Abstract

DAVIS, LUKE. Modeling of the Damping Contributions of O-rings in a Submergible Six-Axis Load Cell. (Under the Direction of Assistant Professor Dr. Kara Peters)

The objective of this research is to provide general guidelines and calibration procedures to accurately model and improve the response time of submergible 6-axis load-cells based on multiple beam configurations sealed with compressible o-rings. This objective is achieved by adding a damping contribution to the existing stiffness model through an appropriate time derivative function. Data collection parameters are experimentally determined to control the noise and prevent the time derivative from becoming unstable. The effects of o-ring type and material properties on the stiffness of a particular submergible six-axis load cell are determined. Following the stiffness study, the damping matrix is derived from data collected during various loading cases, assuming that the damping effect can be modeled as constant in time. A comparison of the effect of material properties, results from stiffness tests, and other data are performed to determine their effect on the damping matrix. Finally, the assumption of constant damping is evaluated through the comparison of the modeled response to the measured system response.
MODELING OF THE DAMPING CONTRIBUTIONS OF O-RINGS IN A
SUBMERSIBLE SIX-AXIS LOAD CELL

by
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BIOGRAPHY

Luke Davis was born in Colorado Springs, Colorado in 1972. He spent the majority of his childhood in Austin, Texas and a small part of it in New Brunswick, New Jersey. He spent his teenage years in Oxford, North Carolina and moved to Raleigh after attending a community college for two years in 1993 after graduating High School. He first became an engineering student at NC State University in 1994. Life circumstances got in the way of a promising engineering career in 1995.

In 2001, Luke returned to the university to complete his undergraduate degree in Mechanical Engineering and graduated in December 2004 with the honor of Cum Laude. Luke began working on his Master of Science in Mechanical Engineering the following semester with a proposed graduation date of May 2006.
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Chapter 1

Introduction

1.1 Force-Torque Load-cells

Force-torque Load cells are utilized in nearly every electronic weighing application that requires repeatable and accurate results with low hysteresis, high resolution, and repeatability. There are many different shapes and sizes of these types of load cells that range in calibrations of ounces to several tons. Many are used in robotics to provide real time force feedback control.

Figure 1.1.1: Photograph of typical load cell configurations [5].
The essential sensing component of the electronic load cell is the electrical resistance strain gauge as seen in Figure 1.1.2. A strain gauge is fabricated from an ultra thin layer of foil or silicon etched to form a series of ultra thin parallel wires. This series of wires is then placed on an ultra thin dielectric substrate material such as polyimide to allow the gauge to be attached to structures for measurement [11].

![Figure 1.1.2: Electrical resistance strain gauge [11].](image)

Once attached to the structure, the strain gauge will conform to the surface deformations that occur due to loading on the structure. When the strain gauge is deformed parallel to the wires, the resistance across the gauges increases or decreases due to the change in geometry of the wires. Similarly, when the strain gauge is deformed perpendicular to the wires, a smaller change in resistance occurs due to the Poisson effect in the substrate material. This transverse strain sensitivity can be calibrated, however not completely eliminated, which leads to cross-talk in the force-torque component measurements of the load-cell, as will be seen later.
The change in resistance in a strain gauge is extremely small however and therefore, typically a Wheatstone Bridge circuit is used amplify the effect of the resistance change to produce a significant positive or negative voltage [1,3]. The quarter bridge circuit shown in Figure 1.1.3 will produce voltages in reaction to a single gauge. This type of strain gauge circuit is simple to design and is commonly used in single axis load cells.

![Quarter Wheatstone Bridge Circuit](image-url)

**Figure 1.1.3: Quarter Wheatstone bridge configuration for measurement of change in resistance of a single strain gage [10].**
Single axis load cells can be accurate with the use of one strain gauge whereas multi axis load cells contain several strain gauges to provide different sensitivities to strain that can be exploited to separate multiple load components. If two strain gauges with identical gauge factors are on opposite sides of a beam with an applied bending moment and axial force, for example, they each produce a highly linear voltage to strain relationship of opposite signs which can be used to measure the two applied loads independently, thus creating a multi-axis load cell [6]. An illustration of this type of circuit is shown in Figure 1.1.4.

