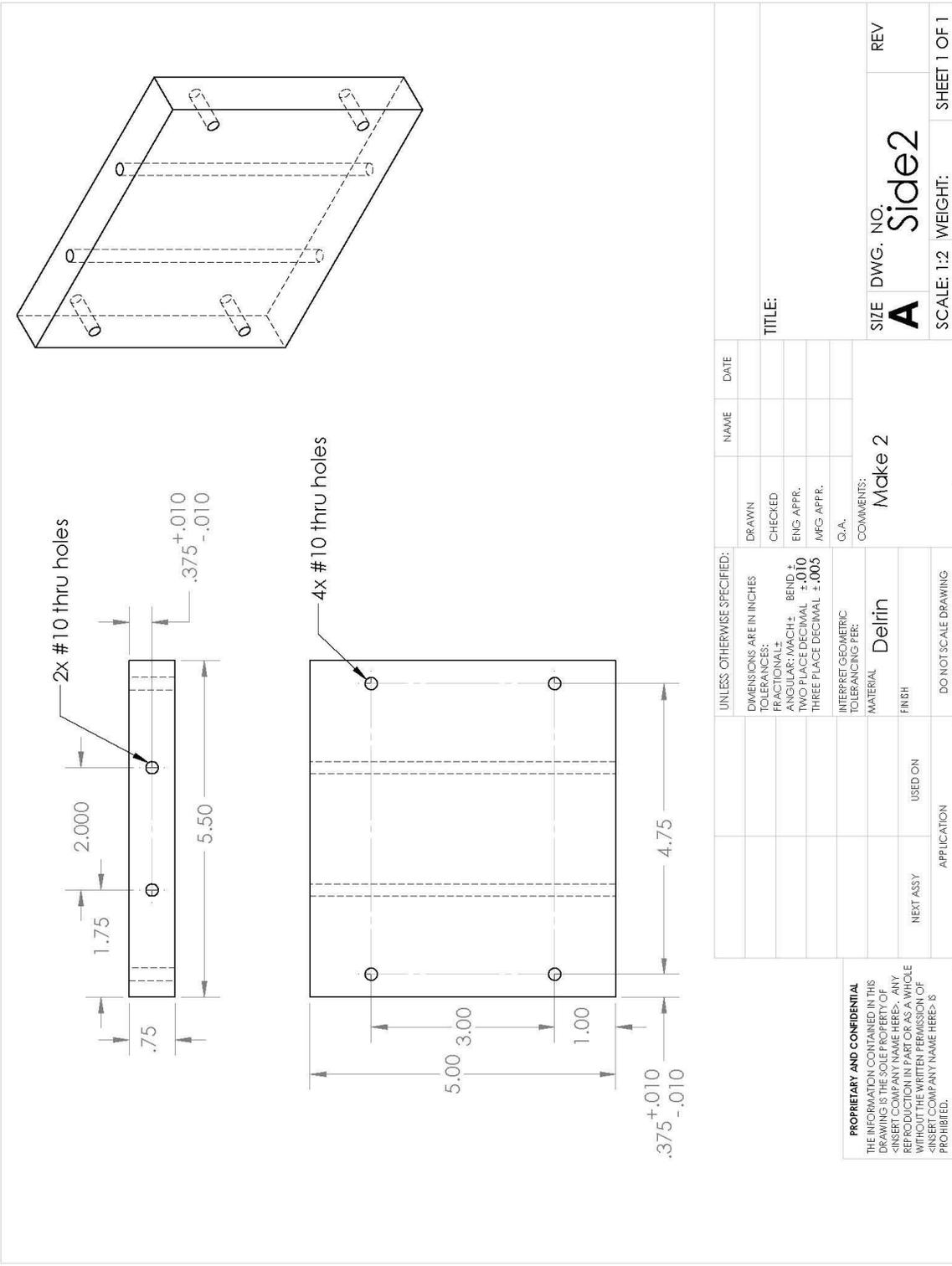


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|---|--|--|--|-----------|--|------------|--|--------------|--|
| <p>PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF DELTRIN. IT IS TO BE USED FOR THE PART OR ASSEMBLY IDENTIFIED HEREON. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF DELTRIN IS PROHIBITED.</p> | | UNLESS OTHERWISE SPECIFIED: | | DRAWN | | NAME | | DATE | |
| | | DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± .005 DECIMAL ± .001 ANGLES ± .010 HOLE DECIMAL ± .010 THREE PLACE DECIMAL ± .005 | | CHECKED | | | | | |
| | | INTERPRET GEOMETRIC TOLERANCING PER: | | ENG APPR. | | | | | |
| | | MATERIAL | | MFG APPR. | | | | | |
| | | FINISH | | G.A. | | | | | |
| | | DO NOT SCALE DRAWING | | COMMENTS: | | | | | |
| NEXT ASSY | | USED ON | | Delrin | | | | | |
| APPLICATION | | | | | | | | | |
| 4 | | 3 | | 2 | | 1 | | | |
| 5 | | 3 | | 2 | | 1 | | | |
| | | | | | | TITLE: | | REV | |
| | | | | | | SIZE | | DWG. NO. | |
| | | | | | | A | | middle | |
| | | | | | | SCALE: 1:2 | | WEIGHT: | |
| | | | | | | | | SHEET 1 OF 1 | |



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| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE |
|--------------------------------------|---|---------------------------------|------|
| DIMENSIONS ARE IN INCHES | | | |
| TOLERANCES: | | DRAWN | |
| FRACTIONAL ± | | CHECKED | |
| DECIMAL ± | | ENG APPR. | |
| THREE PLACE DECIMAL ± .010 | | MFG APPR. | |
| THREE PLACE DECIMAL ± .005 | | | |
| INTERPRET GEOMETRIC TOLERANCING PER: | | | |
| MATERIAL | | COMMENTS: | |
| Delrin | | Make 2 | |
| FINISH | | | |
| NEXT ASSY | | USED ON | |
| APPLICATION | | DO NOT SCALE DRAWING | |
| 5 | 4 | 3 | 2 |
| TITLE: | | SIZE DWG. NO. REV | |
| A Side1 | | SCALE: 1:2 WEIGHT: SHEET 1 OF 1 | |



| UNLESS OTHERWISE SPECIFIED: | | NAME | DATE |
|-----------------------------|--|-------------|------|
| DRAWN | | | |
| CHECKED | | | |
| ENG APPR. | | | |
| MFG APPR. | | | |
| G.A. | | | |
| COMMENTS: | | | |
| Make 2 | | | |
| MATERIAL | | Delrin | |
| FINISH | | USED ON | |
| NEXT ASSY | | APPLICATION | |
| DO NOT SCALE DRAWING | | | |
| 5 | | 3 | |
| 4 | | 2 | |
| 1 | | 1 | |

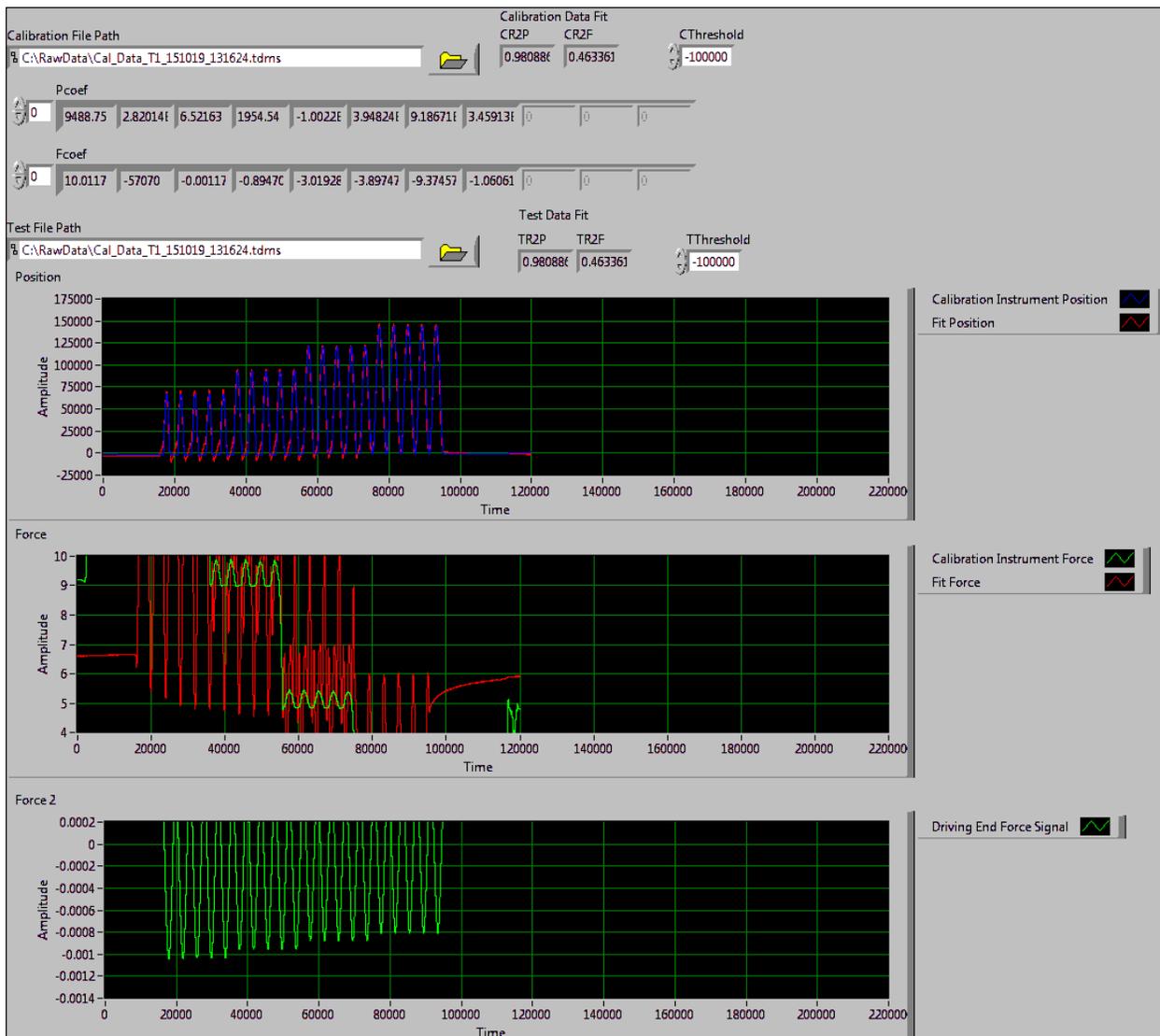
PROPRIETARY AND CONFIDENTIAL
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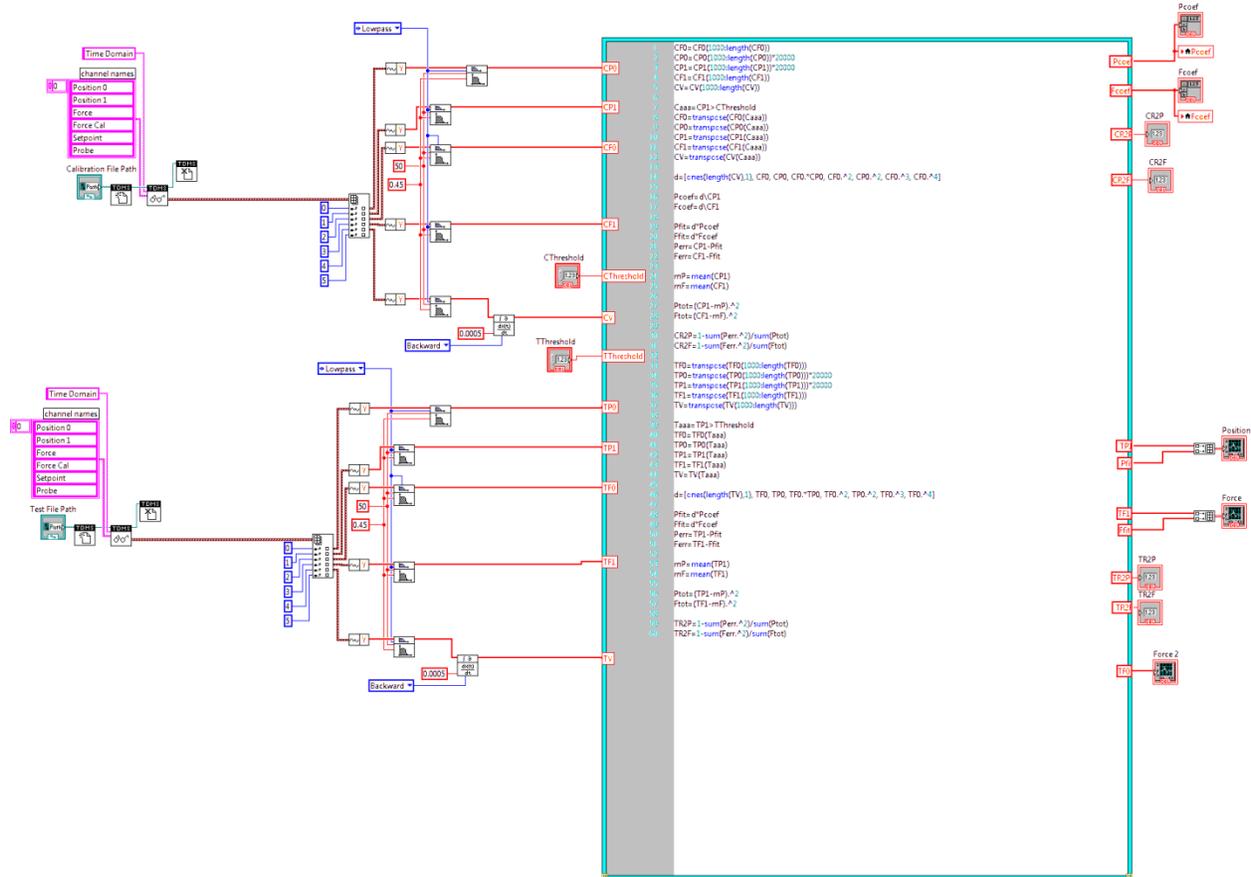
SIZE DWG. NO. **A** Side2 REV
 SCALE: 1:2 WEIGHT: SHEET 1 OF 1

Appendix B) Computer Code

CalAndCheck.vi

CalAndCheck.vi is an analysis program that was used in order to verify an eight parameter calibration model's accuracy. This was utilized in Chapter 4) to help determine relevant variables. Input into the .vi are two files, one data from a calibration protocol, and the second data from a test associated with that calibration. The program then processes the calibration data and obtains the proper calibration parameters. Then, the test data is sent through the calibration equation to obtain probe end force and position. These calculated force and position values are then compared to the measured force and position of the calibration instrument on a plot and through coefficients of determination.





MathScript Text:

```
CF0=CF0(1000:length(CF0))
CP0=CP0(1000:length(CP0))*20000
CP1=CP1(1000:length(CP1))*20000
CF1=CF1(1000:length(CF1))
CV=CV(1000:length(CV))
```

```
Caaa=CP1>CThreshold
CF0=transpose(CF0(Caaa))
CP0=transpose(CP0(Caaa))
CP1=transpose(CP1(Caaa))
CF1=transpose(CF1(Caaa))
CV=transpose(CV(Caaa))
```

```
d=[ones(length(CV),1), CF0, CP0, CF0.*CP0, CF0.^2, CP0.^2, CF0.^3, CF0.^4]
```

```
Pcoef=d\CP1
Fcoef=d\CF1
```

```
Pfit=d*Pcoef
Ffit=d*Fcoef
Perr=CP1-Pfit
```

Ferr=CF1-Ffit

mP=mean(CP1)

mF=mean(CF1)

Ptot=(CP1-mP).^2

Ftot=(CF1-mF).^2

CR2P=1-sum(Perr.^2)/sum(Ptot)

CR2F=1-sum(Ferr.^2)/sum(Ftot)

TF0=transpose(TF0(1000:length(TF0)))

TP0=transpose(TP0(1000:length(TP0)))*20000

TP1=transpose(TP1(1000:length(TP1)))*20000

TF1=transpose(TF1(1000:length(TF1)))

TV=transpose(TV(1000:length(TV)))

Taaa=TP1>TThreshold

TF0=TF0(Taaa)

TP0=TP0(Taaa)

TP1=TP1(Taaa)

TF1=TF1(Taaa)

TV=TV(Taaa)

d=[ones(length(TV),1), TF0, TP0, TF0.*TP0, TF0.^2, TP0.^2, TF0.^3, TF0.^4]

Pfit=d*Pcoef

Ffit=d*Fcoef

Perr=TP1-Pfit

Ferr=TF1-Ffit

mP=mean(TP1)

mF=mean(TF1)

Ptot=(TP1-mP).^2

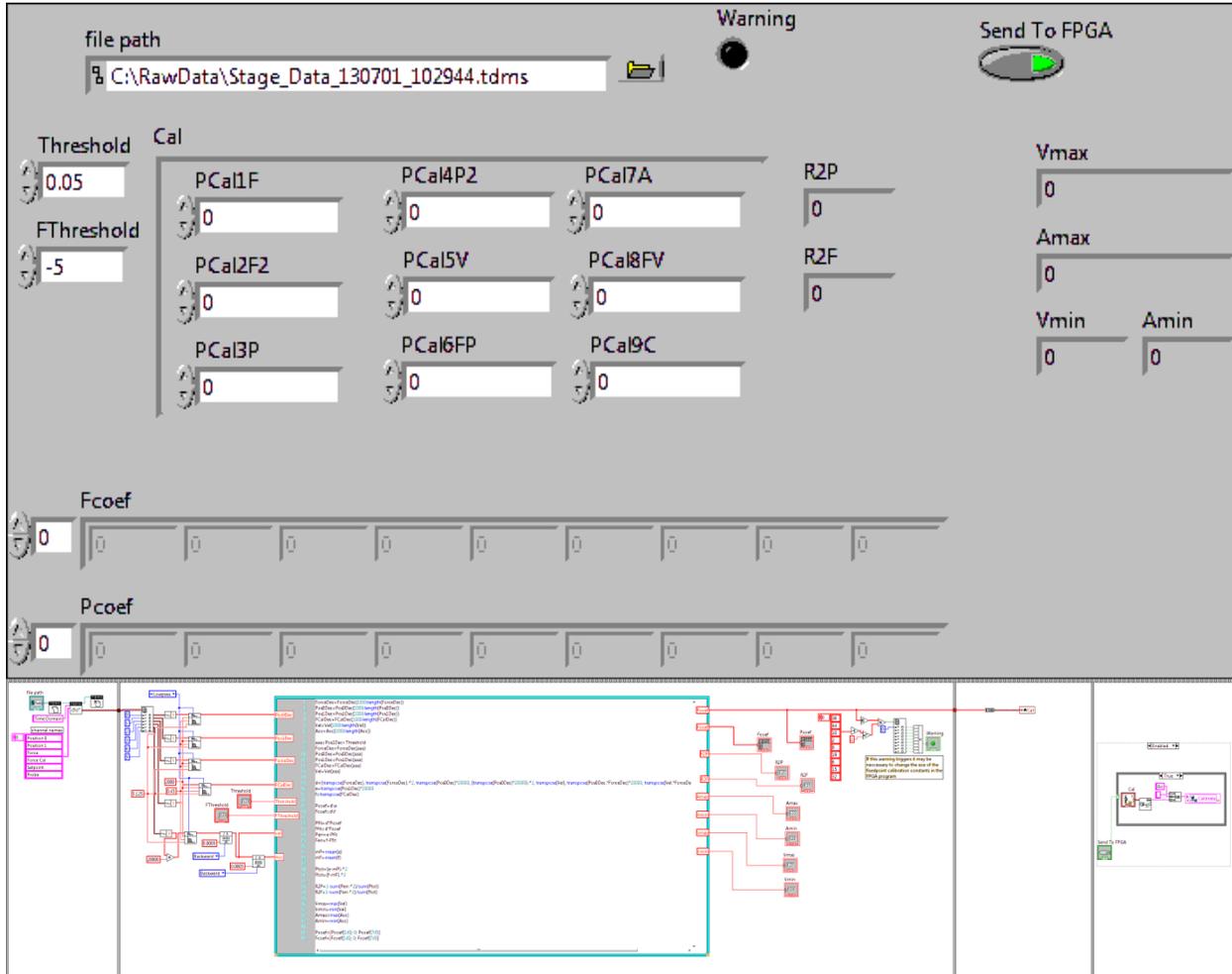
Ftot=(TF1-mF).^2

TR2P=1-sum(Perr.^2)/sum(Ptot)

TR2F=1-sum(Ferr.^2)/sum(Ftot)

Host Calibration Process2.vi

HostCalibrationProcess2.vi is a support program made to be used with the eight parameter calibration process. This .vi takes in the calibration data and outputs the calibration parameters both to the user and, optionally, sent to the FPGA. There is also a warning light that triggers if the calibration parameters are outside the range of the fixedpoint number that they are sent to in the FPGA.