![Compensated Wheatstone bridge](image)

This particular circuit also compensates for thermal expansion of the body along with minute differences in the gauge factors by adding compensation resistors into the circuit. This is the most common method used in industry for multi-axis load cells. The values of the thermal compensation resistors are calculated from loading and unloading data collected at different temperatures. The values of the modulus and bridge balance resistors are determined by other methods and are dependant on the system electronics and hardware [4,6].
1.2 Single-Axis, Multi-Axis, and Submergible Load Cells

Single-axis load cells typically contain cylindrical or square beam geometries whereas multi-axis load cells contain more complex internal structures for gauge mounting. A typical uniaxial load cell can contain a single strain gauge as illustrated in Figures 1.2.1 and 1.2.2. This type of load cell cannot distinguish between the strains due to applied moments or axial forces and can produce data errors if the applied loads are not perfectly aligned in the axial direction.

Figure 1.2.1: Square Beam Single Axis Load Cell [9]. Figure 1.2.2: Cylindrical Single Axis Load Cell [8].
If the geometry of the load-cell is modified to allow strain gauges to be attached along strain paths sensitive to different load components, the load-cell will be able to output multiple voltage values corresponding to separable combinations of the various load components. A typical multi-axis load cell is shown in Figure 1.2.3.

These multi-axis load-cells or force-torque sensors are used in a variety of industrial applications to provide real time force feedback for static and dynamic loading. For instance, a load cell on the end of a robotic arm can be used in a closed loop control system for delicate tasks such as inserting a corrective lens into the frame of a pair of glasses [4]. A single axis load cell is typically not used in this type of application due to the fragile nature of the lens and high probability of reaching critical moment loads before reaching the critical axial loading.

Typical multi-axis load-cells contain two relatively rigid plates that move relative to one another and are connected to a third body, called the transducer body. The transducer body is deformed due to the relative displacement of the rigid plates. This part of the sensor has been designed with a geometry producing strain paths where strain gauges can be mounted to separate and measure the complex applied loads. A common multi-axis load-cell is the 6-axis load-cell. This type of force-torque sensor can determine all three applied forces and all three applied moments simultaneously. For this type of load-cell there is a design trade off
between maximum moment capability and sensitivity to applied forces \([5,4]\). These force-torque sensors have much weaker moment loading capabilities than force loading capabilities. A large 6-axis load cell can typically measure twice the axial force (lbs) than it can measure in torque (inch-lbs). Typically, the smaller the load-cell, the larger this difference becomes, therefore the moment loading capability of the load-cell, relative to the axial loading, decreases.

Due to the relative motion between the two rigid bodies, these load-cells are typically of open construction with air gaps between the bodies that move relative to one another, as shown in Figure 1.2.4 and 1.2.5. These gaps allow air, dust, small particles, and water to pass into the body of the sensor.

**Figure 1.2.4: Open construction 6-axis load cell [5].**

In industrial environments, damage due to these intrusions is highly probable. The exposed strain gauges inside the body are particularly sensitive to corrosion, abrasion, and shorts between the small wires on the etched circuit.

**Figure 1.2.5: 6-axis load-cell [5].**
Protecting the sensor from dust particles and sprayed water can be accomplished with a semi-invasive gap filler or cover of some type. These types of protective measures usually do not adversely affect the performance and do not require compensation. Protecting the sensors from being completely submerged typically requires a deformable compressed seal between the two bodies [4]. This type of seal generates added stiffness and damping between the bodies that is currently not compensated for and delays the response of the load cell to all loads other than quasi-static loading. This damping effect is what will be modeled and compensated for in this research. The particular load-cell geometry considered in this research will be outlined in the following section. However, the general concepts that are developed in the prediction model for this geometry should be applicable to other geometries as well.
1.3 IP68 Delta Load Cell

ATI Industrial Automation in Apex, NC produces the IP68-10m load-cell that was studied in this research. The Multi-Axis Force/Torque Sensor system measures all six components of applied force and torque simultaneously. It consists of a transducer, a shielded high-flex cable, and intelligent data acquisition system or stand-alone controller. The monolithic transducer uses embedded silicon strain gauges to sense forces and torques. Using this type of strain gauge provides high noise immunity and high overload protection [5].

The IP68-10m submergible Delta model, shown in Figure 1.3.2, sensor has the capability of being submerged in fresh water up to 10 meters in depth with full functionality. Table 1.3.1 lists the technical details of this model. The z-axis is the direction along the axis of the load-cell.

![IP68-10m Delta model load-cell](image)

Table 1.3.1: IP68-10m sensor specifications [5]

<table>
<thead>
<tr>
<th>Sensing Ranges</th>
<th>Resolution</th>
<th>Single Axis Overload</th>
<th>Stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fx, Fy (+/- lb)</td>
<td>150</td>
<td>1/128</td>
<td>530</td>
</tr>
<tr>
<td>Fz (+/- lb)</td>
<td>450</td>
<td>1/64</td>
<td>2600</td>
</tr>
<tr>
<td>Tx, Ty (+/- in-lb)</td>
<td>600</td>
<td>3/128</td>
<td>2000</td>
</tr>
<tr>
<td>Tz (+/- in-lb)</td>
<td>600</td>
<td>1/64</td>
<td>3700</td>
</tr>
</tbody>
</table>
The Delta IP68 model has four primary components, the Mounting Adapter Plate (MAP), Tool Adapter Plate (TAP), Transducer Body, and Connector Block, as seen in Figure 1.3.3. The Transducer Body is secured between the MAP and TAP inside the sensor and is composed of three beams that contain the twelve silicon strain gauges used for force/torque measurements.

**Figure 1.3.2: Isometric view of IP68 Delta.**

The MAP is attached to one side of the transducer body via the outside tapped holes. The TAP is attached to the other side of the transducer body via the inside tapped holes. Each set of strain gauges on the transducer body (see Figure 1.3.4) produces a single output voltage via the embedded electronics.

**Figure 1.3.3: Transducer body indicating location of strain gauges.**
To seal the sensor for submersion there is an o-ring located between the MAP and TAP, as seen in Figure 1.3.5. This o-ring seals the normally open boundary between these two parts that provides the necessary space to allow the parts to move relative to one another. Without this o-ring in place, the response of this load-cell to applied forces and moments would be similar to other load-cells.

However, due to the location of the o-ring in the free space between the MAP and TAP, there is damping generated due to the o-ring and plate interaction. This damping causes inaccuracies and delayed response to loads in the x-axis and y-axis directions, which will be investigated in this thesis.

Figure 1.3.4: Exploded view of IP68 Delta.
1.4 Research Objectives

In order to motivate the objectives of this research, we consider the response of an IP68 Delta sensor with a static load of 135 lbs applied on the x-axis with and without a Buna o-ring in place, shown in Figure 1.4.1. The response of the sensor without the O-ring is relatively rapid and reaches the reported accuracy plateau in just a few milliseconds. This particular force-torque load cell has a reported accuracy of 1.25% of the Full Scale (FS) rating of each axis in loading. This particular load-cell is rated to 150lb in the x-axis so the expected error is 1.88lb yielding the allowed measurement range of 133.12 lb to 136.88 lb. The response of the sensor with the o-ring in place, also shown in Figure 1.4.1 is delayed due to the damping effect occurring due to the o-ring interaction.
The sensor output reaches 134.5 lbs after more than two minutes have passed (the full time scale is not shown in Figure 1.4.1). With the o-ring in place, the sensor does not reach the lower accuracy bandwidth of 133.12lb until 23 seconds after the application of the load.

Table 1.4.1 shows the time for the load cell to reach equilibrium for different load amplitudes and different o-rings installed between the MAP and TAP plates. As can be seen, there is a significant time delay in the sensors response to static loads which varies depending upon the type of o-ring used.

Table 1.4.1: Time delay (in seconds) for load cell to reach equilibrium with static loads applied along x-axis.

<table>
<thead>
<tr>
<th>O-ring type</th>
<th>Hardness Shore A</th>
<th>Applied Static Load (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>Silicone</td>
<td>70</td>
<td>83</td>
</tr>
<tr>
<td>FEP – Encapsulated Silicone</td>
<td>85</td>
<td>113</td>
</tr>
<tr>
<td>Viton</td>
<td>75</td>
<td>129</td>
</tr>
<tr>
<td>Buna</td>
<td>65</td>
<td>138</td>
</tr>
</tbody>
</table>
Motivated by these experimental observations, the first objective of this work is to define the data collection parameters including data rate, sample rate, and additional filtering to control the noise and prevent the calculated time derivatives of the output voltages from becoming unstable. As expected, the noise in the calculated time derivative of the voltage outputs is significantly higher than that in the output voltages themselves.