MathScript Text:

```
ForceDec=ForceDec(1000:length(ForceDec))
```

```
Pos0Dec=Pos0Dec(1000:length(Pos0Dec))
```

```
Pos1Dec=Pos1Dec(1000:length(Pos1Dec))
```

```
FcalDec=FcalDec(1000:length(FcalDec))
```

```
Vel=Vel(1000:length(Vel))
```

```
Acc=Acc(1000:length(Acc))
```

```
aaa=Pos1Dec>Threshold
```

```
ForceDec=ForceDec(aaa)
```

```
Pos0Dec=Pos0Dec(aaa)
```

```
Pos1Dec=Pos1Dec(aaa)
```

```
FCalDec=FCalDec(aaa)
Vel=Vel(aaa)
```

```
d=[transpose(ForceDec), transpose(ForceDec).^2, transpose(Pos0Dec)*20000,
(transpose(Pos0Dec)*20000).^2, transpose(Vel), transpose(Pos0Dec.*ForceDec)*20000,
transpose(Vel.*ForceDec), ones(length(ForceDec),1)]
e=transpose(Pos1Dec)*20000
f=transpose(FCalDec)
```

```
Pcoef=d\e
Fcoef=d\f
```

```
Pfit=d*Pcoef
Ffit=d*Fcoef
Perr=e-Pfit
Ferr=f-Ffit
```

```
mP=mean(e)
mF=mean(f)
```

```
Ptot=(e-mP).^2
Ftot=(f-mF).^2
```

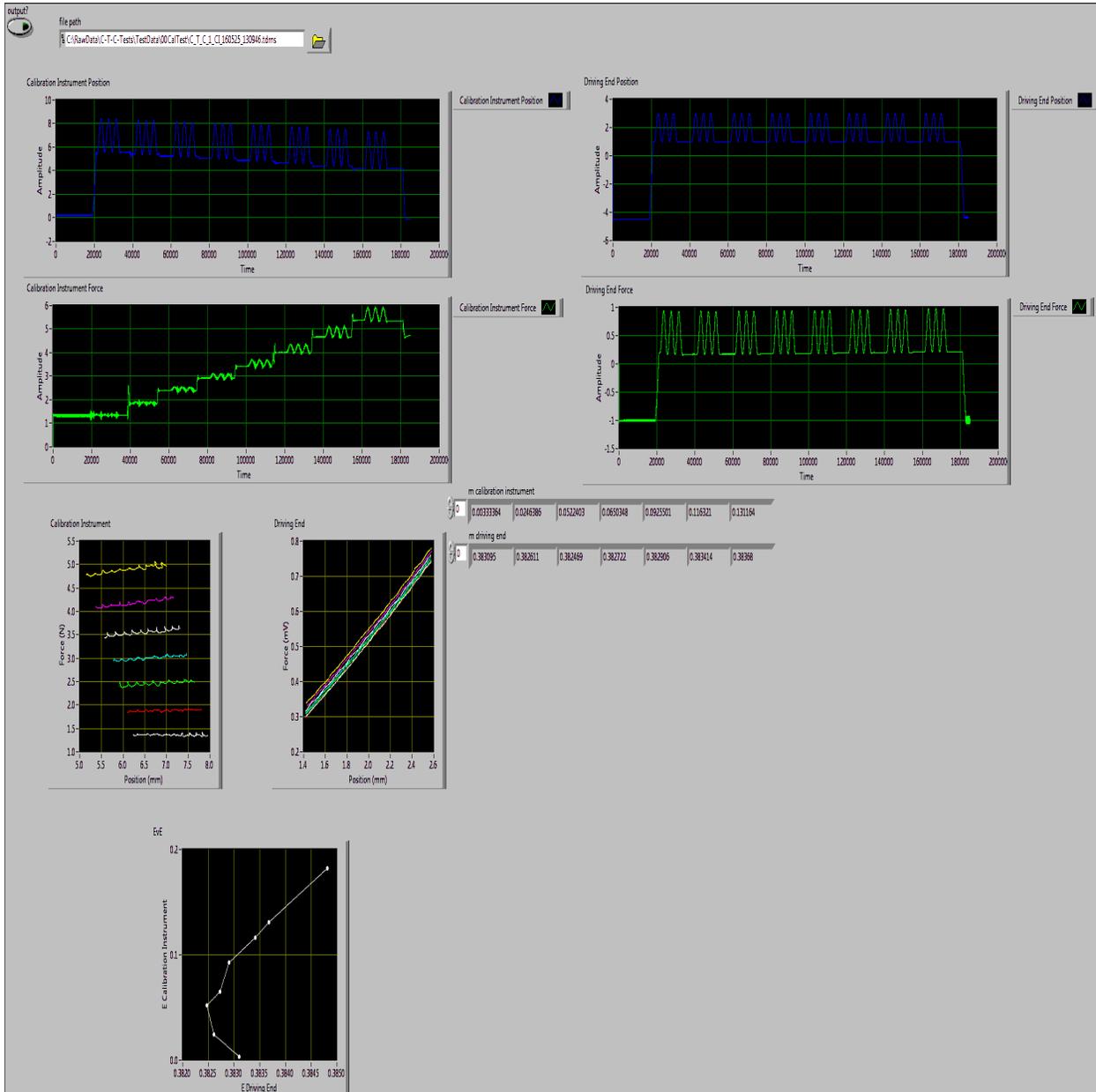
```
R2P=1-sum(Perr.^2)/sum(Ptot)
R2F=1-sum(Ferr.^2)/sum(Ftot)
```

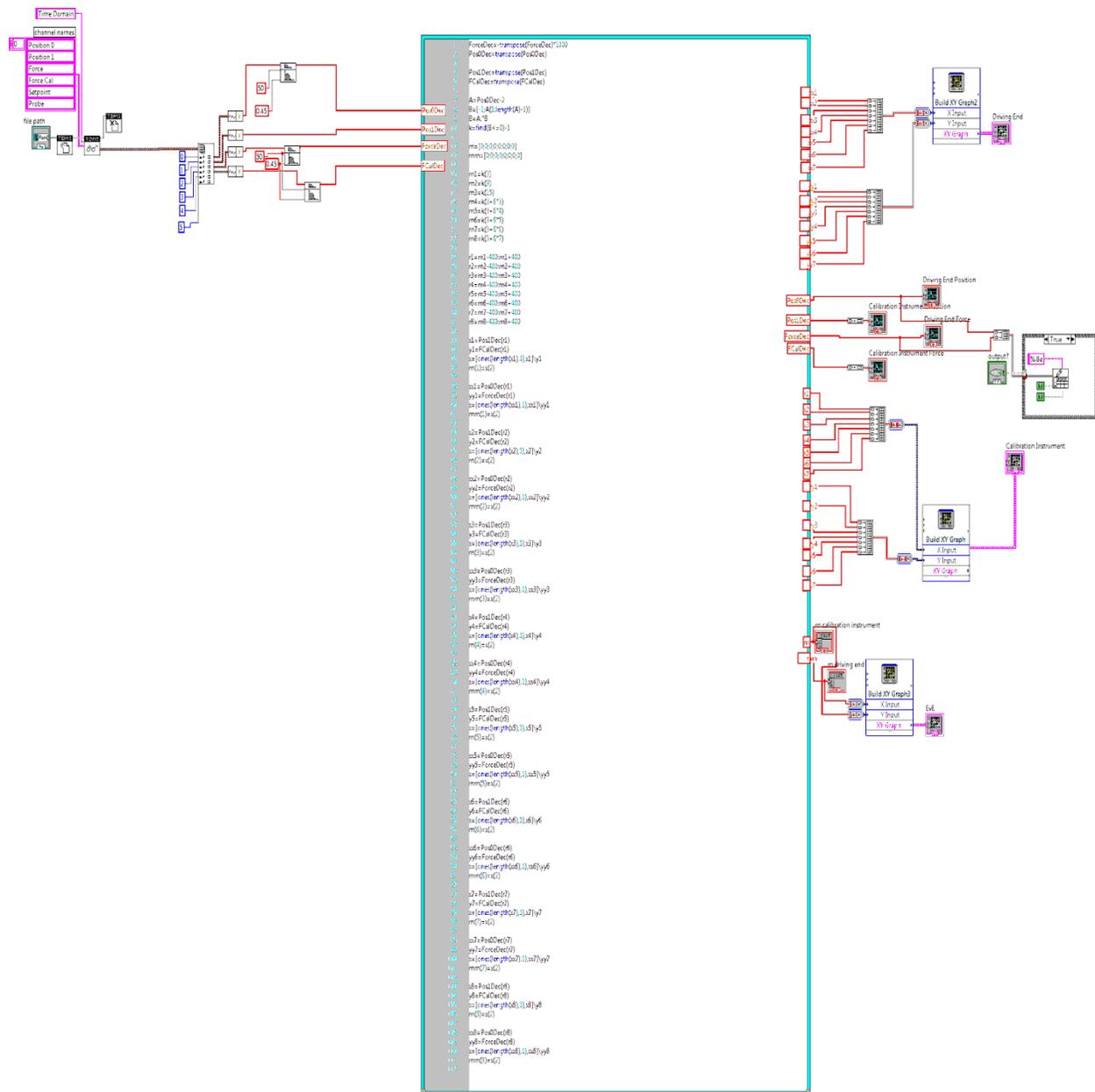
```
Vmax=max(Vel)
Vmin=min(Vel)
Amax=max(Acc)
Amin=min(Acc)
```

```
Pcoef=[Pcoef(1:6); 0; Pcoef(7:8)]
Fcoef=[Fcoef(1:6); 0; Fcoef(7:8)]
```

Slopes2.vi

Slopes2.vi is a data processing program. It takes in the .tdms file of a calibration test, plots the relevant raw data, finds the proper loading segments, plots those loading segments as Force vs Displacement curves, finds the slope of those Force vs Displacement Curves, plots those slopes as calibration E vs driving E, and reports the slopes for other programs to employ. The program can also, optionally, output the force and displacement data as a .txt file if MATLAB or other processing is required.





MathScript Text:

ForceDec=-transpose(ForceDec)*1000

Pos0Dec=transpose(Pos0Dec)

Pos1Dec=transpose(Pos1Dec)

FCalDec=transpose(FCalDec)

A=Pos0Dec-2

B=[-1;A(1:length(A)-1)]

B=A.*B

k=find(B<=0)-1

```
m=[0;0;0;0;0;0;0;0]
mm=[0;0;0;0;0;0;0;0]
```

```
m1=k(3)
m2=k(9)
m3=k(15)
m4=k(3+6*3)
m5=k(3+6*4)
m6=k(3+6*5)
m7=k(3+6*6)
m8=k(3+6*7)
```

```
r1=m1-400:m1+400
r2=m2-400:m2+400
r3=m3-400:m3+400
r4=m4-400:m4+400
r5=m5-400:m5+400
r6=m6-400:m6+400
r7=m7-400:m7+400
r8=m8-400:m8+400
```

```
x1=Pos1Dec(r1)
y1=FCalDec(r1)
x=[ones(length(x1),1),x1]\y1
m(1)=x(2)
```

```
xx1=Pos0Dec(r1)
yy1=ForceDec(r1)
x=[ones(length(xx1),1),xx1]\yy1
mm(1)=x(2)
x2=Pos1Dec(r2)
y2=FCalDec(r2)
x=[ones(length(x2),1),x2]\y2
m(2)=x(2)
```

```
xx2=Pos0Dec(r2)
yy2=ForceDec(r2)
x=[ones(length(xx2),1),xx2]\yy2
mm(2)=x(2)
```

```
x3=Pos1Dec(r3)
y3=FCalDec(r3)
x=[ones(length(x3),1),x3]\y3
m(3)=x(2)
```

xx3=Pos0Dec(r3)
yy3=ForceDec(r3)
x=[ones(length(xx3),1),xx3]\yy3
mm(3)=x(2)

x4=Pos1Dec(r4)
y4=FCalDec(r4)
x=[ones(length(x4),1),x4]\y4
m(4)=x(2)

xx4=Pos0Dec(r4)
yy4=ForceDec(r4)
x=[ones(length(xx4),1),xx4]\yy4
mm(4)=x(2)

x5=Pos1Dec(r5)
y5=FCalDec(r5)
x=[ones(length(x5),1),x5]\y5
m(5)=x(2)

xx5=Pos0Dec(r5)
yy5=ForceDec(r5)
x=[ones(length(xx5),1),xx5]\yy5
mm(5)=x(2)

x6=Pos1Dec(r6)
y6=FCalDec(r6)
x=[ones(length(x6),1),x6]\y6
m(6)=x(2)

xx6=Pos0Dec(r6)
yy6=ForceDec(r6)
x=[ones(length(xx6),1),xx6]\yy6
mm(6)=x(2)

x7=Pos1Dec(r7)
y7=FCalDec(r7)
x=[ones(length(x7),1),x7]\y7
m(7)=x(2)

xx7=Pos0Dec(r7)
yy7=ForceDec(r7)
x=[ones(length(xx7),1),xx7]\yy7
mm(7)=x(2)

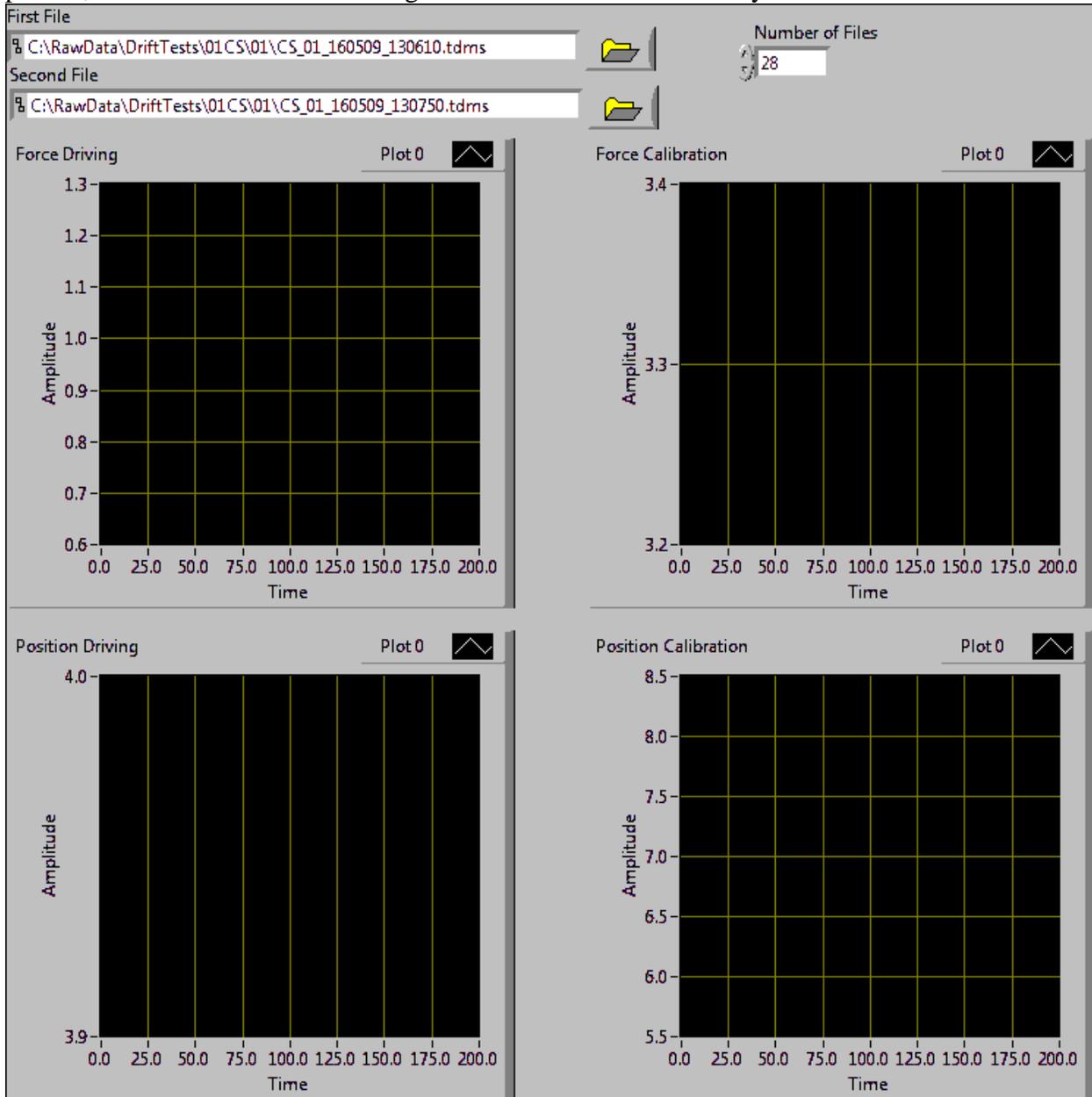
x8=Pos1Dec(r8)

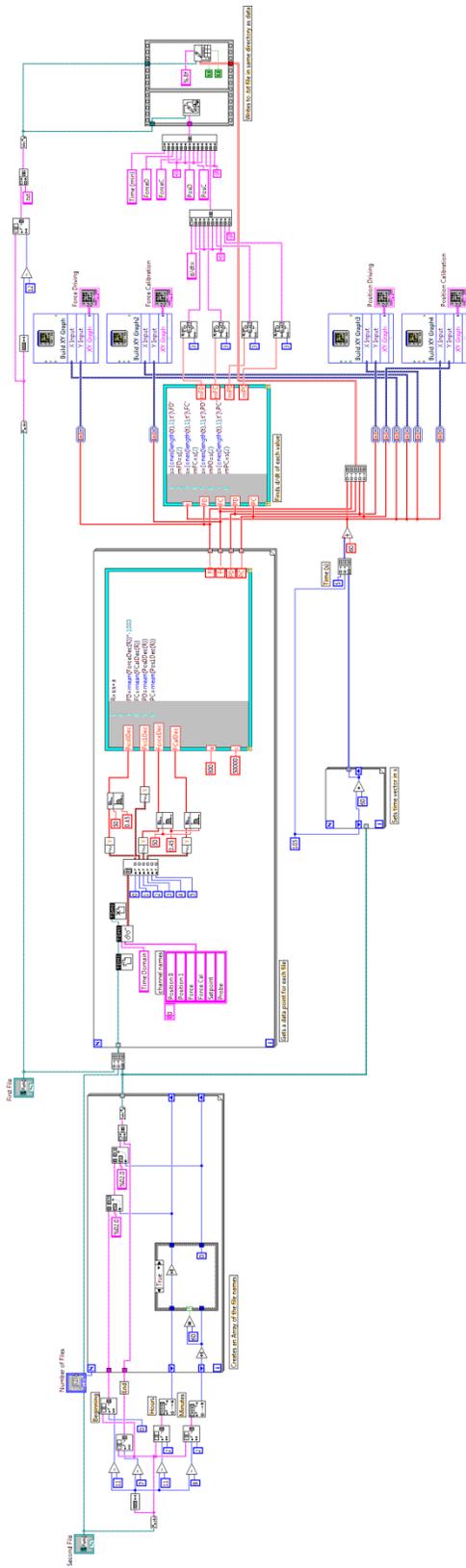
```
y8=FCalDec(r8)
x=[ones(length(x8),1),x8]\y8
m(8)=x(2)
```

```
xx8=Pos0Dec(r8)
yy8=ForceDec(r8)
x=[ones(length(xx8),1),xx8]\yy8
mm(8)=x(2)
```

DriftAnalysis.vi

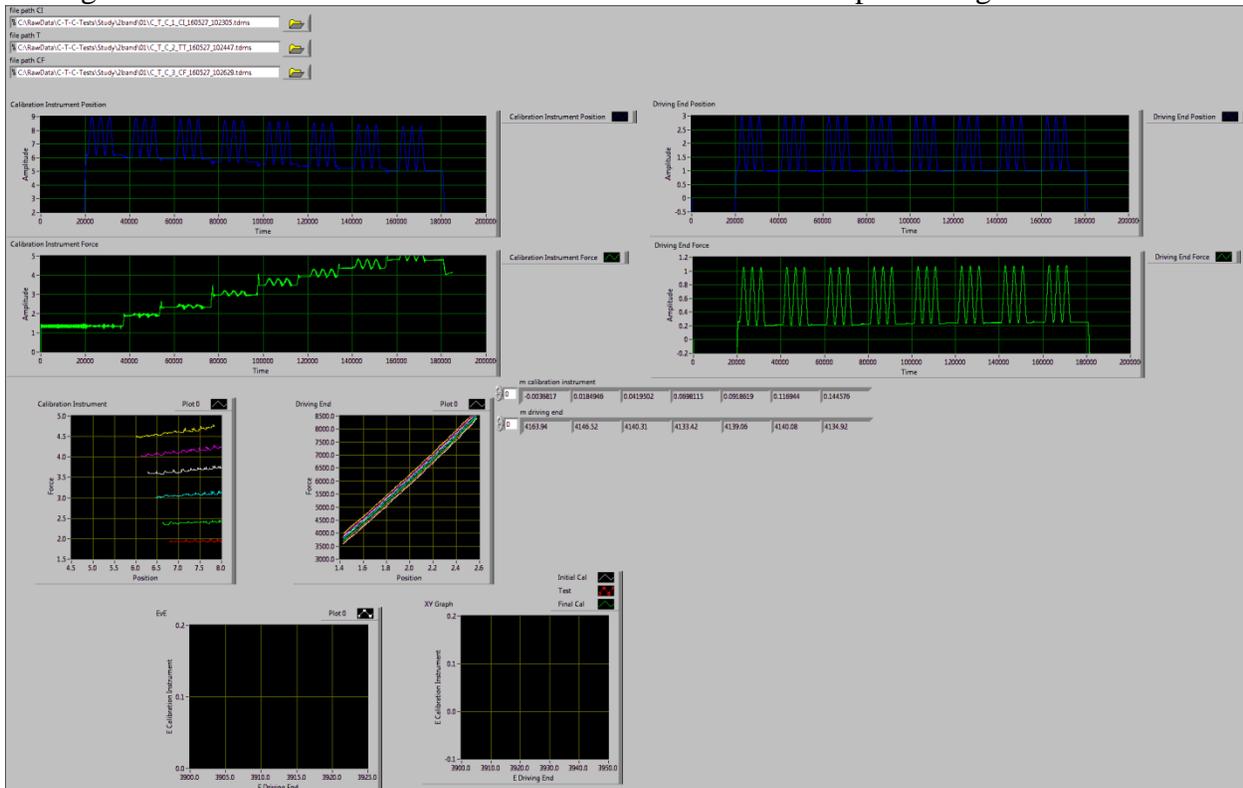
DriftAnalysis.vi is an analysis program that is used with the Drift protocol discussed in Chapter 5. The .vi takes inputs of the first and second file names from a drift test, as well as the number of files to be processed. The .vi then automatically generates the names for the other files that were not input by the user based on the second file's name. Each file is then simplified to four points, which are the average of driving force, driving position, calibration force, and calibration position, by averaging a specific stretch of data. After all of these points are collected time stamps, time values for each point are calculated. Each of the four data points are then plotted, and the values are sent to a generated .txt file for later analysis.