The second objective is to define the effect of the different o-rings on the calibrated stiffness of the load cell through experimental comparisons. Due to the location of the o-ring, forces and torques about the z-axis are unaffected by the stiffness and damping of the o-ring. Loads of this type simply causes the o-ring to slide along the smooth edge of the MAP body, which does not affect the response of the load cell. Therefore the loading to be considered in this thesis will be forces and torques in the x-axis and y-axis directions where the o-ring is compressed from the relative displacement of the plates.

The third objective is to generate the damping matrix from the data collected during various loading cases. It is assumed that the damping matrix is constant, meaning invariant in time. Different o-rings will be placed into the load cell and comparison done to determine the effect of the hardness value and material type on the damping matrix. The o-rings will be lubricated with Teflon prior to assembly to allow relatively frictionless contact between the o-ring and the plates. Finally, the assumption of constant damping will be evaluated through the comparison of the modeled system response to the measured system response.
The work presented will then provide general guidelines and motivate future studies to accurately model and improve the response time of submergible 6-axis load-cells based on multiple beam configurations that are sealed with compressible o-rings.
Chapter 2

Methods and Materials

2.1 Laboratories and Measurement Techniques

All load testing was performed on the loading frame at ATI shown in Figure 2.1.1, developed in house. The laboratory facilities are located in a self-contained, conditioned space on top of an isolated portion of the building foundation, which prevents any unwanted vibrations, or fluctuations in temperature that could affect the force torque load cells during tested. The loading frame, shown in Figure 2.1.1, in which the load cell is mounted, allows the user to hang static loads that apply forces and torques on each respective axis. The stand also holds the DAQ system and computer used to collect the data. Orientation changes can be made to position the load cell such that the desired loading axis is facing straight down. This allows the use of free-weights with hangers to apply accurate loads to the body of the load cell without the influence of pulley systems or guide rails.
Figure 2.1.1: Picture Delta IP68-10m load cell attached to stand with loading tooling attached to the front.
Figure 2.1.2 shows the tooling that is attached to the TAP side of the load cell. It contains machined grooves and steel cables placed in known locations in reference to the origin of the body of the sensor. Applying loads on the cables or grooves allows a known axial loading and torque to be applied.

Figure 2.1.3: Delta IP68-10m force-torque load cell mounted in loading frame with 105 lb Load Applied as Fx component.
Figure 2.1.3 shows a weight applied to the load cell that is oriented in alignment with the x-axis (vertical) down. A hanger with a hook on the end is used to hold the load that is applied. For this research, the loads were applied along the x-axis using the steel cable closest to the body of the load cell as shown in Figure 2.1.4. The position of this hanger is 0.987 inches from the origin of the sensor. Because there is a resulting torque, $M_y$, applied to the load cell due to the offset of the loading point, the values of the strain gauge outputs will be different than if a force could be applied directly to the origin.

The weights and hangers used were tested for accuracy according to ASTM Class 7 standards. The cables are centered on the respective axis and only allow forces to be applied straight down along the axis of the load cell. Each tool has been verified for accuracy up to .001 inches for positioning of the grooves and steel cables.
To apply the loads, the hanger was first placed on top of a hydraulic jack. The weights were then placed on the hanger and the jack lowered until 100% of the weight was on the load cell prior to recording any data. The use of the jack eliminates rapid impact loading to the load-cell, although it was not possible to completely eliminate all vibrations in the load-cell as will be discussed later in this thesis.

Figure 2.1.5: Hydraulic jack used to support weights.

Figure 2.1.6 shows the primary screen of the software interface used by the DAQ system to collect data. The screen image shows the voltage values for a load applied along the x-axis. Each bar is labeled $F_{x,y,z}$ (applied forces) and $T_{x,y,z}$ (applied moments), however for the example in figure 2.1.6 the calibration matrix had not been loaded so only the resolved voltages are displayed. This program includes options to change the data acquisition rate, load and unload calibration matrices, and stop and start data collection. Once the load cell is attached to the stand, the tooling attached to the TAP plate, and connectors plugged into the DAQ system, the software is started and data collection commences.
Figure 2.1.6: Software interface for data collection.
2.2 Generation of Stiffness Matrix

The current method used to calculate the predicted forces from the six strain gauge outputs models the system as a simple spring through the equation;

\[ F = dx k \]  \hspace{1cm} (2.2.1)

Where the force matrix \((F)\) is a 1 x 6 matrix of resolved forces, the stiffness matrix \((k)\) is a 6 x 6 matrix of constants, and the deflection matrix \((dx)\) is a 1 x 6 matrix of the 6 voltages produced from the strain gauges [4,6].

The voltage curves generated from the strain gauge sets are nearly linear within the strain region used by the sensor so the resolved voltage vector \((V)\) is simply a scalar multiple of the deflection \((dx)\) vector so that we can write [10,11];

\[ F = V k \]  \hspace{1cm} (2.2.2)

where \(F\) is the applied load vector,

\[ F = [F_x, F_y, F_z, M_x, M_y, M_z] \]  \hspace{1cm} (2.2.3)

and \(V\) is the measured vector of voltage outputs from each Wheatstone bridge,

\[ V = [V_0, V_1, V_2, V_3, V_4, V_5] \]  \hspace{1cm} (2.2.4)

and \(k\) is now an effective stiffness of the load-cell. The DAQ system includes the calibrated stiffness matrix \((k)\) and reads as input the strain gauge voltage vector from the force-torque load cell. The resolved voltages are then multiplied by the stiffness matrix to obtain the output the force vector \((F)\).
The Delta IP68-10m transducer body, shown in Figure 2.2.1, is comprised of three beams that contain the twelve strain gauges used in the Wheatstone bridge circuits to generate the V0…V5 voltages. The beams are labeled A, B, and C. The top and bottom gauges for each respective beam are paired with one Wheatstone bridge circuit to produce one output voltage. The side gauges for each respective beam are paired to produce another voltage output. This method takes advantage of the effect of opposite sign of strain components for gauges mounted on opposing sides of a beam in bending.

Figure 2.2.1: Transducer body of Delta IP68-10m with axes identification and strain gauge locations.
Table 2.2.1 correlates the output voltages to the respective pairs of strain gauges.

Table 2.2.1: Voltage output relationship to transducer beams.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Strain Gauge Location</th>
<th>Opposing Sides of Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Top and Bottom of Beam</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>V0</td>
<td>V1</td>
</tr>
<tr>
<td>B</td>
<td>V2</td>
<td>V3</td>
</tr>
<tr>
<td>C</td>
<td>V4</td>
<td>V5</td>
</tr>
</tbody>
</table>

The geometry of the transducer body prevents the beams from being subjected to measurable tensile and compressive axial forces. Therefore, the beams are only subject to bending for any applied load. Therefore, V3 and V5 are the primary contributors to forces in along the x-axis because they are voltages produced as a result of bending in beams B and C. For torques about the y-axis, V0 contributes twice that of V2 and V4 whereas V0, V2, and V4 all contribute equally to torques about the z-axis. Because of the symmetry of the body with respect to forces along the x-axis and torques about the y-axis, this work presented in this thesis will concentrate on those forces. This approach has the advantage of eliminating cross talk and weakened signals from beams that are not significantly deflected due to loading such as in the case of beams B and C for forces along the y-axis.
In practice, the effective stiffness or calibration matrix, \( k \), is generated from experimental data collected from the force-torque load cell being calibrated. The procedure to generate \( k \) for the load-cell is a three-step process. First, the electronics are tuned to remove offset errors for each strain gauge. This consists of setting variable resistance pots to adjust gains and bias settings in order to tune the Wheatstone bridge circuits. Secondly, \( m \) known loading cases are applied to the load-cell and the single point resolved strain gauge voltage outputs are recorded for each loading case. These applied loads and measured voltage outputs are collected into an applied force matrix, \( F \) and an output voltage matrix, \( V \), both of dimension \( m \times 6 \).

\[
F = V k \quad (2.2.5)
\]

In principle, one could choose appropriate loading cases for each axis to exactly provide the number of required equations to solve for these constants, however a more robust approach is to apply more cases than needed, making equation (2.2.5) over determined. The additional cases compensates for the effects of manufacturing errors in the transducer and mounting errors in the strain gauges. There is an ideal quantity and ideal types of loads that can be applied to streamline the data collection process. However, this is usually determined experimentally for the best results.