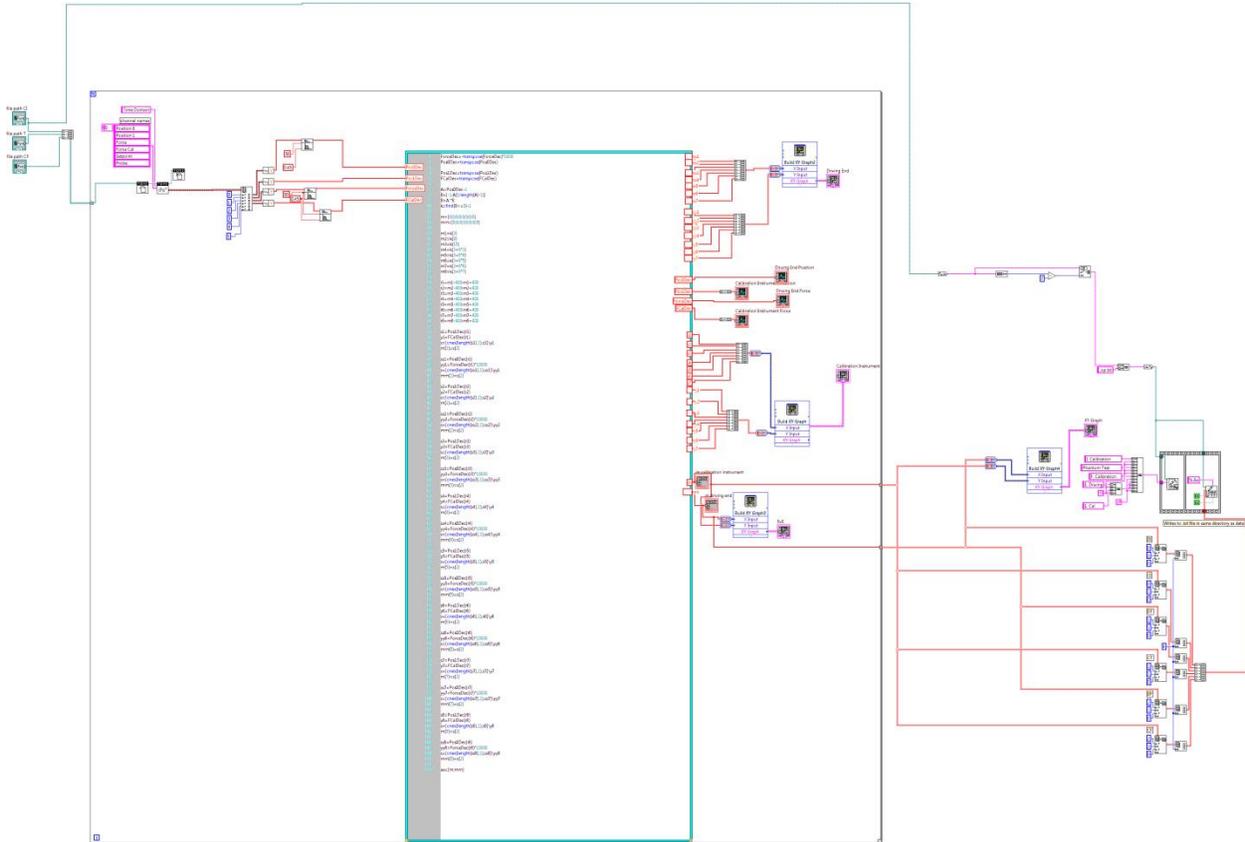




CTC_Analysis.vi

CTC_Analysis.vi is made to be run with the calibrate-test-calibrate testing procedure discussed in Chapter 5. Three files are input into the .vi and each analyzed the same way. First, the raw data is plotted. Next, the program automatically identifies the loading segments of interest. Those segments are then plotted as force vs displacement curves. The slopes of these curves is then calculated and plotted on the E calibration vs E driving plot. After this is done for each file the three comparative elasticity plots are combined and plotted together. Finally, the E driving and E calibration values are saved into a .txt file for future processing.





MathScript Text:

ForceDec=-transpose(ForceDec)*1000

Pos0Dec=transpose(Pos0Dec)

Pos1Dec=transpose(Pos1Dec)

FCalDec=transpose(FCalDec)

A=Pos0Dec-2

B=[-1;A(1:length(A)-1)]

B=A.*B

k=find(B<=0)-1

m=[0;0;0;0;0;0;0]

mm=[0;0;0;0;0;0;0]

m1=k(3)

m2=k(9)

m3=k(15)

m4=k(3+6*3)

m5=k(3+6*4)

m6=k(3+6*5)

m7=k(3+6*6)

m8=k(3+6*7)

r1=m1-400:m1+400

r2=m2-400:m2+400

r3=m3-400:m3+400

r4=m4-400:m4+400

r5=m5-400:m5+400

r6=m6-400:m6+400

r7=m7-400:m7+400

r8=m8-400:m8+400

x1=Pos1Dec(r1)

y1=FCalDec(r1)

x=[ones(length(x1),1),x1]\y1

m(1)=x(2)

xx1=Pos0Dec(r1)

yy1=ForceDec(r1)*10000

x=[ones(length(xx1),1),xx1]\yy1

mm(1)=x(2)

x2=Pos1Dec(r2)

y2=FCalDec(r2)

x=[ones(length(x2),1),x2]\y2

m(2)=x(2)

xx2=Pos0Dec(r2)

yy2=ForceDec(r2)*10000

x=[ones(length(xx2),1),xx2]\yy2

mm(2)=x(2)

x3=Pos1Dec(r3)

y3=FCalDec(r3)

x=[ones(length(x3),1),x3]\y3

m(3)=x(2)

xx3=Pos0Dec(r3)

yy3=ForceDec(r3)*10000

x=[ones(length(xx3),1),xx3]\yy3

mm(3)=x(2)

x4=Pos1Dec(r4)

y4=FCalDec(r4)

x=[ones(length(x4),1),x4]\y4

m(4)=x(2)

```
xx4=Pos0Dec(r4)
yy4=ForceDec(r4)*10000
x=[ones(length(xx4),1),xx4]\yy4
mm(4)=x(2)
```

```
x5=Pos1Dec(r5)
y5=FCalDec(r5)
x=[ones(length(x5),1),x5]\y5
m(5)=x(2)
```

```
xx5=Pos0Dec(r5)
yy5=ForceDec(r5)*10000
x=[ones(length(xx5),1),xx5]\yy5
mm(5)=x(2)
```

```
x6=Pos1Dec(r6)
y6=FCalDec(r6)
x=[ones(length(x6),1),x6]\y6
m(6)=x(2)
```

```
xx6=Pos0Dec(r6)
yy6=ForceDec(r6)*10000
x=[ones(length(xx6),1),xx6]\yy6
mm(6)=x(2)
```

```
x7=Pos1Dec(r7)
y7=FCalDec(r7)
x=[ones(length(x7),1),x7]\y7
m(7)=x(2)
```

```
xx7=Pos0Dec(r7)
yy7=ForceDec(r7)*10000
x=[ones(length(xx7),1),xx7]\yy7
mm(7)=x(2)
```

```
x8=Pos1Dec(r8)
y8=FCalDec(r8)
x=[ones(length(x8),1),x8]\y8
m(8)=x(2)
```

```
xx8=Pos0Dec(r8)
yy8=ForceDec(r8)*10000
x=[ones(length(xx8),1),xx8]\yy8
mm(8)=x(2)
```

```
aa=[m;mm]
```

Appendix C) Example Data

Drift Tests

Values over time (min) for the values of driving force (ForceD in mV), calibration instrument force (ForceC in N), driving position (PosD in mm), and calibration instrument position (PosC in mm) referenced in Chapter 5. Triplicate tests for the isolated driving load cell, drained isolated driving bellows, short nylon tubing with 3mm displacement, long nylon tubing with 3 and 4 mm displacement and copper tubing with 3 and 4mm displacement.

Load Cell Test Trial 1

| Time (min) | ForceD | ForceC | PosD | PosC |
|-------------|------------|-------------|------------|-------------|
| d/dt= | -4.442E-6 | -402.691E-6 | 42.126E-6 | -22.703E-6 |
| 0.08333333 | 0.12319196 | 2.26297885 | 3.99722523 | 0.00002928 |
| 1.75000000 | 0.12326124 | 2.26716849 | 3.99609035 | -0.00002191 |
| 2.75000000 | 0.12329373 | 2.26795000 | 3.99508989 | -0.00004944 |
| 3.75000000 | 0.12326558 | 2.26836481 | 3.99572250 | -0.00006536 |
| 4.75000000 | 0.12328634 | 2.26893777 | 3.99544005 | -0.00010031 |
| 5.75000000 | 0.12333924 | 2.26932992 | 3.99207003 | -0.00013602 |
| 6.75000000 | 0.12328833 | 2.26863766 | 3.99286013 | -0.00015225 |
| 7.75000000 | 0.12329354 | 2.26910947 | 3.99429286 | -0.00018783 |
| 8.75000000 | 0.12334060 | 2.26781152 | 3.99398220 | -0.00020194 |
| 9.75000000 | 0.12333891 | 2.26821631 | 3.99481198 | -0.00023926 |
| 10.75000000 | 0.12333219 | 2.26588962 | 3.99469232 | -0.00025125 |
| 11.75000000 | 0.12331220 | 2.26582893 | 3.99393214 | -0.00028190 |
| 12.75000000 | 0.12334492 | 2.26568483 | 3.99464370 | -0.00030025 |
| 13.75000000 | 0.12331296 | 2.26491721 | 3.99500107 | -0.00032172 |
| 14.75000000 | 0.12331962 | 2.26441872 | 3.99418374 | -0.00034775 |
| 15.75000000 | 0.12326642 | 2.26416762 | 3.99579436 | -0.00036099 |
| 16.75000000 | 0.12326162 | 2.26361697 | 3.99443164 | -0.00039757 |
| 17.75000000 | 0.12320817 | 2.26244067 | 3.99506017 | -0.00040874 |
| 18.75000000 | 0.12325751 | 2.26209810 | 3.99471070 | -0.00044076 |
| 19.75000000 | 0.12325158 | 2.26129274 | 3.99503144 | -0.00045106 |
| 20.75000000 | 0.12322565 | 2.26172239 | 3.99613415 | -0.00047328 |
| 21.75000000 | 0.12319436 | 2.26128737 | 3.99613226 | -0.00050075 |
| 22.75000000 | 0.12322596 | 2.26093633 | 3.99571671 | -0.00052584 |
| 23.75000000 | 0.12317517 | 2.25996568 | 3.99657828 | -0.00054806 |
| 24.75000000 | 0.12320234 | 2.25904692 | 3.99582327 | -0.00055337 |
| 25.75000000 | 0.12319886 | 2.25830467 | 3.99601124 | -0.00057534 |
| 26.75000000 | 0.12318127 | 2.25853280 | 3.99526028 | -0.00059900 |
| 27.75000000 | 0.12314143 | 2.25777478 | 3.99528537 | -0.00061273 |
| 28.75000000 | 0.12318857 | 2.25821438 | 3.99606635 | -0.00063514 |
| 29.75000000 | 0.12319206 | 2.25705027 | 3.99651222 | -0.00064925 |

Load Cell Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|-------------|
| | -2.087E-6 | -27.744E-6 | -250.022E-6 | -13.062E-6 |
| 0.08333333 | 0.12316837 | 2.25594854 | 3.99684305 | -0.00008620 |
| 1.75000000 | 0.12319479 | 2.25602751 | 3.99628351 | -0.00010044 |
| 2.75000000 | 0.12318345 | 2.25619171 | 3.99623065 | -0.00010312 |
| 3.75000000 | 0.12317656 | 2.25589757 | 3.99698679 | -0.00013983 |
| 4.75000000 | 0.12314681 | 2.25513691 | 3.99660330 | -0.00015019 |
| 5.75000000 | 0.12315172 | 2.25539393 | 3.99517682 | -0.00015487 |
| 6.75000000 | 0.12317536 | 2.25555510 | 3.98794717 | -0.00018558 |
| 7.75000000 | 0.12320132 | 2.25473406 | 3.99160314 | -0.00019126 |
| 8.75000000 | 0.12312561 | 2.25532889 | 3.98906780 | -0.00019950 |
| 9.75000000 | 0.12309712 | 2.25428590 | 3.98920544 | -0.00020031 |
| 10.75000000 | 0.12314994 | 2.25445554 | 3.98815120 | -0.00020886 |
| 11.75000000 | 0.12320233 | 2.25407471 | 3.98912501 | -0.00023683 |
| 12.75000000 | 0.12314364 | 2.25496899 | 3.99048931 | -0.00024981 |
| 13.75000000 | 0.12313235 | 2.25566487 | 3.98884119 | -0.00026735 |
| 14.75000000 | 0.12313265 | 2.25470328 | 3.98771519 | -0.00029469 |
| 15.75000000 | 0.12316544 | 2.25501232 | 3.98856496 | -0.00030069 |
| 16.75000000 | 0.12311197 | 2.25549821 | 3.98796148 | -0.00030037 |
| 17.75000000 | 0.12313796 | 2.25433490 | 3.99088874 | -0.00030680 |
| 18.75000000 | 0.12313352 | 2.25411101 | 3.99043784 | -0.00033052 |
| 19.75000000 | 0.12309644 | 2.25497447 | 3.99114207 | -0.00034894 |
| 20.75000000 | 0.12313485 | 2.25447934 | 3.98929860 | -0.00036273 |
| 21.75000000 | 0.12313500 | 2.25505013 | 3.98848245 | -0.00037004 |
| 22.75000000 | 0.12312702 | 2.25437829 | 3.98823354 | -0.00039170 |
| 23.75000000 | 0.12316381 | 2.25531515 | 3.99090757 | -0.00039607 |
| 24.75000000 | 0.12312410 | 2.25491408 | 3.98728534 | -0.00040106 |
| 25.75000000 | 0.12311169 | 2.25431105 | 3.98872406 | -0.00041373 |
| 26.75000000 | 0.12312814 | 2.25430463 | 3.98863566 | -0.00044238 |
| 27.75000000 | 0.12312144 | 2.25501526 | 3.98803246 | -0.00044963 |
| 28.75000000 | 0.12311095 | 2.25525761 | 3.98891438 | -0.00045137 |
| 29.75000000 | 0.12311850 | 2.25588138 | 3.98844850 | -0.00045743 |

Load Cell Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|-------------|
| | -2.434E-6 | -26.858E-6 | -18.897E-6 | -6.361E-6 |
| 0.08333333 | 0.12312002 | 2.25426556 | 3.99632679 | 0.00005768 |
| 1.75000000 | 0.12310894 | 2.25412552 | 3.99639208 | 0.00005137 |
| 2.75000000 | 0.12311561 | 2.25430848 | 3.99624004 | 0.00004925 |
| 3.75000000 | 0.12312089 | 2.25452732 | 3.99572761 | 0.00004469 |
| 4.75000000 | 0.12310381 | 2.25503575 | 3.99610532 | 0.00003433 |
| 5.75000000 | 0.12307828 | 2.25455682 | 3.99650661 | 0.00001242 |
| 6.75000000 | 0.12312306 | 2.25495882 | 3.99629912 | 0.00001548 |
| 7.75000000 | 0.12312331 | 2.25395396 | 3.99594677 | 0.00000137 |
| 8.75000000 | 0.12310558 | 2.25430191 | 3.99616977 | -0.00000062 |
| 9.75000000 | 0.12309891 | 2.25431656 | 3.99608413 | -0.00000268 |
| 10.75000000 | 0.12311855 | 2.25393080 | 3.99660959 | -0.00001473 |
| 11.75000000 | 0.12309569 | 2.25402730 | 3.99640436 | -0.00002915 |
| 12.75000000 | 0.12309173 | 2.25436428 | 3.99628926 | -0.00002634 |
| 13.75000000 | 0.12306592 | 2.25445605 | 3.99630870 | -0.00004295 |
| 14.75000000 | 0.12306826 | 2.25433945 | 3.99658286 | -0.00004607 |
| 15.75000000 | 0.12309104 | 2.25446497 | 3.99623404 | -0.00005037 |
| 16.75000000 | 0.12313044 | 2.25461504 | 3.99646561 | -0.00005125 |
| 17.75000000 | 0.12305499 | 2.25423843 | 3.99666401 | -0.00006242 |
| 18.75000000 | 0.12306610 | 2.25443370 | 3.99637726 | -0.00006529 |
| 19.75000000 | 0.12309814 | 2.25450821 | 3.99632476 | -0.00007072 |
| 20.75000000 | 0.12306931 | 2.25416503 | 3.99640425 | -0.00007428 |
| 21.75000000 | 0.12304782 | 2.25405278 | 3.99603203 | -0.00009238 |
| 22.75000000 | 0.12307363 | 2.25411981 | 3.99569598 | -0.00009906 |
| 23.75000000 | 0.12309914 | 2.25334821 | 3.99579300 | -0.00009919 |
| 24.75000000 | 0.12305162 | 2.25433625 | 3.99598645 | -0.00009994 |
| 25.75000000 | 0.12308195 | 2.25371229 | 3.99587810 | -0.00010218 |
| 26.75000000 | 0.12305609 | 2.25419241 | 3.99575646 | -0.00010462 |
| 27.75000000 | 0.12305109 | 2.25293648 | 3.99573028 | -0.00011679 |
| 28.75000000 | 0.12303995 | 2.25426008 | 3.99543801 | -0.00011804 |
| 29.75000000 | 0.12303466 | 2.25324599 | 3.99558331 | -0.00011991 |

Driving Bellows Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|-------------|
| | -24.493E-6 | -383.611E-6 | -76.803E-6 | -20.660E-6 |
| 0.08333333 | 0.10633603 | 2.22354051 | 3.97591520 | -0.00001086 |
| 1.75000000 | 0.10601252 | 2.22852109 | 3.97353619 | -0.00004370 |
| 2.75000000 | 0.10594568 | 2.22994903 | 3.97300950 | -0.00005705 |
| 3.75000000 | 0.10593201 | 2.22975668 | 3.97276563 | -0.00007210 |
| 4.75000000 | 0.10584265 | 2.22981410 | 3.97259097 | -0.00010081 |
| 5.75000000 | 0.10583523 | 2.22844313 | 3.97187177 | -0.00011985 |
| 6.75000000 | 0.10584000 | 2.22930846 | 3.97260800 | -0.00014757 |
| 7.75000000 | 0.10581511 | 2.22889146 | 3.97199503 | -0.00016355 |
| 8.75000000 | 0.10572952 | 2.22734731 | 3.97068483 | -0.00019213 |
| 9.75000000 | 0.10574391 | 2.22827065 | 3.97121199 | -0.00020418 |
| 10.75000000 | 0.10568057 | 2.22650944 | 3.97008560 | -0.00022990 |
| 11.75000000 | 0.10569581 | 2.22651797 | 3.97139823 | -0.00025375 |
| 12.75000000 | 0.10568520 | 2.22516571 | 3.97135259 | -0.00027697 |
| 13.75000000 | 0.10563915 | 2.22477646 | 3.97102748 | -0.00029931 |
| 14.75000000 | 0.10559906 | 2.22431830 | 3.97097773 | -0.00030624 |
| 15.75000000 | 0.10556764 | 2.22399386 | 3.96995244 | -0.00034007 |
| 16.75000000 | 0.10555636 | 2.22290127 | 3.97012310 | -0.00035512 |
| 17.75000000 | 0.10554146 | 2.22195306 | 3.97112287 | -0.00039089 |
| 18.75000000 | 0.10552462 | 2.22143929 | 3.97159346 | -0.00040306 |
| 19.75000000 | 0.10544872 | 2.22042342 | 3.97003416 | -0.00042559 |
| 20.75000000 | 0.10543556 | 2.22169736 | 3.97031391 | -0.00044825 |
| 21.75000000 | 0.10544037 | 2.22078508 | 3.97062751 | -0.00045612 |
| 22.75000000 | 0.10541541 | 2.21991636 | 3.96992536 | -0.00048596 |
| 23.75000000 | 0.10544173 | 2.22112412 | 3.97157554 | -0.00050062 |
| 24.75000000 | 0.10540315 | 2.21999326 | 3.97127326 | -0.00051461 |
| 25.75000000 | 0.10541651 | 2.22057747 | 3.97115132 | -0.00054201 |
| 26.75000000 | 0.10547676 | 2.22118120 | 3.97225068 | -0.00055175 |
| 27.75000000 | 0.10543893 | 2.22030610 | 3.97164061 | -0.00057491 |
| 28.75000000 | 0.10539294 | 2.21910059 | 3.97171920 | -0.00059039 |
| 29.75000000 | 0.10533921 | 2.21838773 | 3.97100284 | -0.00060499 |

Driving Bellows Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|-------------|
| | -12.865E-6 | -22.103E-6 | 218.833E-9 | -10.822E-6 |
| 0.08333333 | 0.11916125 | 2.21717778 | 3.96726964 | 0.00003190 |
| 1.75000000 | 0.11894664 | 2.21490484 | 3.96919584 | -0.00000106 |
| 2.75000000 | 0.11882731 | 2.21357218 | 3.96922577 | -0.00001598 |
| 3.75000000 | 0.11881244 | 2.21545109 | 3.96853748 | -0.00004582 |
| 4.75000000 | 0.11874160 | 2.21492988 | 3.96725162 | -0.00005212 |
| 5.75000000 | 0.11871758 | 2.21556562 | 3.96686408 | -0.00006429 |
| 6.75000000 | 0.11872906 | 2.21570697 | 3.96684570 | -0.00009095 |
| 7.75000000 | 0.11871302 | 2.21404522 | 3.96675675 | -0.00009844 |
| 8.75000000 | 0.11869243 | 2.21429179 | 3.96687538 | -0.00010075 |
| 9.75000000 | 0.11866884 | 2.21483805 | 3.96547197 | -0.00010755 |
| 10.75000000 | 0.11860187 | 2.21610754 | 3.96512601 | -0.00011629 |
| 11.75000000 | 0.11862992 | 2.21566070 | 3.96604642 | -0.00014395 |
| 12.75000000 | 0.11860396 | 2.21517416 | 3.96562721 | -0.00014856 |
| 13.75000000 | 0.11860734 | 2.21491523 | 3.96578901 | -0.00015050 |
| 14.75000000 | 0.11856115 | 2.21539464 | 3.96516442 | -0.00015268 |
| 15.75000000 | 0.11858709 | 2.21488602 | 3.96570014 | -0.00016779 |
| 16.75000000 | 0.11858535 | 2.21538460 | 3.96570982 | -0.00018065 |
| 17.75000000 | 0.11857562 | 2.21481766 | 3.96566582 | -0.00018620 |
| 18.75000000 | 0.11861373 | 2.21498352 | 3.96656523 | -0.00020050 |
| 19.75000000 | 0.11862426 | 2.21403552 | 3.96818769 | -0.00020581 |
| 20.75000000 | 0.11858311 | 2.21492882 | 3.96704461 | -0.00022865 |
| 21.75000000 | 0.11855743 | 2.21600585 | 3.96669020 | -0.00023777 |
| 22.75000000 | 0.11855254 | 2.21457357 | 3.96746546 | -0.00024988 |
| 23.75000000 | 0.11853555 | 2.21453425 | 3.96634461 | -0.00025337 |
| 24.75000000 | 0.11862133 | 2.21416923 | 3.96763176 | -0.00026854 |
| 25.75000000 | 0.11857754 | 2.21440802 | 3.96746148 | -0.00028714 |
| 26.75000000 | 0.11857503 | 2.21572124 | 3.96841661 | -0.00029195 |
| 27.75000000 | 0.11856440 | 2.21497262 | 3.96804880 | -0.00029270 |
| 28.75000000 | 0.11849750 | 2.21470124 | 3.96766582 | -0.00029881 |
| 29.75000000 | 0.11848070 | 2.21433058 | 3.96752043 | -0.00030387 |

Driving Bellows Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|-------------|
| | -10.389E-6 | 31.350E-6 | -65.401E-6 | -6.193E-6 |
| 0.08333333 | 0.12228252 | 2.21319660 | 3.96776952 | -0.00006273 |
| 1.75000000 | 0.12212625 | 2.21349810 | 3.96809663 | -0.00009388 |
| 2.75000000 | 0.12217944 | 2.21392457 | 3.96944402 | -0.00009881 |
| 3.75000000 | 0.12213541 | 2.21419022 | 3.96996764 | -0.00010050 |
| 4.75000000 | 0.12205616 | 2.21321016 | 3.96757506 | -0.00010381 |
| 5.75000000 | 0.12203632 | 2.21387570 | 3.96825286 | -0.00011829 |
| 6.75000000 | 0.12209225 | 2.21348817 | 3.96990722 | -0.00013639 |
| 7.75000000 | 0.12204697 | 2.21320410 | 3.96888289 | -0.00014688 |
| 8.75000000 | 0.12206599 | 2.21418197 | 3.97002910 | -0.00014825 |
| 9.75000000 | 0.12199669 | 2.21331221 | 3.96851483 | -0.00015187 |
| 10.75000000 | 0.12202067 | 2.21405527 | 3.96797948 | -0.00015350 |
| 11.75000000 | 0.12196310 | 2.21365244 | 3.96783270 | -0.00016055 |
| 12.75000000 | 0.12194458 | 2.21310319 | 3.96960604 | -0.00016523 |
| 13.75000000 | 0.12192615 | 2.21403528 | 3.96683075 | -0.00018820 |
| 14.75000000 | 0.12194164 | 2.21387262 | 3.96646820 | -0.00018914 |
| 15.75000000 | 0.12202240 | 2.21379507 | 3.97007824 | -0.00019844 |
| 16.75000000 | 0.12196214 | 2.21434633 | 3.96758857 | -0.00019919 |
| 17.75000000 | 0.12194061 | 2.21376369 | 3.96629303 | -0.00019806 |
| 18.75000000 | 0.12191191 | 2.21322756 | 3.96654576 | -0.00019994 |
| 19.75000000 | 0.12190264 | 2.21370376 | 3.96565920 | -0.00020000 |
| 20.75000000 | 0.12193494 | 2.21418199 | 3.96900480 | -0.00020256 |
| 21.75000000 | 0.12190690 | 2.21370313 | 3.96621512 | -0.00021960 |
| 22.75000000 | 0.12186362 | 2.21382952 | 3.96769213 | -0.00024045 |
| 23.75000000 | 0.12187338 | 2.21421168 | 3.96703950 | -0.00023908 |
| 24.75000000 | 0.12184018 | 2.21565700 | 3.96616148 | -0.00024207 |
| 25.75000000 | 0.12200513 | 2.21486131 | 3.97031816 | -0.00024707 |
| 26.75000000 | 0.12186865 | 2.21412692 | 3.96717008 | -0.00024919 |
| 27.75000000 | 0.12185449 | 2.21458673 | 3.96492439 | -0.00025037 |
| 28.75000000 | 0.12189736 | 2.21375174 | 3.96796037 | -0.00025000 |
| 29.75000000 | 0.12190314 | 2.21415252 | 3.96838097 | -0.00025599 |

Short Tubing 4mm Displacement Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|------------|
| | -17.500E-3 | 104.869E-6 | -664.066E-6 | -51.812E-3 |
| 0.08333333 | 1.39321524 | 2.33515667 | 3.94218478 | 9.14985518 |
| 1.75000000 | 1.30628305 | 2.31172380 | 3.96674681 | 9.09974288 |
| 2.75000000 | 1.27158155 | 2.29644624 | 3.96674718 | 9.06305424 |
| 3.75000000 | 1.24379502 | 2.31121928 | 3.97371877 | 9.02391124 |
| 4.75000000 | 1.21536989 | 2.31211556 | 3.97441676 | 8.97866623 |
| 5.75000000 | 1.18967845 | 2.30970796 | 3.97607405 | 8.93335874 |
| 6.75000000 | 1.17006796 | 2.30572273 | 3.98643393 | 8.89392047 |
| 7.75000000 | 1.14775771 | 2.33624739 | 3.98782237 | 8.84020106 |
| 8.75000000 | 1.12916946 | 2.30575410 | 3.99564663 | 8.80083839 |
| 9.75000000 | 1.11051602 | 2.29802959 | 3.99998149 | 8.75566086 |
| 10.75000000 | 1.09132453 | 2.33278037 | 3.99993850 | 8.69849607 |
| 11.75000000 | 1.05478614 | 2.31472754 | 3.95967879 | 8.60251910 |
| 12.75000000 | 1.03734459 | 2.32101103 | 3.95929013 | 8.54712054 |
| 13.75000000 | 1.02102855 | 2.32435607 | 3.95935086 | 8.49244744 |
| 14.75000000 | 1.00495827 | 2.31180998 | 3.95942184 | 8.44081929 |
| 15.75000000 | 0.98987101 | 2.31437422 | 3.95934699 | 8.38614888 |
| 16.75000000 | 0.97507690 | 2.29682499 | 3.95938796 | 8.33672422 |
| 17.75000000 | 0.96108307 | 2.30688520 | 3.95934289 | 8.28163208 |
| 18.75000000 | 0.94736308 | 2.31147663 | 3.95912430 | 8.22764763 |
| 19.75000000 | 0.93429829 | 2.32818409 | 3.95901683 | 8.17155581 |
| 20.75000000 | 0.92164203 | 2.33454457 | 3.95905141 | 8.11877622 |
| 21.75000000 | 0.90901766 | 2.31572733 | 3.95917250 | 8.07254288 |
| 22.75000000 | 0.89698835 | 2.31812257 | 3.95909840 | 8.02206017 |
| 23.75000000 | 0.88513124 | 2.31343888 | 3.95918113 | 7.97384938 |
| 24.75000000 | 0.87355236 | 2.30813902 | 3.95925781 | 7.92715843 |
| 25.75000000 | 0.86228308 | 2.30397401 | 3.95929349 | 7.88097372 |
| 26.75000000 | 0.85183129 | 2.32745607 | 3.95927149 | 7.82869270 |
| 27.75000000 | 0.84103249 | 2.31531341 | 3.95926130 | 7.78557272 |
| 28.75000000 | 0.83058047 | 2.31351876 | 3.95940108 | 7.74153421 |
| 29.75000000 | 0.82144841 | 2.32251652 | 3.95948124 | 7.69786255 |

Short Tubing 4mm Displacement Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|------------|
| | -12.419E-3 | 232.640E-6 | -547.545E-6 | -39.604E-3 |
| 0.08333333 | 1.31454815 | 2.32360795 | 3.96164573 | 8.95803052 |
| 1.75000000 | 1.24835306 | 2.31151284 | 3.96570034 | 8.87573102 |
| 2.75000000 | 1.22895756 | 2.33537092 | 3.96556325 | 8.83729576 |
| 3.75000000 | 1.21055959 | 2.32317270 | 3.96504780 | 8.80269189 |
| 4.75000000 | 1.19403916 | 2.29183347 | 3.96598508 | 8.77164906 |
| 5.75000000 | 1.17882330 | 2.29067516 | 3.96740884 | 8.73690131 |
| 6.75000000 | 1.17111946 | 2.31476532 | 3.98323122 | 8.71213121 |
| 7.75000000 | 1.15670537 | 2.32435912 | 3.98434994 | 8.67454938 |
| 8.75000000 | 1.14255629 | 2.30967794 | 3.98506786 | 8.64044295 |
| 9.75000000 | 1.12905857 | 2.30380435 | 3.98575207 | 8.60414919 |
| 10.75000000 | 1.11619789 | 2.31650150 | 3.98641519 | 8.56408452 |
| 11.75000000 | 1.10351787 | 2.31026647 | 3.98739498 | 8.52727085 |
| 12.75000000 | 1.07989555 | 2.31781805 | 3.96242574 | 8.45534969 |
| 13.75000000 | 1.06817672 | 2.32532478 | 3.96214208 | 8.41315749 |
| 14.75000000 | 1.05636351 | 2.31902430 | 3.96164004 | 8.37356648 |
| 15.75000000 | 1.04490005 | 2.30930810 | 3.96144531 | 8.33522703 |
| 16.75000000 | 1.03351477 | 2.30070449 | 3.96091475 | 8.29693527 |
| 17.75000000 | 1.02272507 | 2.30495965 | 3.96073619 | 8.25635861 |
| 18.75000000 | 1.01243060 | 2.31305218 | 3.96092467 | 8.21547921 |
| 19.75000000 | 1.00239015 | 2.32783716 | 3.96074749 | 8.17252278 |
| 20.75000000 | 0.99245048 | 2.33629700 | 3.96078237 | 8.13132253 |
| 21.75000000 | 0.98238464 | 2.33164440 | 3.96056575 | 8.09342079 |
| 22.75000000 | 0.97270418 | 2.32763864 | 3.96053254 | 8.05561548 |
| 23.75000000 | 0.96311079 | 2.32409590 | 3.96040219 | 8.01787547 |
| 24.75000000 | 0.95363161 | 2.31396233 | 3.96015286 | 7.98175743 |
| 25.75000000 | 0.94460856 | 2.31355742 | 3.96024605 | 7.94506386 |
| 26.75000000 | 0.93557556 | 2.30734530 | 3.96015562 | 7.90882815 |
| 27.75000000 | 0.92671758 | 2.30651537 | 3.95987159 | 7.87165574 |
| 28.75000000 | 0.91848619 | 2.32711690 | 3.95984207 | 7.83135705 |
| 29.75000000 | 0.90990055 | 2.32380828 | 3.95989143 | 7.79592029 |

Short Tubing 4mm Displacement Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|------------|
| | -10.155E-3 | 126.760E-6 | -612.632E-6 | -32.443E-3 |
| 0.08333333 | 1.31089916 | 2.32998637 | 3.95993022 | 8.89018458 |
| 1.75000000 | 1.25787885 | 2.31891383 | 3.96852936 | 8.81142228 |
| 2.75000000 | 1.24292932 | 2.31515870 | 3.96880936 | 8.78189301 |
| 3.75000000 | 1.22907337 | 2.30772881 | 3.96899193 | 8.75324657 |
| 4.75000000 | 1.21630751 | 2.30937404 | 3.96928705 | 8.72342260 |
| 5.75000000 | 1.20412103 | 2.32792581 | 3.96975933 | 8.69038845 |
| 6.75000000 | 1.19282446 | 2.32868835 | 3.97103030 | 8.66143939 |
| 7.75000000 | 1.18149701 | 2.32185155 | 3.97182822 | 8.63274963 |
| 8.75000000 | 1.17005776 | 2.30813431 | 3.97185643 | 8.60426904 |
| 9.75000000 | 1.15945995 | 2.30673152 | 3.97244680 | 8.57414838 |
| 10.75000000 | 1.14920412 | 2.29685363 | 3.97328940 | 8.54600000 |
| 11.75000000 | 1.13948799 | 2.29762079 | 3.97457505 | 8.51624988 |
| 12.75000000 | 1.13462859 | 2.30259630 | 3.98611309 | 8.49820949 |
| 13.75000000 | 1.12494804 | 2.29826915 | 3.98683941 | 8.46854045 |
| 14.75000000 | 1.11584682 | 2.31493489 | 3.98779321 | 8.43467815 |
| 15.75000000 | 1.10819327 | 2.31098434 | 3.99160636 | 8.40853571 |
| 16.75000000 | 1.08452867 | 2.30870679 | 3.95916114 | 8.33268652 |
| 17.75000000 | 1.07571946 | 2.30933655 | 3.95868517 | 8.30047959 |
| 18.75000000 | 1.06680880 | 2.30911452 | 3.95772026 | 8.26781323 |
| 19.75000000 | 1.05811378 | 2.32045139 | 3.95733708 | 8.23302640 |
| 20.75000000 | 1.04983800 | 2.33482587 | 3.95665739 | 8.19746049 |
| 21.75000000 | 1.04152490 | 2.32686039 | 3.95658999 | 8.16715318 |
| 22.75000000 | 1.03341104 | 2.32382245 | 3.95642445 | 8.13690206 |
| 23.75000000 | 1.02540686 | 2.32064813 | 3.95638994 | 8.10617615 |
| 24.75000000 | 1.01803117 | 2.32536909 | 3.95664440 | 8.07458801 |
| 25.75000000 | 1.01047626 | 2.31971774 | 3.95709104 | 8.04633240 |
| 26.75000000 | 1.00303744 | 2.31756653 | 3.95733382 | 8.01676941 |
| 27.75000000 | 0.99565332 | 2.31912019 | 3.95719488 | 7.98560955 |
| 28.75000000 | 0.98825690 | 2.31576136 | 3.95703924 | 7.95616117 |
| 29.75000000 | 0.98095490 | 2.30882890 | 3.95707927 | 7.92776448 |

Long Tubing 3mm Displacement Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|------------|
| | -6.295E-3 | -243.514E-6 | 739.225E-6 | -27.888E-3 |
| 0.08333333 | 0.88001204 | 3.30973947 | 2.96118692 | 7.41098920 |
| 1.75000000 | 0.83818438 | 3.31130646 | 2.96145024 | 7.27356561 |
| 2.75000000 | 0.82706567 | 3.29440529 | 2.96150378 | 7.23571030 |
| 3.75000000 | 0.81739461 | 3.30043037 | 2.96157207 | 7.19543851 |
| 4.75000000 | 0.80871118 | 3.32860387 | 2.96159858 | 7.15181554 |
| 5.75000000 | 0.80016275 | 3.32166333 | 2.96153016 | 7.11839906 |
| 6.75000000 | 0.79229123 | 3.31737993 | 2.96151007 | 7.08578745 |
| 7.75000000 | 0.78464346 | 3.30951313 | 2.96150333 | 7.05541336 |
| 8.75000000 | 0.77727981 | 3.30515699 | 2.96156206 | 7.02517179 |
| 9.75000000 | 0.77032413 | 3.30575416 | 2.96176907 | 6.99439663 |
| 10.75000000 | 0.76360140 | 3.31552665 | 2.96170365 | 6.96182029 |
| 11.75000000 | 0.75678297 | 3.31281929 | 2.96170072 | 6.93322778 |
| 12.75000000 | 0.75031296 | 3.30380488 | 2.96171651 | 6.90615924 |
| 13.75000000 | 0.74379086 | 3.29555660 | 2.96192186 | 6.87977466 |
| 14.75000000 | 0.73731220 | 3.29016967 | 2.96145341 | 6.85265337 |
| 15.75000000 | 0.73145130 | 3.29512770 | 2.96217043 | 6.82328589 |
| 16.75000000 | 0.72554155 | 3.30790553 | 2.96167118 | 6.79260986 |
| 17.75000000 | 0.72503131 | 3.31093362 | 2.97647923 | 6.78460568 |
| 18.75000000 | 0.71926963 | 3.31363241 | 2.97633576 | 6.75778452 |
| 19.75000000 | 0.71384080 | 3.30807820 | 2.97684454 | 6.73412828 |
| 20.75000000 | 0.70827486 | 3.30596732 | 2.97654972 | 6.70850375 |
| 21.75000000 | 0.70291005 | 3.30615421 | 2.97670067 | 6.68411635 |
| 22.75000000 | 0.69765196 | 3.30931064 | 2.97669514 | 6.65819757 |
| 23.75000000 | 0.69241698 | 3.30811133 | 2.97660856 | 6.63442235 |
| 24.75000000 | 0.68720558 | 3.30008044 | 2.97664717 | 6.61203002 |
| 25.75000000 | 0.68193164 | 3.29535457 | 2.97640360 | 6.58952141 |
| 26.75000000 | 0.67713674 | 3.30038422 | 2.97663644 | 6.56445749 |
| 27.75000000 | 0.67240205 | 3.31296619 | 2.97671257 | 6.53835499 |
| 28.75000000 | 0.66741701 | 3.30560708 | 2.97648320 | 6.51697953 |
| 29.75000000 | 0.66277852 | 3.30380388 | 2.97689875 | 6.49574014 |

Long Tubing 3mm Displacement Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|------------|
| | -5.391E-3 | -15.680E-6 | 19.979E-6 | -23.793E-3 |
| 0.08333333 | 0.88992576 | 3.29322060 | 2.96120735 | 7.33809938 |
| 1.75000000 | 0.85859031 | 3.31136390 | 2.96137260 | 7.22790000 |
| 2.75000000 | 0.85095065 | 3.32926972 | 2.96138527 | 7.19362054 |
| 3.75000000 | 0.84398411 | 3.32834703 | 2.96142855 | 7.16587366 |
| 4.75000000 | 0.83733479 | 3.31576734 | 2.96146104 | 7.14253396 |
| 5.75000000 | 0.83098368 | 3.30777155 | 2.96141642 | 7.11809744 |
| 6.75000000 | 0.82473819 | 3.30326061 | 2.96141317 | 7.09329875 |
| 7.75000000 | 0.81880014 | 3.29816511 | 2.96148164 | 7.07005574 |
| 8.75000000 | 0.81294249 | 3.29806350 | 2.96141822 | 7.04500618 |
| 9.75000000 | 0.80741020 | 3.30307795 | 2.96142618 | 7.01885350 |
| 10.75000000 | 0.80199038 | 3.31870605 | 2.96152542 | 6.98989782 |
| 11.75000000 | 0.79649934 | 3.32745623 | 2.96146927 | 6.96363789 |
| 12.75000000 | 0.79113911 | 3.32611198 | 2.96152129 | 6.94017728 |
| 13.75000000 | 0.78558089 | 3.31779710 | 2.96130312 | 6.91861017 |
| 14.75000000 | 0.78019815 | 3.30049387 | 2.96143728 | 6.89904126 |
| 15.75000000 | 0.77498667 | 3.28710949 | 2.96137639 | 6.87964263 |
| 16.75000000 | 0.76982341 | 3.28733737 | 2.96126316 | 6.85610175 |
| 17.75000000 | 0.76481773 | 3.28537721 | 2.96127259 | 6.83430119 |
| 18.75000000 | 0.75999308 | 3.28819400 | 2.96114409 | 6.81118109 |
| 19.75000000 | 0.75536786 | 3.29501279 | 2.96138589 | 6.78700231 |
| 20.75000000 | 0.75051945 | 3.29577945 | 2.96131360 | 6.76465524 |
| 21.75000000 | 0.74596083 | 3.30065870 | 2.96161353 | 6.74238439 |
| 22.75000000 | 0.74122214 | 3.30754565 | 2.96109246 | 6.71818340 |
| 23.75000000 | 0.73692840 | 3.31383704 | 2.96169321 | 6.69583883 |
| 24.75000000 | 0.73239239 | 3.31786137 | 2.96133221 | 6.67362441 |
| 25.75000000 | 0.72827382 | 3.31954125 | 2.96211470 | 6.65301223 |
| 26.75000000 | 0.72360858 | 3.31444095 | 2.96171668 | 6.63318652 |
| 27.75000000 | 0.71938160 | 3.31495259 | 2.96218442 | 6.61272965 |
| 28.75000000 | 0.71484370 | 3.31526185 | 2.96162358 | 6.59118090 |
| 29.75000000 | 0.71110812 | 3.31850669 | 2.96291133 | 6.57190144 |

Long Tubing 3mm Displacement Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|------------|
| | -4.554E-3 | -228.495E-6 | 10.646E-6 | -20.419E-3 |
| 0.08333333 | 0.86585435 | 3.31902311 | 2.95935368 | 7.18180830 |
| 1.75000000 | 0.83678412 | 3.31079736 | 2.95945764 | 7.08132135 |
| 2.75000000 | 0.82986468 | 3.31437231 | 2.95935016 | 7.05298958 |
| 3.75000000 | 0.82379849 | 3.31423188 | 2.95930730 | 7.02839694 |
| 4.75000000 | 0.81823529 | 3.30623347 | 2.95939543 | 7.00707828 |
| 5.75000000 | 0.81291077 | 3.30571875 | 2.95938757 | 6.98491330 |
| 6.75000000 | 0.80782837 | 3.30713774 | 2.95936494 | 6.96289076 |
| 7.75000000 | 0.80293251 | 3.30767296 | 2.95941219 | 6.94108040 |
| 8.75000000 | 0.79805002 | 3.30658442 | 2.95932642 | 6.91937110 |
| 9.75000000 | 0.79331575 | 3.30305150 | 2.95916080 | 6.89965518 |
| 10.75000000 | 0.78859889 | 3.29573434 | 2.95929412 | 6.88107397 |
| 11.75000000 | 0.78399689 | 3.28981091 | 2.95920870 | 6.86206292 |
| 12.75000000 | 0.77945003 | 3.28910232 | 2.95924371 | 6.84193084 |
| 13.75000000 | 0.77505085 | 3.29066150 | 2.95924015 | 6.82168340 |
| 14.75000000 | 0.77079682 | 3.29810145 | 2.95912059 | 6.79936667 |
| 15.75000000 | 0.76664511 | 3.31041362 | 2.95923964 | 6.77655637 |
| 16.75000000 | 0.76267161 | 3.32500605 | 2.95934342 | 6.75310069 |
| 17.75000000 | 0.75839432 | 3.32264086 | 2.95936440 | 6.73425050 |
| 18.75000000 | 0.75423570 | 3.31190879 | 2.95949655 | 6.71740649 |
| 19.75000000 | 0.74998239 | 3.30577569 | 2.95943199 | 6.70029001 |
| 20.75000000 | 0.74586910 | 3.30379741 | 2.95954978 | 6.68202029 |
| 21.75000000 | 0.74187097 | 3.30623483 | 2.95947034 | 6.66209663 |
| 22.75000000 | 0.73790943 | 3.31623192 | 2.95945130 | 6.64059657 |
| 23.75000000 | 0.73410303 | 3.31586914 | 2.95957769 | 6.62237253 |
| 24.75000000 | 0.73012386 | 3.31225838 | 2.95964681 | 6.60511623 |
| 25.75000000 | 0.72629741 | 3.31137029 | 2.95959375 | 6.58703708 |
| 26.75000000 | 0.72318571 | 3.31057973 | 2.95966777 | 6.57172615 |
| 27.75000000 | 0.71920681 | 3.30177621 | 2.95971062 | 6.55501211 |
| 28.75000000 | 0.71525834 | 3.29032023 | 2.95948519 | 6.54021211 |
| 29.75000000 | 0.71144374 | 3.28082266 | 2.95957518 | 6.52538583 |

Long Tubing 4mm Displacement Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|------------|
| | -7.135E-3 | -41.508E-6 | -1.332E-3 | -26.315E-3 |
| 0.08333333 | 1.21040533 | 3.30339558 | 3.96940423 | 8.36024825 |
| 1.75000000 | 1.16603460 | 3.29517818 | 3.97881165 | 8.25692016 |
| 2.75000000 | 1.15568840 | 3.29463403 | 3.97959421 | 8.22608552 |
| 3.75000000 | 1.14955217 | 3.29725441 | 3.98742970 | 8.20592441 |
| 4.75000000 | 1.14122949 | 3.29975397 | 3.98787155 | 8.17820974 |
| 5.75000000 | 1.13373083 | 3.30566065 | 3.98868172 | 8.15170312 |
| 6.75000000 | 1.12652524 | 3.31241169 | 3.98943434 | 8.12592890 |
| 7.75000000 | 1.11965335 | 3.30831688 | 3.99061883 | 8.10239488 |
| 8.75000000 | 1.11535413 | 3.31374177 | 3.99729606 | 8.08428546 |
| 9.75000000 | 1.10847290 | 3.29821556 | 3.99803854 | 8.06371923 |
| 10.75000000 | 1.10180532 | 3.29105711 | 3.99857293 | 8.04091280 |
| 11.75000000 | 1.09552788 | 3.28167548 | 3.99961801 | 8.01989070 |
| 12.75000000 | 1.08898655 | 3.27652660 | 3.99995547 | 7.99738845 |
| 13.75000000 | 1.08250272 | 3.28211337 | 3.99999712 | 7.97173283 |
| 14.75000000 | 1.07636288 | 3.29229745 | 3.99998039 | 7.94540549 |
| 15.75000000 | 1.05483074 | 3.30357212 | 3.95924231 | 7.86834114 |
| 16.75000000 | 1.04913210 | 3.30712555 | 3.95955513 | 7.84467878 |
| 17.75000000 | 1.04336272 | 3.31593902 | 3.95922139 | 7.81841161 |
| 18.75000000 | 1.03748024 | 3.31362831 | 3.95943889 | 7.79513983 |
| 19.75000000 | 1.03143252 | 3.30685252 | 3.95948769 | 7.77348021 |
| 20.75000000 | 1.02549197 | 3.29651236 | 3.95946704 | 7.75253702 |
| 21.75000000 | 1.01987354 | 3.30049376 | 3.95928770 | 7.72833702 |
| 22.75000000 | 1.01440577 | 3.31079336 | 3.95944649 | 7.70317310 |
| 23.75000000 | 1.00887085 | 3.31410593 | 3.95934189 | 7.67955449 |
| 24.75000000 | 1.00331268 | 3.30829723 | 3.95911943 | 7.65817990 |
| 25.75000000 | 0.99788161 | 3.30173287 | 3.95912309 | 7.63767566 |
| 26.75000000 | 0.99260567 | 3.30113655 | 3.95908853 | 7.61628402 |
| 27.75000000 | 0.98740154 | 3.29251416 | 3.95941645 | 7.59700893 |
| 28.75000000 | 0.98203068 | 3.28366474 | 3.95901499 | 7.57619482 |
| 29.75000000 | 0.97690062 | 3.28530271 | 3.95919877 | 7.55441754 |

Long Tubing 4mm Displacement Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|------------|
| | -5.531E-3 | -17.006E-6 | -194.297E-6 | -20.332E-3 |
| 0.08333333 | 1.22188878 | 3.29419520 | 3.96847032 | 8.32118745 |
| 1.75000000 | 1.18521095 | 3.28473717 | 3.97695476 | 8.22721873 |
| 2.75000000 | 1.17699220 | 3.28672600 | 3.97698668 | 8.20131099 |
| 3.75000000 | 1.17035204 | 3.29853168 | 3.97727817 | 8.17747953 |
| 4.75000000 | 1.16420581 | 3.31513303 | 3.97747559 | 8.15357353 |
| 5.75000000 | 1.15829701 | 3.30924274 | 3.97786844 | 8.13497865 |
| 6.75000000 | 1.15259393 | 3.30291039 | 3.97817613 | 8.11711017 |
| 7.75000000 | 1.14699900 | 3.29663467 | 3.97853040 | 8.09949775 |
| 8.75000000 | 1.14165920 | 3.29374887 | 3.97906442 | 8.08100487 |
| 9.75000000 | 1.13633459 | 3.29218133 | 3.97954135 | 8.06248564 |
| 10.75000000 | 1.13120069 | 3.29175738 | 3.98024918 | 8.04381124 |
| 11.75000000 | 1.12628066 | 3.28976545 | 3.98144364 | 8.02636866 |
| 12.75000000 | 1.12328494 | 3.28228702 | 3.98779172 | 8.01556317 |
| 13.75000000 | 1.11811740 | 3.27314964 | 3.98825336 | 7.99875431 |
| 14.75000000 | 1.11311360 | 3.27662461 | 3.98871944 | 7.97927278 |
| 15.75000000 | 1.10846522 | 3.29305828 | 3.98942283 | 7.95715418 |
| 16.75000000 | 1.10362219 | 3.29708052 | 3.99014571 | 7.93798783 |
| 17.75000000 | 1.09905215 | 3.30227822 | 3.99093694 | 7.91863883 |
| 18.75000000 | 1.09659942 | 3.30440235 | 3.99757267 | 7.90722672 |
| 19.75000000 | 1.09151890 | 3.29173775 | 3.99799868 | 7.89103851 |
| 20.75000000 | 1.08648581 | 3.28280006 | 3.99859206 | 7.87357990 |
| 21.75000000 | 1.08164943 | 3.27704328 | 3.99909746 | 7.85624089 |
| 22.75000000 | 1.07692665 | 3.27442122 | 3.99988006 | 7.83830206 |
| 23.75000000 | 1.07251331 | 3.29432633 | 3.99997769 | 7.81505743 |
| 24.75000000 | 1.05268628 | 3.30500090 | 3.95938842 | 7.74155025 |
| 25.75000000 | 1.04813020 | 3.30167289 | 3.95940344 | 7.72403514 |
| 26.75000000 | 1.04332953 | 3.29626488 | 3.95915943 | 7.70612047 |
| 27.75000000 | 1.03877970 | 3.29275583 | 3.95908991 | 7.68809519 |
| 28.75000000 | 1.03423161 | 3.30019873 | 3.95875464 | 7.66781330 |
| 29.75000000 | 1.03019586 | 3.30385232 | 3.95927963 | 7.64895162 |

Long Tubing 4mm Displacement Test Trial 3:

| Time (min) | ForceD | ForceC | PosD | PosC |
|-------------|------------|------------|-------------|------------|
| d/dt= | -2.771E-3 | -41.464E-6 | -132.146E-6 | -12.775E-3 |
| 0.08333333 | 1.22721841 | 3.28522653 | 3.96187356 | 8.31168414 |
| 1.75000000 | 1.19272551 | 3.31589554 | 3.96103989 | 8.20889625 |
| 2.75000000 | 1.18507291 | 3.31341007 | 3.96128974 | 8.18530256 |
| 3.75000000 | 1.17856306 | 3.30767017 | 3.96162471 | 8.16518021 |
| 4.75000000 | 1.17258890 | 3.29814199 | 3.96197426 | 8.14749625 |
| 5.75000000 | 1.16701633 | 3.28456273 | 3.96249743 | 8.13141248 |
| 6.75000000 | 1.16165248 | 3.27512820 | 3.96325148 | 8.11547903 |
| 7.75000000 | 1.15652106 | 3.26664352 | 3.96417494 | 8.09941948 |
| 8.75000000 | 1.15770267 | 3.27571912 | 3.98040759 | 8.09844975 |
| 9.75000000 | 1.15208771 | 3.26679246 | 3.98025144 | 8.08120868 |
| 10.75000000 | 1.14707677 | 3.26846484 | 3.98049789 | 8.06202409 |
| 11.75000000 | 1.14230673 | 3.28802215 | 3.98086464 | 8.04008002 |
| 12.75000000 | 1.13769289 | 3.30355699 | 3.98106663 | 8.01836273 |
| 13.75000000 | 1.13289927 | 3.30243943 | 3.98149749 | 8.00019032 |
| 14.75000000 | 1.12813740 | 3.29733782 | 3.98194048 | 7.98362622 |
| 15.75000000 | 1.12342478 | 3.28504209 | 3.98230705 | 7.96836885 |
| 16.75000000 | 1.11869984 | 3.27847042 | 3.98275729 | 7.95272154 |
| 17.75000000 | 1.11426678 | 3.27616867 | 3.98338042 | 7.93613427 |
| 18.75000000 | 1.10976512 | 3.27454743 | 3.98394043 | 7.91885811 |
| 19.75000000 | 1.10538101 | 3.28438083 | 3.98439106 | 7.89952335 |
| 20.75000000 | 1.10122980 | 3.28731702 | 3.98502008 | 7.88182753 |
| 21.75000000 | 1.09689852 | 3.28563849 | 3.98552912 | 7.86531348 |
| 22.75000000 | 1.09258771 | 3.27751376 | 3.98635782 | 7.85057622 |
| 23.75000000 | 1.09082702 | 3.27147255 | 3.99340822 | 7.84289551 |
| 24.75000000 | 1.08672150 | 3.26530496 | 3.99433261 | 7.82797022 |
| 25.75000000 | 1.07059723 | 3.30430856 | 3.96138645 | 7.76008571 |
| 26.75000000 | 1.06623344 | 3.29796244 | 3.96098540 | 7.74311423 |
| 27.75000000 | 1.06200730 | 3.29479386 | 3.96093411 | 7.72619107 |
| 28.75000000 | 1.05786137 | 3.29427927 | 3.96076868 | 7.70927066 |
| 29.75000000 | 1.05343689 | 3.29215536 | 3.96011919 | 7.69225543 |

Copper Tubing 3mm Displacement Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|------------|
| | -6.713E-3 | -319.434E-6 | 27.469E-6 | -29.857E-3 |
| 0.08333333 | 0.71513638 | 3.21804511 | 2.97861708 | 6.53884026 |
| 1.75000000 | 0.69289879 | 3.21050768 | 2.97847416 | 6.49140474 |
| 2.75000000 | 0.68271404 | 3.22793761 | 2.97863834 | 6.44829576 |
| 3.75000000 | 0.67318704 | 3.22627386 | 2.97859688 | 6.40999376 |
| 4.75000000 | 0.66432172 | 3.23202075 | 2.97856866 | 6.37124863 |
| 5.75000000 | 0.65570063 | 3.22784210 | 2.97852189 | 6.33627104 |
| 6.75000000 | 0.64736337 | 3.22644474 | 2.97859322 | 6.30051142 |
| 7.75000000 | 0.63925014 | 3.22117055 | 2.97851047 | 6.26713527 |
| 8.75000000 | 0.63169935 | 3.22615257 | 2.97869672 | 6.23196854 |
| 9.75000000 | 0.62420234 | 3.22727289 | 2.97868916 | 6.19841567 |
| 10.75000000 | 0.61699546 | 3.22176749 | 2.97872977 | 6.16776024 |
| 11.75000000 | 0.60979753 | 3.20876256 | 2.97886033 | 6.13970986 |
| 12.75000000 | 0.60274446 | 3.19995949 | 2.97879182 | 6.11062584 |
| 13.75000000 | 0.59614111 | 3.21276862 | 2.97887270 | 6.07663539 |
| 14.75000000 | 0.58974353 | 3.22862832 | 2.97881213 | 6.04241486 |
| 15.75000000 | 0.58325053 | 3.22168611 | 2.97884681 | 6.01505287 |
| 16.75000000 | 0.57690515 | 3.21982210 | 2.97885439 | 5.98660387 |
| 17.75000000 | 0.57085545 | 3.22306507 | 2.97887769 | 5.95716810 |
| 18.75000000 | 0.56476294 | 3.21084144 | 2.97887450 | 5.93240618 |
| 19.75000000 | 0.55884263 | 3.21032636 | 2.97892190 | 5.90594007 |
| 20.75000000 | 0.55316101 | 3.21335435 | 2.97907357 | 5.87807247 |
| 21.75000000 | 0.54760958 | 3.22005941 | 2.97909406 | 5.84988995 |
| 22.75000000 | 0.54212832 | 3.22768576 | 2.97916217 | 5.82156629 |
| 23.75000000 | 0.53651398 | 3.22261432 | 2.97916319 | 5.79684576 |
| 24.75000000 | 0.53106099 | 3.21862699 | 2.97918190 | 5.77262328 |
| 25.75000000 | 0.52568351 | 3.21825519 | 2.97914371 | 5.74692871 |
| 26.75000000 | 0.52051430 | 3.21818048 | 2.97923637 | 5.72207728 |
| 27.75000000 | 0.51531505 | 3.21153812 | 2.97926134 | 5.69930799 |
| 28.75000000 | 0.51011208 | 3.20841097 | 2.97925629 | 5.67614600 |
| 29.75000000 | 0.50527807 | 3.21202575 | 2.97920696 | 5.65089788 |

Copper Tubing 3mm Displacement Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|------------|
| | -5.023E-3 | -167.076E-6 | 17.253E-6 | -22.773E-3 |
| 0.08333333 | 0.67757778 | 3.24514956 | 2.97950912 | 7.01230630 |
| 1.75000000 | 0.66582659 | 3.23669317 | 2.97935916 | 6.98698689 |
| 2.75000000 | 0.65943596 | 3.22780496 | 2.97923417 | 6.96527684 |
| 3.75000000 | 0.65332978 | 3.22090421 | 2.97932087 | 6.94275262 |
| 4.75000000 | 0.64735348 | 3.21932919 | 2.97927269 | 6.91818240 |
| 5.75000000 | 0.64175109 | 3.22540800 | 2.97932852 | 6.89238277 |
| 6.75000000 | 0.63622860 | 3.23423470 | 2.97934899 | 6.86574494 |
| 7.75000000 | 0.63069277 | 3.23004487 | 2.97942019 | 6.84265062 |
| 8.75000000 | 0.62518866 | 3.22393600 | 2.97940396 | 6.82010100 |
| 9.75000000 | 0.61979207 | 3.22421406 | 2.97939391 | 6.79556586 |
| 10.75000000 | 0.61450336 | 3.22765318 | 2.97934794 | 6.77138215 |
| 11.75000000 | 0.60929838 | 3.22234105 | 2.97942953 | 6.74938252 |
| 12.75000000 | 0.60425287 | 3.22347568 | 2.97949730 | 6.72542316 |
| 13.75000000 | 0.59899291 | 3.22075806 | 2.97935022 | 6.70246673 |
| 14.75000000 | 0.59402912 | 3.22367790 | 2.97947868 | 6.67871105 |
| 15.75000000 | 0.58916739 | 3.23421205 | 2.97958822 | 6.65307772 |
| 16.75000000 | 0.58428401 | 3.23983002 | 2.97946087 | 6.62826211 |
| 17.75000000 | 0.57944949 | 3.23837605 | 2.97948911 | 6.60576273 |
| 18.75000000 | 0.57465714 | 3.23522322 | 2.97954670 | 6.58491492 |
| 19.75000000 | 0.56984627 | 3.22925263 | 2.97957920 | 6.56386174 |
| 20.75000000 | 0.56522630 | 3.22522004 | 2.97964284 | 6.54285393 |
| 21.75000000 | 0.56052884 | 3.22324183 | 2.97958620 | 6.52154426 |
| 22.75000000 | 0.55594454 | 3.21854734 | 2.97963886 | 6.50119201 |
| 23.75000000 | 0.55139840 | 3.21239672 | 2.97969843 | 6.48137953 |
| 24.75000000 | 0.54693898 | 3.21112320 | 2.97971105 | 6.46041586 |
| 25.75000000 | 0.54274834 | 3.22683880 | 2.97974339 | 6.43511717 |
| 26.75000000 | 0.53851778 | 3.23606275 | 2.97972474 | 6.41171923 |
| 27.75000000 | 0.53418168 | 3.23564927 | 2.97979419 | 6.39087322 |
| 28.75000000 | 0.52990394 | 3.23028554 | 2.97976838 | 6.37168159 |
| 29.75000000 | 0.52564497 | 3.22110880 | 2.97982294 | 6.35396248 |

Copper Tubing 3mm Displacement Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|------------|
| | -4.004E-3 | 325.240E-6 | 418.844E-6 | -18.867E-3 |
| 0.08333333 | 0.61996366 | 3.22316062 | 2.91672311 | 6.72684295 |
| 1.75000000 | 0.62759708 | 3.24137230 | 2.97893731 | 6.76649151 |
| 2.75000000 | 0.62250811 | 3.22869843 | 2.97888663 | 6.75043995 |
| 3.75000000 | 0.61749574 | 3.21781250 | 2.97888498 | 6.73288614 |
| 4.75000000 | 0.61278528 | 3.21683319 | 2.97889504 | 6.71239594 |
| 5.75000000 | 0.60819053 | 3.22941693 | 2.97890327 | 6.68793340 |
| 6.75000000 | 0.60372310 | 3.25010965 | 2.97889960 | 6.66218583 |
| 7.75000000 | 0.59920225 | 3.24997782 | 2.97882580 | 6.64097278 |
| 8.75000000 | 0.59467814 | 3.24701476 | 2.97883485 | 6.62129276 |
| 9.75000000 | 0.59023530 | 3.23913489 | 2.97890343 | 6.60335537 |
| 10.75000000 | 0.58591515 | 3.23424416 | 2.97881453 | 6.58451223 |
| 11.75000000 | 0.58147568 | 3.22681765 | 2.97882732 | 6.56588589 |
| 12.75000000 | 0.57714300 | 3.22623169 | 2.97877072 | 6.54612959 |
| 13.75000000 | 0.57286226 | 3.22393152 | 2.97881824 | 6.52694906 |
| 14.75000000 | 0.56871963 | 3.22448074 | 2.97875959 | 6.50717328 |
| 15.75000000 | 0.56465379 | 3.22737210 | 2.97879548 | 6.48717672 |
| 16.75000000 | 0.56061582 | 3.23188188 | 2.97871155 | 6.46621099 |
| 17.75000000 | 0.55675060 | 3.22996654 | 2.97878383 | 6.44762584 |
| 18.75000000 | 0.55267931 | 3.22607097 | 2.97877632 | 6.43013015 |
| 19.75000000 | 0.54879346 | 3.21964696 | 2.97878752 | 6.41303502 |
| 20.75000000 | 0.54535048 | 3.22271079 | 2.97881101 | 6.39517778 |
| 21.75000000 | 0.54166319 | 3.23303227 | 2.97890715 | 6.37367740 |
| 22.75000000 | 0.53783232 | 3.24028102 | 2.97886938 | 6.35348839 |
| 23.75000000 | 0.53413181 | 3.24129302 | 2.97887157 | 6.33492547 |
| 24.75000000 | 0.53044064 | 3.23632477 | 2.97888588 | 6.31844164 |
| 25.75000000 | 0.52683303 | 3.23133398 | 2.97898670 | 6.30275930 |
| 26.75000000 | 0.52324089 | 3.23333658 | 2.97903462 | 6.28455094 |
| 27.75000000 | 0.51976356 | 3.24018405 | 2.97897992 | 6.26478221 |
| 28.75000000 | 0.51637528 | 3.25093669 | 2.97901076 | 6.24455393 |
| 29.75000000 | 0.51300836 | 3.25323465 | 2.97915481 | 6.22663233 |

Copper Tubing 4mm Displacement Test Trial 1:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|-------------|------------|------------|
| | -5.151E-3 | -158.581E-6 | -29.718E-6 | -21.137E-3 |
| 0.08333333 | 0.92359938 | 3.24286178 | 3.96085170 | 7.69229800 |
| 1.75000000 | 0.90953216 | 3.23743052 | 3.96062304 | 7.67843190 |
| 2.75000000 | 0.90304066 | 3.22862791 | 3.96072958 | 7.66070156 |
| 3.75000000 | 0.89687005 | 3.22981542 | 3.96073698 | 7.63865936 |
| 4.75000000 | 0.89111600 | 3.24441103 | 3.96086921 | 7.61280612 |
| 5.75000000 | 0.88510623 | 3.25350556 | 3.96078812 | 7.58825793 |
| 6.75000000 | 0.87925882 | 3.25226586 | 3.96074964 | 7.56608358 |
| 7.75000000 | 0.87341980 | 3.24512126 | 3.96080625 | 7.54543521 |
| 8.75000000 | 0.86790286 | 3.24348092 | 3.96081312 | 7.52368315 |
| 9.75000000 | 0.86238458 | 3.25507894 | 3.96078844 | 7.49872197 |
| 10.75000000 | 0.85711528 | 3.26406628 | 3.96062997 | 7.47384750 |
| 11.75000000 | 0.85184815 | 3.25529823 | 3.96074560 | 7.45467659 |
| 12.75000000 | 0.84635888 | 3.23963791 | 3.96048816 | 7.43656873 |
| 13.75000000 | 0.84110887 | 3.22770787 | 3.96059162 | 7.41851155 |
| 14.75000000 | 0.83593701 | 3.22283339 | 3.96062757 | 7.39781124 |
| 15.75000000 | 0.83084681 | 3.22201949 | 3.96026560 | 7.37691767 |
| 16.75000000 | 0.82579304 | 3.22427587 | 3.96028417 | 7.35409120 |
| 17.75000000 | 0.82096950 | 3.22542863 | 3.96044240 | 7.33335811 |
| 18.75000000 | 0.81600466 | 3.22338131 | 3.96053481 | 7.31223814 |
| 19.75000000 | 0.81112795 | 3.22874029 | 3.96051077 | 7.28940605 |
| 20.75000000 | 0.80652077 | 3.23843842 | 3.96051807 | 7.26684700 |
| 21.75000000 | 0.80208868 | 3.23815464 | 3.96128784 | 7.24636860 |
| 22.75000000 | 0.79707143 | 3.23517018 | 3.95994040 | 7.22574082 |
| 23.75000000 | 0.79262022 | 3.23885551 | 3.95998746 | 7.20529463 |
| 24.75000000 | 0.78830727 | 3.23736947 | 3.96047558 | 7.18578177 |
| 25.75000000 | 0.78369757 | 3.23642233 | 3.96007129 | 7.16570574 |
| 26.75000000 | 0.77921663 | 3.23844355 | 3.95987744 | 7.14535075 |
| 27.75000000 | 0.77492485 | 3.24255421 | 3.95999210 | 7.12399338 |
| 28.75000000 | 0.77068188 | 3.24803446 | 3.95976465 | 7.10363052 |
| 29.75000000 | 0.76646046 | 3.24908946 | 3.96004502 | 7.08377840 |

Copper Tubing 4mm Displacement Test Trial 2:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|------------|------------|
| | -4.224E-3 | 255.461E-6 | -20.361E-6 | -18.314E-3 |
| 0.08333333 | 0.87374749 | 3.23025087 | 3.96075775 | 7.44557010 |
| 1.75000000 | 0.86314293 | 3.23741317 | 3.96122581 | 7.42723283 |
| 2.75000000 | 0.85806523 | 3.24136303 | 3.96158443 | 7.40822778 |
| 3.75000000 | 0.85294362 | 3.23551844 | 3.96144037 | 7.39091529 |
| 4.75000000 | 0.84793124 | 3.23090093 | 3.96130775 | 7.37320587 |
| 5.75000000 | 0.84319381 | 3.23227725 | 3.96097481 | 7.35273390 |
| 6.75000000 | 0.83854019 | 3.23236426 | 3.96105690 | 7.33285986 |
| 7.75000000 | 0.83398097 | 3.23857282 | 3.96104056 | 7.31285474 |
| 8.75000000 | 0.82950789 | 3.24059145 | 3.96118008 | 7.29275468 |
| 9.75000000 | 0.82488021 | 3.23995737 | 3.96065368 | 7.27315312 |
| 10.75000000 | 0.82038343 | 3.24030438 | 3.96069282 | 7.25474170 |
| 11.75000000 | 0.81615161 | 3.23789509 | 3.96104182 | 7.23669401 |
| 12.75000000 | 0.81182956 | 3.23680485 | 3.96128891 | 7.21811604 |
| 13.75000000 | 0.80751412 | 3.23693199 | 3.96086493 | 7.19844538 |
| 14.75000000 | 0.80358509 | 3.24524530 | 3.96132513 | 7.17918633 |
| 15.75000000 | 0.79926347 | 3.24705698 | 3.96086930 | 7.15943371 |
| 16.75000000 | 0.79526385 | 3.24694866 | 3.96131349 | 7.14183464 |
| 17.75000000 | 0.79112747 | 3.24380614 | 3.96098380 | 7.12355350 |
| 18.75000000 | 0.78716650 | 3.23961334 | 3.96109076 | 7.10743346 |
| 19.75000000 | 0.78308100 | 3.23699064 | 3.96057612 | 7.08986841 |
| 20.75000000 | 0.77915791 | 3.24397035 | 3.96095274 | 7.07029507 |
| 21.75000000 | 0.77524795 | 3.24808477 | 3.96060558 | 7.05138883 |
| 22.75000000 | 0.77144877 | 3.24234808 | 3.96087046 | 7.03517965 |
| 23.75000000 | 0.76755760 | 3.24102285 | 3.96065771 | 7.01790368 |
| 24.75000000 | 0.76362574 | 3.23313693 | 3.96071247 | 7.00232341 |
| 25.75000000 | 0.76002978 | 3.23088934 | 3.96118380 | 6.98657428 |
| 26.75000000 | 0.75619890 | 3.22933739 | 3.96062328 | 6.96992903 |
| 27.75000000 | 0.75263541 | 3.23820499 | 3.96083602 | 6.95139526 |
| 28.75000000 | 0.74896152 | 3.24848235 | 3.96049897 | 6.93089750 |
| 29.75000000 | 0.74539862 | 3.25294130 | 3.96030916 | 6.91228539 |

Copper Tubing 4mm Displacement Test Trial 3:

| Time (min) d/dt= | ForceD | ForceC | PosD | PosC |
|---------------------|------------|------------|-------------|------------|
| | -1.931E-3 | 52.889E-6 | -187.764E-6 | -10.056E-3 |
| 0.08333333 | 0.85322695 | 3.24935003 | 3.96202218 | 7.26225662 |
| 1.75000000 | 0.84373122 | 3.23390112 | 3.96211672 | 7.25344913 |
| 2.75000000 | 0.83921917 | 3.22404694 | 3.96236865 | 7.24045212 |
| 3.75000000 | 0.83497365 | 3.21579913 | 3.96255697 | 7.22603102 |
| 4.75000000 | 0.83082507 | 3.21381714 | 3.96286437 | 7.20974963 |
| 5.75000000 | 0.82666298 | 3.22194108 | 3.96256249 | 7.18975699 |
| 6.75000000 | 0.82269999 | 3.23723935 | 3.96253201 | 7.16905350 |
| 7.75000000 | 0.81882544 | 3.24805127 | 3.96255833 | 7.14870474 |
| 8.75000000 | 0.81479938 | 3.24887871 | 3.96240067 | 7.13091991 |
| 9.75000000 | 0.81081829 | 3.24561124 | 3.96260851 | 7.11488321 |
| 10.75000000 | 0.80686701 | 3.24194208 | 3.96239446 | 7.09887004 |
| 11.75000000 | 0.80310504 | 3.24631820 | 3.96237699 | 7.08136486 |
| 12.75000000 | 0.79940583 | 3.24948618 | 3.96269524 | 7.06414469 |
| 13.75000000 | 0.79573168 | 3.25033455 | 3.96255454 | 7.04662634 |
| 14.75000000 | 0.79204506 | 3.25912175 | 3.96259612 | 7.02791067 |
| 15.75000000 | 0.78841145 | 3.26525032 | 3.96244893 | 7.00983471 |
| 16.75000000 | 0.78468573 | 3.26016299 | 3.96234898 | 6.99433845 |
| 17.75000000 | 0.78110167 | 3.25445581 | 3.96257109 | 6.98019170 |
| 18.75000000 | 0.77731845 | 3.24421372 | 3.96224528 | 6.96634245 |
| 19.75000000 | 0.77361398 | 3.23281692 | 3.96207375 | 6.95329831 |
| 20.75000000 | 0.77010989 | 3.22433022 | 3.96219428 | 6.93945137 |
| 21.75000000 | 0.76671700 | 3.22886675 | 3.96235514 | 6.92303427 |
| 22.75000000 | 0.76346503 | 3.24016701 | 3.96247487 | 6.90429788 |
| 23.75000000 | 0.75984029 | 3.23915787 | 3.96184274 | 6.88761785 |
| 24.75000000 | 0.75663439 | 3.23775111 | 3.96211354 | 6.87306960 |
| 25.75000000 | 0.75296158 | 3.23436756 | 3.96183163 | 6.85807004 |
| 26.75000000 | 0.74932227 | 3.23175471 | 3.96058282 | 6.84198015 |
| 27.75000000 | 0.74696170 | 3.23057103 | 3.96398674 | 6.83046248 |
| 28.75000000 | 0.74380039 | 3.23166326 | 3.96433030 | 6.81513839 |
| 29.75000000 | 0.74098210 | 3.24416787 | 3.96548429 | 6.79727522 |

Calibrate-Test-Calibrate Bench Tests

Presented here are values from calibrate-test-calibrate bench testing, which was discussed in Chapter 5. Values for driving end elasticity (E. Driving in mV/mm) and calibration instrument elasticity (E. Cal in N/mm) for each of the three repetitions of the calibration procedure.

Calibrate-Test-Calibrate 2 Band Test 1:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|----------------|---------------|---------------|----------------|----------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.21840481E+3 | -2.55577492E-3 | 4.16422670E+3 | 4.93293853E-2 | 4.16394123E+3 | -3.68169559E-3 |
| 4.19421861E+3 | 2.09856518E-2 | 4.15769824E+3 | 4.87984156E-2 | 4.14651717E+3 | 1.84945574E-2 |
| 4.17967347E+3 | 4.91757165E-2 | 4.15309381E+3 | 5.09278939E-2 | 4.14030686E+3 | 4.19501906E-2 |
| 4.17553248E+3 | 6.98137910E-2 | 4.14994436E+3 | 4.44624911E-2 | 4.13342258E+3 | 6.98114567E-2 |
| 4.17060420E+3 | 9.15109075E-2 | 4.14762206E+3 | 4.61740599E-2 | 4.13906264E+3 | 9.18619189E-2 |
| 4.16613489E+3 | 1.19554112E-1 | 4.14685305E+3 | 4.63430636E-2 | 4.14008331E+3 | 1.16943515E-1 |
| 4.16412521E+3 | 1.35648536E-1 | 4.14682857E+3 | 4.33539703E-2 | 4.13492078E+3 | 1.44576343E-1 |
| 4.16610483E+3 | 1.59619101E-1 | 4.14482236E+3 | 5.13539684E-2 | 4.13673694E+3 | 1.60565137E-1 |

Calibrate-Test-Calibrate 2 Band Test 2:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.06643040E+3 | 3.86961612E-4 | 4.05526833E+3 | 4.31919146E-2 | 4.11563317E+3 | 6.42628795E-4 |
| 4.06239253E+3 | 2.67271972E-2 | 4.05565268E+3 | 4.96371999E-2 | 4.10828267E+3 | 1.73939649E-2 |
| 4.05556375E+3 | 4.34892676E-2 | 4.05239327E+3 | 5.24477095E-2 | 4.10688856E+3 | 3.44192400E-2 |
| 4.05715461E+3 | 6.53489177E-2 | 4.04979607E+3 | 4.60366928E-2 | 4.09989741E+3 | 5.92991946E-2 |
| 4.06166309E+3 | 8.54248943E-2 | 4.04988669E+3 | 6.30883373E-2 | 4.10032418E+3 | 8.65562479E-2 |
| 4.06314613E+3 | 1.18026652E-1 | 4.04660306E+3 | 5.06689040E-2 | 4.09928396E+3 | 1.12297173E-1 |
| 4.06623110E+3 | 1.40746922E-1 | 4.04501474E+3 | 5.73919627E-2 | 4.10049046E+3 | 1.37609675E-1 |
| 4.06609870E+3 | 1.60718942E-1 | 4.04348734E+3 | 5.09423915E-2 | 4.10375211E+3 | 1.57461109E-1 |

Calibrate-Test-Calibrate 2 Band Test 3:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|----------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.53012953E+3 | 1.90507467E-3 | 4.42679810E+3 | 4.19483893E-2 | 4.39062310E+3 | -3.84555238E-3 |
| 4.49204306E+3 | 1.95568513E-2 | 4.41517333E+3 | 4.00622709E-2 | 4.36782072E+3 | 1.88172057E-2 |
| 4.46522794E+3 | 3.49859360E-2 | 4.40971979E+3 | 4.09146910E-2 | 4.36217146E+3 | 5.28375065E-2 |
| 4.44636107E+3 | 6.81489660E-2 | 4.40562088E+3 | 4.85509343E-2 | 4.34738287E+3 | 6.64799961E-2 |
| 4.43058679E+3 | 8.78681668E-2 | 4.39183176E+3 | 4.47594884E-2 | 4.33804798E+3 | 9.17211840E-2 |
| 4.41707909E+3 | 1.05551008E-1 | 4.38709292E+3 | 4.60366313E-2 | 4.33546423E+3 | 1.11763724E-1 |
| 4.40568325E+3 | 1.30751473E-1 | 4.37999185E+3 | 4.32227333E-2 | 4.32637626E+3 | 1.39924072E-1 |
| 4.40280107E+3 | 1.59208861E-1 | 4.37378334E+3 | 4.56984107E-2 | 4.32978928E+3 | 1.60008539E-1 |

Calibrate-Test-Calibrate 5 Band Test 1:

| I. Calibration | | Band Test | F. Calibration | | | |
|----------------|----------------|---------------|----------------|---------------|----------------|--|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal | |
| 4.52981196E+3 | -7.27480497E-3 | 4.40946732E+3 | 9.89730317E-2 | 4.39831991E+3 | -6.09205404E-4 | |
| 4.49684341E+3 | 1.83891420E-2 | 4.40007930E+3 | 1.01887504E-1 | 4.37701742E+3 | 2.27444145E-2 | |
| 4.47255446E+3 | 3.40020335E-2 | 4.39452131E+3 | 1.01013172E-1 | 4.36086400E+3 | 3.90356927E-2 | |
| 4.45123589E+3 | 6.37727650E-2 | 4.39331101E+3 | 1.04815974E-1 | 4.35230349E+3 | 5.97317166E-2 | |
| 4.43708429E+3 | 8.19844336E-2 | 4.38275684E+3 | 1.04412038E-1 | 4.34714526E+3 | 7.67029056E-2 | |
| 4.42558493E+3 | 9.52142074E-2 | 4.38001087E+3 | 1.16623669E-1 | 4.34305143E+3 | 1.00539385E-1 | |
| 4.41848370E+3 | 1.31697904E-1 | 4.37263588E+3 | 1.13158872E-1 | 4.33454417E+3 | 1.18742979E-1 | |
| 4.41309082E+3 | 1.59774799E-1 | 4.36767771E+3 | 1.06546539E-1 | 4.33302465E+3 | 1.47429748E-1 | |

Calibrate-Test-Calibrate 5 Band Test 2:

| I. Calibration | | Band Test | F. Calibration | | | |
|----------------|----------------|---------------|----------------|---------------|----------------|--|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal | |
| 4.44139825E+3 | -8.73667185E-3 | 4.34799835E+3 | 1.16941792E-1 | 4.34694882E+3 | -4.77267039E-3 | |
| 4.41261100E+3 | 2.29210931E-2 | 4.34137487E+3 | 1.13752039E-1 | 4.32504985E+3 | 1.61105162E-2 | |
| 4.39458893E+3 | 4.10759445E-2 | 4.34439230E+3 | 1.20238067E-1 | 4.31593986E+3 | 3.83761529E-2 | |
| 4.38102137E+3 | 6.59006639E-2 | 4.33837517E+3 | 1.17408125E-1 | 4.31354769E+3 | 6.16802624E-2 | |
| 4.37318846E+3 | 8.99851872E-2 | 4.33222842E+3 | 1.17687009E-1 | 4.30203312E+3 | 7.42938286E-2 | |
| 4.37035124E+3 | 1.10697347E-1 | 4.32766245E+3 | 1.15137869E-1 | 4.30395004E+3 | 1.07244739E-1 | |
| 4.36279031E+3 | 1.40029887E-1 | 4.32362791E+3 | 1.16160175E-1 | 4.29861687E+3 | 1.34550977E-1 | |
| 4.35624423E+3 | 1.56502566E-1 | 4.32205411E+3 | 1.17546659E-1 | 4.29905426E+3 | 1.58337312E-1 | |

Calibrate-Test-Calibrate 5 Band Test 3:

| I. Calibration | | Band Test | F. Calibration | | | |
|----------------|----------------|---------------|----------------|---------------|----------------|--|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal | |
| 4.88217436E+3 | -9.85663597E-3 | 4.62672168E+3 | 1.08986276E-1 | 4.67837286E+3 | -1.96284184E-3 | |
| 4.82674550E+3 | 2.14329808E-2 | 4.60984796E+3 | 1.10195707E-1 | 4.64332816E+3 | 2.03648944E-2 | |
| 4.76768046E+3 | 3.79199173E-2 | 4.61325234E+3 | 1.07042523E-1 | 4.60720847E+3 | 4.99977548E-2 | |
| 4.72748527E+3 | 6.65596130E-2 | 4.60509587E+3 | 1.14426581E-1 | 4.58378438E+3 | 6.08347662E-2 | |
| 4.67846348E+3 | 7.80799666E-2 | 4.59694812E+3 | 1.07697008E-1 | 4.56583352E+3 | 8.23958201E-2 | |
| 4.64896930E+3 | 1.00387638E-1 | 4.58289580E+3 | 1.04413664E-1 | 4.54988600E+3 | 9.69481086E-2 | |
| 4.63144857E+3 | 1.29204616E-1 | 4.57779389E+3 | 1.07616153E-1 | 4.54550482E+3 | 1.37500587E-1 | |
| 4.60710857E+3 | 1.50895572E-1 | 4.57286722E+3 | 1.08759835E-1 | 4.53076217E+3 | 1.56278325E-1 | |

Repeated Calibration

Presented here are data from the repeated calibration tests discussed in Chapter 5. Values for driving end elasticity (E. Driving in mV/mm) and calibration instrument elasticity (E. Cal in N/mm) for each of the ten repetitions of the calibration procedure.

Repeated Calibration Test 1:

| 01 | | 02 | | 03 | |
|---------------|---------------|---------------|---------------|---------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.27683537E+3 | 6.94105781E-3 | 4.24753075E+3 | 4.69362513E-3 | 4.23065676E+3 | 5.12695114E-3 |
| 4.25897958E+3 | 3.27658606E-2 | 4.24154501E+3 | 2.39833511E-2 | 4.22160460E+3 | 1.72220197E-2 |
| 4.25525474E+3 | 5.40792532E-2 | 4.23673069E+3 | 5.15848585E-2 | 4.22421799E+3 | 6.15149406E-2 |
| 4.25218905E+3 | 7.18413451E-2 | 4.23597525E+3 | 8.15515450E-2 | 4.22196077E+3 | 7.58633103E-2 |
| 4.24727696E+3 | 8.98743308E-2 | 4.23199672E+3 | 8.84614009E-2 | 4.21543546E+3 | 9.07031424E-2 |
| 4.24985293E+3 | 1.13197000E-1 | 4.23194577E+3 | 1.03089036E-1 | 4.21681396E+3 | 1.15225192E-1 |
| 4.24405090E+3 | 1.38075149E-1 | 4.22860651E+3 | 1.31011315E-1 | 4.21616606E+3 | 1.28701557E-1 |
| 4.23824151E+3 | 1.52181742E-1 | 4.23017846E+3 | 1.62063823E-1 | 4.22082185E+3 | 1.57685937E-1 |

| 04 | | 05 | | 06 | |
|---------------|----------------|---------------|---------------|---------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.20873660E+3 | -1.34965851E-3 | 4.19360141E+3 | 1.12634366E-2 | 4.17368771E+3 | 6.16713740E-3 |
| 4.20660567E+3 | 2.55333848E-2 | 4.19408298E+3 | 2.54165188E-2 | 4.17639161E+3 | 2.31293431E-2 |
| 4.20422117E+3 | 5.00261844E-2 | 4.18396665E+3 | 4.04145857E-2 | 4.17052719E+3 | 4.22065009E-2 |
| 4.20018011E+3 | 6.00845988E-2 | 4.18891093E+3 | 6.78184168E-2 | 4.17272098E+3 | 7.22924306E-2 |
| 4.20028879E+3 | 8.63494489E-2 | 4.18548685E+3 | 9.06265449E-2 | 4.17056190E+3 | 9.13200960E-2 |
| 4.20153759E+3 | 1.13341265E-1 | 4.18735422E+3 | 1.22087128E-1 | 4.17238395E+3 | 1.16432855E-1 |
| 4.19946165E+3 | 1.34952026E-1 | 4.19225547E+3 | 1.49689239E-1 | 4.17303049E+3 | 1.40261169E-1 |
| 4.20428886E+3 | 1.63839161E-1 | 4.19234598E+3 | 1.62129515E-1 | 4.17863348E+3 | 1.60664178E-1 |

| 07 | | 08 | | 09 | |
|---------------|---------------|---------------|----------------|---------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.15890142E+3 | 5.54438598E-3 | 4.14738740E+3 | -5.72696091E-4 | 4.12566570E+3 | 1.04841594E-3 |
| 4.16165579E+3 | 2.60668479E-2 | 4.14414063E+3 | 2.19489038E-2 | 4.12755083E+3 | 2.44024912E-2 |
| 4.15472340E+3 | 3.95466049E-2 | 4.14195767E+3 | 5.14312688E-2 | 4.12901424E+3 | 5.05313673E-2 |
| 4.15630200E+3 | 7.60227619E-2 | 4.14931737E+3 | 7.69064082E-2 | 4.13330989E+3 | 7.96088041E-2 |
| 4.15689357E+3 | 8.77693417E-2 | 4.14397735E+3 | 9.65308307E-2 | 4.13208500E+3 | 1.00527797E-1 |
| 4.15855582E+3 | 1.06873337E-1 | 4.14740572E+3 | 1.23683277E-1 | 4.13655105E+3 | 1.27453518E-1 |
| 4.16280152E+3 | 1.35337653E-1 | 4.15337548E+3 | 1.58053338E-1 | 4.13506259E+3 | 1.41153641E-1 |
| 4.15954360E+3 | 1.48368836E-1 | 4.15351138E+3 | 1.61437572E-1 | 4.13731412E+3 | 1.61367032E-1 |

| 10 | |
|---------------|---------------|
| E. Driving | E. Cal |
| 4.11540638E+3 | 9.01106425E-3 |
| 4.11373397E+3 | 2.26489877E-2 |
| 4.11695846E+3 | 4.46883656E-2 |
| 4.11378315E+3 | 6.27927020E-2 |
| 4.11652540E+3 | 9.11610033E-2 |
| 4.11821075E+3 | 1.13119210E-1 |
| 4.12341627E+3 | 1.44940836E-1 |
| 4.12400423E+3 | 1.63918201E-1 |

Repeated Calibration Test 2:

| | | | | | |
|---------------|---------------|---------------|---------------|---------------|---------------|
| 01 | | 02 | | 03 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.17059850E+3 | 3.62753086E-3 | 4.15642216E+3 | 3.55054759E-3 | 4.14095997E+3 | 6.97798257E-3 |
| 4.16576059E+3 | 2.54831057E-2 | 4.15091961E+3 | 3.00840668E-2 | 4.13749473E+3 | 2.28252574E-2 |
| 4.16205519E+3 | 4.38733061E-2 | 4.14679224E+3 | 5.18583274E-2 | 4.13227237E+3 | 3.83025227E-2 |
| 4.16009553E+3 | 6.27220543E-2 | 4.14968355E+3 | 7.75330501E-2 | 4.13219716E+3 | 7.07952138E-2 |
| 4.16219086E+3 | 9.40140013E-2 | 4.14321751E+3 | 8.66362451E-2 | 4.13421739E+3 | 9.03456553E-2 |
| 4.15769636E+3 | 1.15045655E-1 | 4.14961238E+3 | 1.21912893E-1 | 4.13637830E+3 | 1.13172519E-1 |
| 4.16051126E+3 | 1.32920449E-1 | 4.14804003E+3 | 1.44689521E-1 | 4.13572443E+3 | 1.33596319E-1 |
| 4.16085020E+3 | 1.55254688E-1 | 4.15328891E+3 | 1.59940301E-1 | 4.14086068E+3 | 1.62155889E-1 |
| 04 | | 05 | | 06 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.12623848E+3 | 7.62728910E-3 | 4.11280163E+3 | 6.79789470E-3 | 4.10550613E+3 | 1.12318763E-2 |
| 4.12241088E+3 | 2.96346255E-2 | 4.10782268E+3 | 1.71989825E-2 | 4.09701028E+3 | 1.78783108E-2 |
| 4.12284581E+3 | 5.38960498E-2 | 4.11215899E+3 | 5.35124922E-2 | 4.09997916E+3 | 4.43020179E-2 |
| 4.12090232E+3 | 5.63329754E-2 | 4.10823921E+3 | 7.32001778E-2 | 4.09705010E+3 | 7.35361497E-2 |
| 4.12571347E+3 | 9.10521582E-2 | 4.11060397E+3 | 9.24581586E-2 | 4.10081230E+3 | 9.71367881E-2 |
| 4.12407280E+3 | 1.14102525E-1 | 4.11544036E+3 | 1.11130066E-1 | 4.10050359E+3 | 1.19954146E-1 |
| 4.12477692E+3 | 1.38302497E-1 | 4.11970783E+3 | 1.38104312E-1 | 4.10383936E+3 | 1.42615649E-1 |
| 4.13047680E+3 | 1.64471086E-1 | 4.11412120E+3 | 1.57258930E-1 | 4.10488508E+3 | 1.64428065E-1 |
| 07 | | 08 | | 09 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.08749786E+3 | 6.21846758E-3 | 4.07404148E+3 | 1.22678430E-2 | 4.06165568E+3 | 7.68499494E-3 |
| 4.08804421E+3 | 2.71404027E-2 | 4.07438629E+3 | 2.22692495E-2 | 4.06012783E+3 | 2.40845304E-2 |
| 4.08408259E+3 | 4.12070240E-2 | 4.07091661E+3 | 4.31879597E-2 | 4.06305705E+3 | 4.97127312E-2 |
| 4.08320143E+3 | 6.59003044E-2 | 4.07473457E+3 | 6.54984020E-2 | 4.06842716E+3 | 7.59053229E-2 |
| 4.09249031E+3 | 9.78851750E-2 | 4.07395436E+3 | 8.56129950E-2 | 4.06646770E+3 | 1.09062068E-1 |
| 4.09125189E+3 | 1.18507953E-1 | 4.08106846E+3 | 1.17843643E-1 | 4.07151205E+3 | 1.23796843E-1 |
| 4.09304027E+3 | 1.41906950E-1 | 4.08274745E+3 | 1.32701322E-1 | 4.07488065E+3 | 1.45809035E-1 |
| 4.09430835E+3 | 1.64370851E-1 | 4.08548285E+3 | 1.64051031E-1 | 4.07083233E+3 | 1.60226355E-1 |
| 10 | | | | | |
| E. Driving | E. Cal | | | | |
| 4.04810299E+3 | 4.96632894E-3 | | | | |
| 4.04554216E+3 | 1.94973418E-2 | | | | |
| 4.04952178E+3 | 4.72215975E-2 | | | | |
| 4.05037473E+3 | 7.01302032E-2 | | | | |
| 4.05476338E+3 | 1.02055662E-1 | | | | |
| 4.05880829E+3 | 1.27797751E-1 | | | | |
| 4.05972936E+3 | 1.44249780E-1 | | | | |
| 4.06208083E+3 | 1.58185456E-1 | | | | |

Repeated Calibration Test 3:

| | | | | | |
|---------------|---------------|---------------|---------------|---------------|---------------|
| 01 | | 02 | | 03 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.40799916E+3 | 5.80845492E-3 | 4.38502437E+3 | 1.59514632E-3 | 4.36176611E+3 | 8.38802307E-3 |
| 4.39630996E+3 | 2.40254486E-2 | 4.36465162E+3 | 2.68400077E-2 | 4.35800070E+3 | 2.36337194E-2 |
| 4.37306390E+3 | 3.77039084E-2 | 4.35980142E+3 | 5.04994720E-2 | 4.34779362E+3 | 4.31004888E-2 |
| 4.36791160E+3 | 6.18984802E-2 | 4.35617363E+3 | 6.82997460E-2 | 4.34661438E+3 | 6.81901399E-2 |
| 4.36206551E+3 | 7.65896265E-2 | 4.35234033E+3 | 8.62145108E-2 | 4.34142508E+3 | 8.72935665E-2 |
| 4.35608617E+3 | 1.06982621E-1 | 4.34981210E+3 | 1.12166149E-1 | 4.33727395E+3 | 1.06536198E-1 |
| 4.35128780E+3 | 1.28971040E-1 | 4.34514264E+3 | 1.29474840E-1 | 4.33439984E+3 | 1.24642957E-1 |
| 4.35198690E+3 | 1.45664790E-1 | 4.34472675E+3 | 1.47250286E-1 | 4.33290801E+3 | 1.57404614E-1 |
| 04 | | 05 | | 06 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.34640647E+3 | 1.23000324E-3 | 4.32648261E+3 | 2.83368821E-3 | 4.30760163E+3 | 1.41095283E-2 |
| 4.33431853E+3 | 2.02544872E-2 | 4.32643301E+3 | 3.22564655E-2 | 4.30018242E+3 | 3.49742119E-2 |
| 4.33018286E+3 | 4.69702761E-2 | 4.31439914E+3 | 5.00486822E-2 | 4.29412137E+3 | 4.57835970E-2 |
| 4.32531306E+3 | 6.74248401E-2 | 4.31515458E+3 | 7.35336627E-2 | 4.29456239E+3 | 7.63990890E-2 |
| 4.32508559E+3 | 9.08424757E-2 | 4.30735952E+3 | 8.50346956E-2 | 4.29448415E+3 | 9.74910466E-2 |
| 4.31971421E+3 | 1.02692042E-1 | 4.30513463E+3 | 1.07877344E-1 | 4.29076691E+3 | 1.16219734E-1 |
| 4.31591134E+3 | 1.18503247E-1 | 4.30558831E+3 | 1.28958270E-1 | 4.29633711E+3 | 1.40264004E-1 |
| 4.31899454E+3 | 1.55273656E-1 | 4.30581394E+3 | 1.52880081E-1 | 4.29426028E+3 | 1.60175359E-1 |
| 07 | | 08 | | 09 | |
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.29448534E+3 | 7.90255605E-3 | 4.26710283E+3 | 4.27855931E-3 | 4.25585327E+3 | 6.68270073E-3 |
| 4.28600022E+3 | 3.07622449E-2 | 4.26603338E+3 | 2.07226707E-2 | 4.25049682E+3 | 2.91894692E-2 |
| 4.27916513E+3 | 4.19125097E-2 | 4.25795098E+3 | 4.99203339E-2 | 4.25405217E+3 | 5.65702413E-2 |
| 4.27357838E+3 | 6.73210581E-2 | 4.25985905E+3 | 7.09402696E-2 | 4.24960353E+3 | 7.05944988E-2 |
| 4.27519681E+3 | 8.10429117E-2 | 4.25844472E+3 | 8.76526621E-2 | 4.24791454E+3 | 9.06411870E-2 |
| 4.27852239E+3 | 1.05460402E-1 | 4.25980829E+3 | 1.06612810E-1 | 4.24804441E+3 | 1.13188943E-1 |
| 4.27786993E+3 | 1.31471715E-1 | 4.26447418E+3 | 1.36582141E-1 | 4.25014137E+3 | 1.27470119E-1 |
| 4.27927179E+3 | 1.59359778E-1 | 4.26293583E+3 | 1.58590302E-1 | 4.25142768E+3 | 1.58704936E-1 |
| 10 | | | | | |
| E. Driving | E. Cal | | | | |
| 4.23674786E+3 | 1.60937990E-3 | | | | |
| 4.24094275E+3 | 2.14967811E-2 | | | | |
| 4.23533238E+3 | 4.48103256E-2 | | | | |
| 4.23396475E+3 | 7.08613722E-2 | | | | |
| 4.23098509E+3 | 8.00060259E-2 | | | | |
| 4.23658233E+3 | 1.13416491E-1 | | | | |
| 4.23522982E+3 | 1.34376888E-1 | | | | |
| 4.23555232E+3 | 1.52349939E-1 | | | | |

Calibrate-Test-Calibrate Phantom Tests

Presented here are values from calibrate-test-calibrate phantom testing, which was discussed in Chapter 5. Values for driving end elasticity (E. Driving in mV/mm) and calibration instrument elasticity (E. Cal in N/mm) for each of the three repetitions of the calibration procedure.

Calibrate-Test-Calibrate Phantom 1 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|----------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.31905736E+3 | -1.78151631E-3 | 4.33322448E+3 | 4.89426056E+0 | 4.28210449E+3 | 7.67516373E-3 |
| 4.30524265E+3 | 2.94349310E-2 | 4.33126793E+3 | 6.63033264E+1 | 4.27703498E+3 | 3.78447266E-2 |
| 4.29791717E+3 | 4.82954880E-2 | 4.32261204E+3 | 5.70960721E+0 | 4.27360047E+3 | 6.21918537E-2 |
| 4.29347366E+3 | 6.64710058E-2 | 4.32171496E+3 | -7.20946409E+0 | 4.26914491E+3 | 9.12089639E-2 |
| 4.28393304E+3 | 9.12393279E-2 | 4.32163910E+3 | 5.55869586E+0 | 4.26587429E+3 | 9.96050926E-2 |
| 4.28660177E+3 | 1.15002903E-1 | 4.32159712E+3 | -3.63249139E-1 | 4.26909789E+3 | 1.17096363E-1 |
| 4.27875186E+3 | 1.40270227E-1 | 4.31961111E+3 | -1.55413050E+0 | 4.26427124E+3 | 1.38684269E-1 |
| 4.28334716E+3 | 1.60698096E-1 | 4.31761898E+3 | -1.40431705E+0 | 4.26240247E+3 | 1.63524798E-1 |

Calibrate-Test-Calibrate Phantom 1 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.32384937E+3 | 6.45563889E-3 | 4.33551679E+3 | 2.22383571E+1 | 4.27724370E+3 | 1.58564348E-3 |
| 4.30592465E+3 | 3.45686327E-2 | 4.33517469E+3 | -2.39641055E+0 | 4.26907528E+3 | 3.01702201E-2 |
| 4.30042020E+3 | 5.38960033E-2 | 4.33622834E+3 | -3.68697366E+1 | 4.26523061E+3 | 6.42287800E-2 |
| 4.29517256E+3 | 7.91514429E-2 | 4.33284947E+3 | 1.61442639E+1 | 4.26027714E+3 | 8.25968534E-2 |
| 4.28735671E+3 | 9.04784502E-2 | 4.33350995E+3 | 1.35207906E+1 | 4.25979439E+3 | 1.05577242E-1 |
| 4.28213844E+3 | 1.11974421E-1 | 4.32829784E+3 | 2.78478913E+1 | 4.25784948E+3 | 1.20451011E-1 |
| 4.28151011E+3 | 1.40791087E-1 | 4.32413305E+3 | 7.19540508E+0 | 4.25467958E+3 | 1.41727885E-1 |
| 4.28109706E+3 | 1.57176447E-1 | 4.32658999E+3 | -2.61890367E+1 | 4.25578648E+3 | 1.61665992E-1 |

Calibrate-Test-Calibrate Phantom 1 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.30315379E+3 | 5.91922596E-3 | 4.32135549E+3 | 3.43503637E+1 | 4.26304893E+3 | 9.19474846E-3 |
| 4.29064634E+3 | 2.46077046E-2 | 4.32199063E+3 | 1.55944939E+1 | 4.25181322E+3 | 2.91810542E-2 |
| 4.28757423E+3 | 4.54801511E-2 | 4.31796430E+3 | -2.29495727E+1 | 4.24968135E+3 | 5.25237913E-2 |
| 4.27711116E+3 | 6.94778528E-2 | 4.31513336E+3 | -6.61869648E+1 | 4.24923766E+3 | 7.03706589E-2 |
| 4.27154628E+3 | 9.40435908E-2 | 4.31468362E+3 | -2.24783537E+1 | 4.24147763E+3 | 8.89765536E-2 |
| 4.26840492E+3 | 1.21624793E-1 | 4.31025869E+3 | -1.57000717E+1 | 4.24292344E+3 | 1.18651706E-1 |
| 4.26898248E+3 | 1.42187162E-1 | 4.30360117E+3 | -8.42714854E-1 | 4.24376211E+3 | 1.41856876E-1 |
| 4.26408519E+3 | 1.53582146E-1 | 4.30426427E+3 | 9.34212171E+0 | 4.24333223E+3 | 1.60449164E-1 |

Calibrate-Test-Calibrate Phantom 5 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.64280735E+3 | 1.31200338E-2 | 3.91691864E+3 | -6.00972336E+0 | 3.57070116E+3 | 1.22289600E-2 |
| 3.63775597E+3 | 2.63839748E-2 | 3.89674479E+3 | -3.25399838E+1 | 3.57826765E+3 | 4.28116748E-2 |
| 3.64040745E+3 | 5.72465923E-2 | 3.87687117E+3 | -6.94023363E+0 | 3.58070504E+3 | 6.45620815E-2 |
| 3.64545445E+3 | 8.17680131E-2 | 3.87242876E+3 | -3.84680533E+0 | 3.58568461E+3 | 7.62207681E-2 |
| 3.64824209E+3 | 1.00493875E-1 | 3.86864205E+3 | -6.81569518E+1 | 3.59247020E+3 | 1.04890273E-1 |
| 3.65308799E+3 | 1.24588510E-1 | 3.86828646E+3 | -4.24191963E+0 | 3.59494238E+3 | 1.27459994E-1 |
| 3.65155569E+3 | 1.43150712E-1 | 3.86738058E+3 | -8.28104731E-1 | 3.60144673E+3 | 1.55570728E-1 |
| 3.66028970E+3 | 1.70814692E-1 | 3.86194787E+3 | -1.00494382E+0 | 3.60414497E+3 | 1.67737955E-1 |

Calibrate-Test-Calibrate Phantom 5 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.57639963E+3 | 2.03058579E-2 | 3.85010534E+3 | 1.98346135E+0 | 3.55599125E+3 | 1.47574524E-2 |
| 3.57388479E+3 | 3.48338052E-2 | 3.85116711E+3 | 9.91231781E-1 | 3.56399786E+3 | 3.12142433E-2 |
| 3.57901003E+3 | 5.92133552E-2 | 3.84635097E+3 | -7.34047327E+0 | 3.56298421E+3 | 4.07038831E-2 |
| 3.58789515E+3 | 8.80920306E-2 | 3.84072481E+3 | 4.70992160E+1 | 3.57835129E+3 | 7.60923786E-2 |
| 3.58809722E+3 | 1.07419400E-1 | 3.83482357E+3 | 9.24299171E-1 | 3.57598193E+3 | 9.34409611E-2 |
| 3.59497554E+3 | 1.32598754E-1 | 3.83503768E+3 | 3.59562595E+0 | 3.58398917E+3 | 1.16146285E-1 |
| 3.59567724E+3 | 1.49663162E-1 | 3.83098809E+3 | 1.13064352E+1 | 3.58568111E+3 | 1.40796514E-1 |
| 3.60061012E+3 | 1.72774587E-1 | 3.82449332E+3 | 1.19024172E+0 | 3.59116157E+3 | 1.68466049E-1 |

Calibrate-Test-Calibrate Phantom 5 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|----------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.58065506E+3 | -1.39035371E-3 | 3.85899895E+3 | -1.38490465E+1 | 3.57763509E+3 | 8.99433529E-3 |
| 3.58877063E+3 | 3.58142940E-2 | 3.86539913E+3 | 3.73609196E+0 | 3.58558931E+3 | 3.57510178E-2 |
| 3.59389373E+3 | 5.71153591E-2 | 3.86380761E+3 | -2.40319625E-1 | 3.58792466E+3 | 6.62147993E-2 |
| 3.59738474E+3 | 8.23297167E-2 | 3.86299469E+3 | 1.54781262E+0 | 3.59099284E+3 | 8.07973675E-2 |
| 3.60360176E+3 | 1.06421039E-1 | 3.86368865E+3 | -5.09057322E-1 | 3.59583890E+3 | 1.01795438E-1 |
| 3.60979774E+3 | 1.31014501E-1 | 3.86149634E+3 | -4.48931337E+0 | 3.60240038E+3 | 1.15439003E-1 |
| 3.60944773E+3 | 1.49825528E-1 | 3.86131318E+3 | 2.22927961E+0 | 3.60941701E+3 | 1.51290406E-1 |
| 3.61861005E+3 | 1.73671799E-1 | 3.85973125E+3 | -4.49861819E+0 | 3.61297144E+3 | 1.70963560E-1 |

Higher Elasticity Calibrate-Test-Calibrate Bench Tests

Presented here are values from calibrate-test-calibrate bench testing, which was discussed in Chapter 6. Values for driving end elasticity (E. Driving in mV/mm) and calibration instrument elasticity (E. Cal in N/mm) for each of the three repetitions of the calibration procedure.

Calibrate-Test-Calibrate 2 Band Test 1:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.05476206E+3 | 1.52623402E-1 | 4.05550728E+3 | 2.79969384E-1 | 4.03243989E+3 | 1.53434229E-1 |
| 4.06500123E+3 | 2.88861428E-1 | 4.06174719E+3 | 2.85977708E-1 | 4.06411266E+3 | 2.91108561E-1 |
| 4.10402065E+3 | 4.50640496E-1 | 4.05952827E+3 | 2.81380328E-1 | 4.09924420E+3 | 4.43694171E-1 |
| 4.14172411E+3 | 5.97845677E-1 | 4.06552714E+3 | 2.90024990E-1 | 4.12305170E+3 | 5.67309269E-1 |
| 4.17894897E+3 | 7.17435869E-1 | 4.06110744E+3 | 2.84716191E-1 | 4.17534578E+3 | 7.33264926E-1 |
| 4.22952100E+3 | 8.52482092E-1 | 4.06743160E+3 | 2.93040727E-1 | 4.22471151E+3 | 8.53258757E-1 |
| 4.28221612E+3 | 9.93625298E-1 | 4.05761349E+3 | 2.96163387E-1 | 4.28138494E+3 | 9.96969712E-1 |
| 4.34759593E+3 | 1.18164285E+0 | 4.06362917E+3 | 3.01367300E-1 | 4.34126254E+3 | 1.16460534E+0 |

Calibrate-Test-Calibrate 2 Band Test 2:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.01746206E+3 | 1.50688000E-1 | 4.02650429E+3 | 2.88478458E-1 | 4.00684789E+3 | 1.45959394E-1 |
| 4.04376058E+3 | 2.96577221E-1 | 4.03096025E+3 | 2.97389632E-1 | 4.03009240E+3 | 2.92565475E-1 |
| 4.07203065E+3 | 4.25486073E-1 | 4.03625660E+3 | 2.98757877E-1 | 4.06910065E+3 | 4.45213166E-1 |
| 4.10063666E+3 | 5.67812264E-1 | 4.03610654E+3 | 2.99264357E-1 | 4.10705285E+3 | 5.91218349E-1 |
| 4.15663978E+3 | 7.39417262E-1 | 4.03664194E+3 | 3.03520614E-1 | 4.15943527E+3 | 7.34673436E-1 |
| 4.21492232E+3 | 8.94038106E-1 | 4.03402537E+3 | 3.01377626E-1 | 4.19859217E+3 | 8.45379474E-1 |
| 4.27034743E+3 | 1.03329407E+0 | 4.03461524E+3 | 3.07562191E-1 | 4.25902513E+3 | 9.89847224E-1 |
| 4.33217970E+3 | 1.20038219E+0 | 4.03967321E+3 | 3.10023964E-1 | 4.31543873E+3 | 1.14659593E+0 |

Calibrate-Test-Calibrate 2 Band Test 3:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.99054797E+3 | 1.54713782E-1 | 4.01225526E+3 | 2.93584019E-1 | 3.98783843E+3 | 1.54396236E-1 |
| 4.01456348E+3 | 2.83509030E-1 | 4.01362847E+3 | 2.99838436E-1 | 4.00706429E+3 | 2.88214387E-1 |
| 4.03776388E+3 | 4.29762495E-1 | 4.01182184E+3 | 3.00455550E-1 | 4.03492663E+3 | 4.32178995E-1 |
| 4.09287182E+3 | 5.99725023E-1 | 4.01370155E+3 | 3.02007433E-1 | 4.08084523E+3 | 5.81789634E-1 |
| 4.13787766E+3 | 7.42112839E-1 | 4.00718604E+3 | 2.87211569E-1 | 4.12038360E+3 | 7.19563104E-1 |
| 4.19551541E+3 | 9.00778720E-1 | 4.00867552E+3 | 2.95469407E-1 | 4.16008504E+3 | 8.72908404E-1 |
| 4.23769560E+3 | 1.06869615E+0 | 4.01190169E+3 | 3.01061511E-1 | 4.20121745E+3 | 1.02376727E+0 |
| 4.27966340E+3 | 1.22369448E+0 | 4.01016545E+3 | 3.05355540E-1 | 4.27644542E+3 | 1.19059459E+0 |

Calibrate-Test-Calibrate 5 Band Test 1:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.99533517E+3 | 1.41499222E-1 | 4.13136625E+3 | 7.25653686E-1 | 3.98933689E+3 | 1.44775365E-1 |
| 4.01505068E+3 | 2.83855000E-1 | 4.13918938E+3 | 7.41620719E-1 | 4.01341716E+3 | 2.91420109E-1 |
| 4.04608257E+3 | 4.31095993E-1 | 4.14057093E+3 | 7.45469900E-1 | 4.04590862E+3 | 4.44180290E-1 |
| 4.08706414E+3 | 5.80274380E-1 | 4.13824498E+3 | 7.40360038E-1 | 4.08375657E+3 | 5.83254010E-1 |
| 4.13763780E+3 | 7.34456098E-1 | 4.14213920E+3 | 7.43820698E-1 | 4.13463257E+3 | 7.41097139E-1 |
| 4.18561483E+3 | 8.55398712E-1 | 4.13926006E+3 | 7.48657213E-1 | 4.18831066E+3 | 8.91995114E-1 |
| 4.24858072E+3 | 1.02406348E+0 | 4.14350944E+3 | 7.45002792E-1 | 4.24919288E+3 | 1.04731475E+0 |
| 4.30096462E+3 | 1.16118703E+0 | 4.13943708E+3 | 7.48914711E-1 | 4.31208985E+3 | 1.22174463E+0 |

Calibrate-Test-Calibrate 5 Band Test 2:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.99477590E+3 | 1.53841233E-1 | 4.13344912E+3 | 7.43297338E-1 | 3.98717166E+3 | 1.52712024E-1 |
| 4.02408987E+3 | 3.04626357E-1 | 4.13678686E+3 | 7.45227562E-1 | 4.00877192E+3 | 2.98467022E-1 |
| 4.04839646E+3 | 4.32361855E-1 | 4.13545511E+3 | 7.46889893E-1 | 4.04881768E+3 | 4.61866188E-1 |
| 4.08617546E+3 | 5.85054727E-1 | 4.14008144E+3 | 7.53377366E-1 | 4.08199484E+3 | 6.08349739E-1 |
| 4.13280612E+3 | 7.30101436E-1 | 4.13630193E+3 | 7.48752983E-1 | 4.13186129E+3 | 7.44040828E-1 |
| 4.19753607E+3 | 8.96727375E-1 | 4.13477031E+3 | 7.49147174E-1 | 4.16762488E+3 | 8.81928960E-1 |
| 4.22873119E+3 | 1.02946316E+0 | 4.13849383E+3 | 7.54318373E-1 | 4.21168379E+3 | 1.04797421E+0 |
| 4.28133641E+3 | 1.19498092E+0 | 4.13550376E+3 | 7.46845353E-1 | 4.27557235E+3 | 1.20826755E+0 |

Calibrate-Test-Calibrate 5 Band Test 3:

| I. Calibration | | Band Test | | F. Calibration | |
|----------------|---------------|---------------|---------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.98696073E+3 | 1.62138658E-1 | 4.12833580E+3 | 7.46406409E-1 | 3.97563107E+3 | 1.54272674E-1 |
| 4.01267319E+3 | 2.99960173E-1 | 4.12447977E+3 | 7.53892481E-1 | 4.00163198E+3 | 2.84251267E-1 |
| 4.03999612E+3 | 4.43065819E-1 | 4.12974421E+3 | 7.56519638E-1 | 4.03734488E+3 | 4.53572574E-1 |
| 4.08062337E+3 | 5.95349064E-1 | 4.12490272E+3 | 7.52039626E-1 | 4.06975739E+3 | 5.96508817E-1 |
| 4.12287809E+3 | 7.44089078E-1 | 4.11992963E+3 | 7.47253811E-1 | 4.11630258E+3 | 7.43261986E-1 |
| 4.18119075E+3 | 8.90363894E-1 | 4.12662375E+3 | 7.56182198E-1 | 4.15953338E+3 | 8.82648625E-1 |
| 4.22261799E+3 | 1.02070892E+0 | 4.12807282E+3 | 7.64885838E-1 | 4.19929598E+3 | 1.01849524E+0 |
| 4.26340784E+3 | 1.16896816E+0 | 4.12533671E+3 | 7.59780199E-1 | 4.25955791E+3 | 1.19197408E+0 |

Instrument Phantom Validation Tests

Presented here are values from calibrate-test-calibrate phantom testing, which was discussed in Chapter 6. Values for driving end elasticity (E. Driving in mV/mm) and calibration instrument elasticity (E. Cal in N/mm) for each of the three repetitions of the calibration procedure.

Calibrate-Test-Calibrate Phantom 1 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.51946703E+3 | 1.46583411E-1 | 3.52939238E+3 | -1.94266304E+0 | 3.50469026E+3 | 1.42208024E-1 |
| 3.55897883E+3 | 2.94236942E-1 | 3.52799079E+3 | -6.95047827E+0 | 3.54682979E+3 | 3.04152827E-1 |
| 3.61323749E+3 | 4.64623631E-1 | 3.52885031E+3 | 6.20622358E+0 | 3.59709611E+3 | 4.64867355E-1 |
| 3.66997865E+3 | 6.03879756E-1 | 3.52762192E+3 | 1.16916928E+1 | 3.66168526E+3 | 6.25482855E-1 |
| 3.73532199E+3 | 7.51344893E-1 | 3.52780196E+3 | -2.93372225E+0 | 3.71698223E+3 | 7.58669426E-1 |
| 3.80577300E+3 | 9.39187780E-1 | 3.52608635E+3 | 3.36776227E+0 | 3.78489379E+3 | 8.89925094E-1 |
| 3.85668895E+3 | 1.05570318E+0 | 3.52215398E+3 | 7.52271002E+1 | 3.84303455E+3 | 1.05449285E+0 |
| 3.93687719E+3 | 1.22002172E+0 | 3.52815329E+3 | 2.95070610E+0 | 3.92238131E+3 | 1.24112087E+0 |

Calibrate-Test-Calibrate Phantom 1 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.50381902E+3 | 1.45795943E-1 | 3.51531615E+3 | -1.28436975E+0 | 3.50031073E+3 | 1.46792098E-1 |
| 3.54161531E+3 | 2.80718584E-1 | 3.51497778E+3 | -6.85507645E-2 | 3.54290268E+3 | 3.07121495E-1 |
| 3.59426785E+3 | 4.66225107E-1 | 3.51431454E+3 | 4.01187393E+0 | 3.59201674E+3 | 4.48716128E-1 |
| 3.66307222E+3 | 6.38680371E-1 | 3.51400537E+3 | 2.22137754E+0 | 3.64153836E+3 | 5.79100743E-1 |
| 3.71810054E+3 | 7.48503010E-1 | 3.51612655E+3 | 1.05275358E+0 | 3.71638637E+3 | 7.32963386E-1 |
| 3.79010901E+3 | 9.27907452E-1 | 3.51160864E+3 | 7.33472104E-1 | 3.77788101E+3 | 8.81899719E-1 |
| 3.83558651E+3 | 1.04005686E+0 | 3.51260071E+3 | 2.42279492E+0 | 3.84606365E+3 | 1.07140931E+0 |
| 3.90301959E+3 | 1.24168231E+0 | 3.51300254E+3 | -3.01150076E+0 | 3.93948762E+3 | 1.18926408E+0 |

Calibrate-Test-Calibrate Phantom 1 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.50021441E+3 | 1.57028526E-1 | 3.50500961E+3 | -2.51173559E+0 | 3.50047798E+3 | 1.58189419E-1 |
| 3.53160930E+3 | 2.86571500E-1 | 3.50586724E+3 | 1.72458337E+0 | 3.54575926E+3 | 3.23437624E-1 |
| 3.58864676E+3 | 4.52371320E-1 | 3.50291298E+3 | -1.33091746E-1 | 3.58993256E+3 | 4.72033205E-1 |
| 3.64648950E+3 | 5.93197137E-1 | 3.50571268E+3 | -1.85256602E+0 | 3.63681109E+3 | 5.99189711E-1 |
| 3.71532621E+3 | 7.41161467E-1 | 3.50647988E+3 | -1.79113296E+0 | 3.69099924E+3 | 7.51231980E-1 |
| 3.76208937E+3 | 8.96607429E-1 | 3.50139569E+3 | -1.49079594E+0 | 3.75249734E+3 | 9.16753687E-1 |
| 3.81681859E+3 | 1.06639847E+0 | 3.50637668E+3 | 7.00864115E+0 | 3.80812722E+3 | 1.06226211E+0 |
| 3.94806996E+3 | 1.20343335E+0 | 3.50721181E+3 | 8.50939121E-1 | 3.89126574E+3 | 1.25108808E+0 |

Calibrate-Test-Calibrate Phantom 2 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.66677524E+3 | 1.46195901E-1 | 3.70906092E+3 | 3.57851525E+0 | 3.66624730E+3 | 1.55272213E-1 |
| 3.70864898E+3 | 3.09573342E-1 | 3.71043182E+3 | 2.29870112E+0 | 3.70641509E+3 | 3.21746409E-1 |
| 3.74771728E+3 | 4.47540170E-1 | 3.70911786E+3 | -7.20160549E+0 | 3.75476130E+3 | 4.82919931E-1 |
| 3.81517823E+3 | 6.29329749E-1 | 3.70909662E+3 | 7.63453422E+0 | 3.80436957E+3 | 6.13968450E-1 |
| 3.88484117E+3 | 7.91571558E-1 | 3.70901304E+3 | 1.35797308E+1 | 3.84004435E+3 | 7.45242847E-1 |
| 3.91419307E+3 | 8.56298494E-1 | 3.70822603E+3 | 3.41490746E+0 | 3.88648598E+3 | 8.85608458E-1 |
| 3.97663311E+3 | 1.03865639E+0 | 3.70489981E+3 | 6.95937776E+0 | 3.95462979E+3 | 1.01028301E+0 |
| 4.03739138E+3 | 1.21648618E+0 | 3.71078489E+3 | 1.32087327E+0 | 4.01493254E+3 | 1.20036382E+0 |

Calibrate-Test-Calibrate Phantom 2 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.66243891E+3 | 1.58507412E-1 | 3.69453300E+3 | 8.78837478E-1 | 3.65763471E+3 | 1.56856546E-1 |
| 3.70165709E+3 | 3.10076193E-1 | 3.69574074E+3 | 1.01731787E+1 | 3.69067041E+3 | 3.03508832E-1 |
| 3.74443393E+3 | 4.68492501E-1 | 3.69696177E+3 | 3.24668626E+0 | 3.73901448E+3 | 4.73783763E-1 |
| 3.80117720E+3 | 6.12306575E-1 | 3.69778548E+3 | -7.71259239E+0 | 3.80472718E+3 | 6.36395507E-1 |
| 3.85309425E+3 | 7.33157177E-1 | 3.69636462E+3 | 2.32037219E+0 | 3.85664841E+3 | 7.79610868E-1 |
| 3.90953531E+3 | 9.21044502E-1 | 3.69546307E+3 | 4.76938201E+0 | 3.90961307E+3 | 8.99468304E-1 |
| 3.95234804E+3 | 1.07341956E+0 | 3.69491389E+3 | -7.21846376E+0 | 3.96655157E+3 | 1.04899867E+0 |
| 4.01615573E+3 | 1.23119791E+0 | 3.69995000E+3 | 8.79436940E+0 | 4.04097604E+3 | 1.23120662E+0 |

Calibrate-Test-Calibrate Phantom 2 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.66117292E+3 | 1.74070009E-1 | 3.69616112E+3 | 4.09621902E+0 | 3.64907565E+3 | 1.50317552E-1 |
| 3.69740212E+3 | 3.18479063E-1 | 3.69520595E+3 | 7.20512072E+0 | 3.68688050E+3 | 3.00430799E-1 |
| 3.74144667E+3 | 4.74471016E-1 | 3.69037647E+3 | -6.79522480E+0 | 3.72895222E+3 | 4.43789949E-1 |
| 3.79480053E+3 | 6.28865654E-1 | 3.69084124E+3 | 4.69103775E-1 | 3.76883670E+3 | 6.06521028E-1 |
| 3.84847118E+3 | 7.52175474E-1 | 3.69214233E+3 | 2.48191968E+0 | 3.80312139E+3 | 7.22014018E-1 |
| 3.91004011E+3 | 8.97273020E-1 | 3.69186517E+3 | -1.57752160E-1 | 3.88742549E+3 | 9.16695301E-1 |
| 3.97235903E+3 | 1.06769909E+0 | 3.69221782E+3 | 7.23513971E+0 | 3.94091594E+3 | 1.08628484E+0 |
| 4.02352673E+3 | 1.21784870E+0 | 3.69372491E+3 | 2.59819274E+0 | 4.03455010E+3 | 1.25593115E+0 |

Calibrate-Test-Calibrate Phantom 3 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.60763089E+3 | 1.63962621E-1 | 3.70257594E+3 | 8.73266904E+0 | 3.59702748E+3 | 1.66393546E-1 |
| 3.64004305E+3 | 3.08288359E-1 | 3.70073508E+3 | 1.11782766E+1 | 3.63011850E+3 | 3.00156369E-1 |
| 3.68896145E+3 | 4.65150697E-1 | 3.70068918E+3 | 7.71349037E+0 | 3.68074667E+3 | 4.49967467E-1 |
| 3.74684313E+3 | 6.15679749E-1 | 3.70391161E+3 | -2.29414736E+0 | 3.73192957E+3 | 5.97827037E-1 |
| 3.80742891E+3 | 7.80456706E-1 | 3.70408785E+3 | -8.10058831E+0 | 3.79330288E+3 | 7.30845329E-1 |
| 3.86664916E+3 | 9.30535443E-1 | 3.70261600E+3 | 7.44257727E+0 | 3.84437253E+3 | 9.02982557E-1 |
| 3.92422186E+3 | 1.07851662E+0 | 3.70032950E+3 | 1.04452628E+1 | 3.90702727E+3 | 1.08496149E+0 |
| 3.98917272E+3 | 1.26339575E+0 | 3.70115944E+3 | -1.99508568E+1 | 4.00000200E+3 | 1.22600309E+0 |

Calibrate-Test-Calibrate Phantom 3 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.62068014E+3 | 1.56469807E-1 | 3.71651734E+3 | -3.73629369E+0 | 3.61220858E+3 | 1.52672208E-1 |
| 3.65367050E+3 | 2.96741826E-1 | 3.71117567E+3 | 9.55984235E+0 | 3.65617340E+3 | 3.17978044E-1 |
| 3.70179535E+3 | 4.50137982E-1 | 3.71474482E+3 | -3.13934161E+0 | 3.71041300E+3 | 5.08462156E-1 |
| 3.75712696E+3 | 6.08164128E-1 | 3.71048486E+3 | -5.09825961E+0 | 3.75667062E+3 | 6.30930839E-1 |
| 3.82078967E+3 | 7.48168796E-1 | 3.71602517E+3 | -3.01884930E+1 | 3.81106780E+3 | 7.51644474E-1 |
| 3.86627004E+3 | 8.88320049E-1 | 3.71624545E+3 | 2.47251828E+1 | 3.88545434E+3 | 9.49560062E-1 |
| 3.92056440E+3 | 1.05045595E+0 | 3.71145288E+3 | 1.29044020E+1 | 3.92691213E+3 | 1.05992872E+0 |
| 3.98611890E+3 | 1.23847716E+0 | 3.71659886E+3 | -4.76353212E+0 | 4.00577100E+3 | 1.24910237E+0 |

Calibrate-Test-Calibrate Phantom 3 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.61202453E+3 | 1.90393374E-1 | 3.69945549E+3 | -2.05870213E+1 | 3.60429945E+3 | 1.73892035E-1 |
| 3.64925795E+3 | 3.45796732E-1 | 3.69952970E+3 | 5.96302919E+0 | 3.64475324E+3 | 3.37022737E-1 |
| 3.69668231E+3 | 5.13651827E-1 | 3.69921111E+3 | 2.88578572E+1 | 3.69098812E+3 | 4.96981394E-1 |
| 3.74984206E+3 | 6.51286600E-1 | 3.69800755E+3 | -7.70678208E+1 | 3.73909291E+3 | 6.38802926E-1 |
| 3.79515392E+3 | 7.65314610E-1 | 3.69483417E+3 | -2.98024730E+1 | 3.74745204E+3 | 6.41849326E-1 |
| 3.86077963E+3 | 9.12959661E-1 | 3.69932953E+3 | -2.01963857E+1 | 3.82652087E+3 | 9.03418919E-1 |
| 3.92767306E+3 | 1.07829887E+0 | 3.69958989E+3 | 8.85378159E+0 | 3.88049951E+3 | 1.05578052E+0 |
| 3.98993462E+3 | 1.24656494E+0 | 3.69791632E+3 | 4.47291212E+0 | 3.95775851E+3 | 1.26938118E+0 |

Calibrate-Test-Calibrate Phantom 4 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.82432150E+3 | 1.53953613E-1 | 3.92559869E+3 | 1.35102089E+0 | 3.80639159E+3 | 1.46672026E-1 |
| 3.85452051E+3 | 2.85724819E-1 | 3.92901753E+3 | 9.25557273E+0 | 3.84468011E+3 | 2.99722839E-1 |
| 3.88170912E+3 | 4.33961877E-1 | 3.92722480E+3 | 6.63376001E+0 | 3.88586861E+3 | 4.75244949E-1 |
| 3.92407798E+3 | 6.05701832E-1 | 3.92752784E+3 | 7.46366105E-1 | 3.94722407E+3 | 6.59429860E-1 |
| 3.95946929E+3 | 7.56611569E-1 | 3.92933632E+3 | 3.30749279E+0 | 3.97321912E+3 | 7.91382276E-1 |
| 4.01468033E+3 | 8.98192618E-1 | 3.92650900E+3 | 1.03916470E+0 | 4.01599298E+3 | 9.06162178E-1 |
| 4.09717426E+3 | 1.06440518E+0 | 3.92957362E+3 | -2.64169815E+0 | 4.09731293E+3 | 1.03377312E+0 |
| 4.17691808E+3 | 1.23541001E+0 | 3.92807059E+3 | -4.30948709E+0 | 4.16249461E+3 | 1.21087160E+0 |

Calibrate-Test-Calibrate Phantom 4 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.78514730E+3 | 1.56701156E-1 | 3.89706590E+3 | 7.70593781E+0 | 3.79077806E+3 | 1.73436199E-1 |
| 3.82489040E+3 | 2.99223245E-1 | 3.89541624E+3 | -4.66130776E+0 | 3.82586762E+3 | 3.36768866E-1 |
| 3.86413664E+3 | 4.64887455E-1 | 3.89480185E+3 | 9.22807493E+0 | 3.85845857E+3 | 4.64555751E-1 |
| 3.90427557E+3 | 6.48002754E-1 | 3.89870535E+3 | 3.74805659E+0 | 3.90548107E+3 | 6.15258866E-1 |
| 3.92175579E+3 | 7.53311938E-1 | 3.89873089E+3 | -3.74574638E+1 | 3.93433568E+3 | 7.68132530E-1 |
| 3.97991938E+3 | 8.87707188E-1 | 3.89688676E+3 | -1.45783205E+0 | 3.93536690E+3 | 8.90392727E-1 |
| 4.06378349E+3 | 9.98261068E-1 | 3.89796193E+3 | 1.04750835E+1 | 4.01515103E+3 | 1.06591082E+0 |
| 4.12188871E+3 | 1.20917122E+0 | 3.90283015E+3 | 1.40588972E+1 | 4.12509336E+3 | 1.20052597E+0 |

Calibrate-Test-Calibrate Phantom 4 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.78084415E+3 | 1.26471057E-1 | 3.87463865E+3 | -2.89544559E+0 | 3.78578997E+3 | 1.60213075E-1 |
| 3.82285940E+3 | 3.33478788E-1 | 3.87876739E+3 | 5.09696841E+0 | 3.81550977E+3 | 3.09593372E-1 |
| 3.79864687E+3 | 4.88542484E-1 | 3.87694387E+3 | 2.34893223E+1 | 3.86479974E+3 | 4.93684963E-1 |
| 3.90537747E+3 | 6.26233569E-1 | 3.87782801E+3 | -2.22141558E+0 | 3.91595037E+3 | 6.34416377E-1 |
| 3.94099152E+3 | 7.63682564E-1 | 3.88062477E+3 | 1.00792014E+0 | 3.93717828E+3 | 7.06189981E-1 |
| 3.99416446E+3 | 9.57999152E-1 | 3.88178114E+3 | -7.00528320E+0 | 3.96902196E+3 | 8.23313132E-1 |
| 4.03224509E+3 | 1.09526479E+0 | 3.88342986E+3 | -4.52475499E-1 | 4.02855133E+3 | 1.00673052E+0 |
| 4.11384181E+3 | 1.20492310E+0 | 3.88080781E+3 | -4.45453485E+0 | 4.10304460E+3 | 1.20036155E+0 |

Calibrate-Test-Calibrate Phantom 5 Test 1:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 3.66800467E+3 | 1.55279830E-1 | 3.97593177E+3 | 2.63403216E+1 | 3.67086921E+3 | 1.78451174E-1 |
| 3.69914946E+3 | 2.95204764E-1 | 3.97485633E+3 | 1.25641460E+1 | 3.70560280E+3 | 3.33161854E-1 |
| 3.74623497E+3 | 4.58510126E-1 | 3.96781987E+3 | -3.09780838E+0 | 3.75074626E+3 | 4.87427160E-1 |
| 3.79093607E+3 | 5.96188842E-1 | 3.96747759E+3 | 1.39175615E+0 | 3.79636178E+3 | 6.27648609E-1 |
| 3.86048559E+3 | 7.44266204E-1 | 3.96215088E+3 | -1.80295508E-1 | 3.85121077E+3 | 7.36081263E-1 |
| 3.90576774E+3 | 8.61255040E-1 | 3.95598063E+3 | 3.63457751E+0 | 3.89904113E+3 | 8.67148055E-1 |
| 3.97753498E+3 | 1.03859244E+0 | 3.95558975E+3 | -1.15709464E+1 | 3.94279372E+3 | 1.03524104E+0 |
| 4.05470376E+3 | 1.22887517E+0 | 3.94753768E+3 | -7.38465944E-1 | 4.02009529E+3 | 1.25086753E+0 |

Calibrate-Test-Calibrate Phantom 5 Test 2:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.04881971E+3 | 1.31121268E-1 | 4.30636315E+3 | -2.84085721E+0 | 4.05156910E+3 | 1.61805748E-1 |
| 4.07295430E+3 | 2.78160660E-1 | 4.32022908E+3 | -6.33206375E+0 | 4.07375325E+3 | 3.04457552E-1 |
| 4.10910792E+3 | 4.48269417E-1 | 4.31549620E+3 | 4.36175082E+0 | 4.10438684E+3 | 4.54936298E-1 |
| 4.13104566E+3 | 5.68576130E-1 | 4.32092665E+3 | -1.64082901E+0 | 4.14146055E+3 | 6.06261398E-1 |
| 4.18099739E+3 | 7.07124703E-1 | 4.33046548E+3 | 3.58934616E+0 | 4.18985360E+3 | 7.49404480E-1 |
| 4.23081618E+3 | 8.42615899E-1 | 4.32312340E+3 | -8.57921524E+0 | 4.23782418E+3 | 8.70701044E-1 |
| 4.28150031E+3 | 9.78584983E-1 | 4.33040262E+3 | 9.67600888E+0 | 4.28790549E+3 | 1.02856026E+0 |
| 4.33399655E+3 | 1.14273660E+0 | 4.32292240E+3 | -8.61568714E+0 | 4.31223051E+3 | 1.17962176E+0 |

Calibrate-Test-Calibrate Phantom 5 Test 3:

| I. Calibration | | Phantom Test | | F. Calibration | |
|----------------|---------------|---------------|----------------|----------------|---------------|
| E. Driving | E. Cal | E. Driving | E. Cal | E. Driving | E. Cal |
| 4.00734817E+3 | 1.45024566E-1 | 4.25323332E+3 | -8.91529277E+0 | 4.00759617E+3 | 1.54532724E-1 |
| 4.02846711E+3 | 2.90303967E-1 | 4.25646316E+3 | 7.65581566E+0 | 4.02669303E+3 | 3.00908236E-1 |
| 4.05997827E+3 | 4.30964837E-1 | 4.25073769E+3 | 7.79027277E-1 | 4.05999239E+3 | 4.53109564E-1 |
| 4.09570156E+3 | 5.74818181E-1 | 4.25256045E+3 | 6.15886399E+0 | 4.09630590E+3 | 6.02757573E-1 |
| 4.14570155E+3 | 7.10550187E-1 | 4.25074708E+3 | 6.32217683E-1 | 4.14848946E+3 | 7.45997046E-1 |
| 4.20751103E+3 | 8.96515813E-1 | 4.25015371E+3 | 2.10445782E+0 | 4.19755550E+3 | 8.82531342E-1 |
| 4.24950550E+3 | 1.01750479E+0 | 4.25150127E+3 | 8.44931845E-1 | 4.23934062E+3 | 1.05982948E+0 |
| 4.29371280E+3 | 1.15499355E+0 | 4.25440736E+3 | -6.49596586E+0 | 4.29117643E+3 | 1.20246959E+0 |