To solve the equation for the stiffness matrix we apply the Least Squares Method so that;

\[
V^T F = V^T V k \quad (2.2.6)
\]

\[
\left[V^T V \right]^{-1} V^T F = k \quad (2.2.7)
\]
The stiffness matrix found through equation (2.2.7) can then be put into the DAQ system and plugged back into equation (2.2.2) to calculate the predicted forces and torques being applied to the sensor. For load-cells without o-rings, the voltage data can be collected nearly instantaneously. For load-cells with o-rings, however, it is necessary to wait until the voltages stabilize prior to recording the data point. This method works well with a low percentage of error on the order of 0.5% of Full Scale (FS) to 1.25% of FS for sensors without o-rings between the MAP and TAP plate. The errors for the sensors with o-rings are related to the time the load is applied. If the loads are applied quasi-statically, there is no additional error. For the 135lb loading case shown in Figure 1.4.1, the error at the time the load is applied is 2.67% FS and drops to 1.67% FS after ten seconds.
2.3 Generation of Damping Matrix

To add the damping contribution of the o-ring into the model we introduce the constant damping matrix $C$, into equation (2.2.2) so that;

$$F = V^T + \begin{pmatrix} \frac{d}{dt} V \\ C \end{pmatrix} (2.3.1)$$

The appropriateness of this formulation incorporating a constant damping matrix will be evaluated in a later chapter through the experimental results. Similar to the stiffness matrix, the damping matrix has dimension 6 x 6. Notice the force and voltage matrices are no longer vectors do to the addition of the derivative. Streaming data over a finite time will have to be collected so that the damping contribution can be determined. Since the stiffness matrix can be calculated from the experimental data with quasi-static loading (i.e. $\frac{dV}{dt} = 0$), the damping matrix is found in a separate step from the stiffness matrix. Now we assume that the applied force and voltage output matrices are the same as used for the calibration of the stiffness matrix in the previous section, except that we evaluate these at multiple time steps.

As before, we can use the least squares method to solve for $C$ at each time step giving,

$$V^TF = V^T V^T + V^T V^T C (2.3.2)$$

$$\begin{pmatrix} V^T V \end{pmatrix}^{-1} V^T \begin{pmatrix} F - V^T \end{pmatrix} = C (2.3.3)$$

Because there is no damping at $t = 0$ or after equilibrium has been reached, this equation is only valid for the interval,

$$0 < t < \left( t @ \left( F - V^T = 0 \right) \right)$$
In theory, the damping matrix calculated using equation (2.3.3) should produce results of the same quality as the stiffness matrix using equation (2.2.2) regardless of the data rate. However, several issues appear in the calculation of the damping matrix that need to be addressed. The most important of these is filtering the inevitable noise generated by collecting streaming data to calculate the derivative function. The data for all experiments described in this thesis were collected at 1000Hz. Due to the noise measured by the DAQ system at this high data rate, the derivative part of the function is unstable. Increasing the sample rate, or averaging the data, balances this instability but decreases the overall samples rate. At the same time, there is a design trade off: high speed data collection with a low sample rate decreases the response time of the system but sacrifices accuracy; high speed data collection with a high sample rate increases accuracy but sacrifices response time.

![Graph showing stiffness contribution, stiffness and damping, and applied load.](image)

Figure 2.3.1: Calculated $F_x$ component of load-cell response with applied load of 135 lb along the x-axis collected with an overall sample rate of 62.5Hz.
Once the stiffness and damping matrices have been determined from the experimental data, the force vector is calculated using these matrices and the measured output voltage data for one of the loading cases considered previously. The purpose of this step is to evaluate the validity of equation (2.3.1) by comparing the calculated output force vector to the known applied force vector. Figure 2.3.1 shows a plot of the $F_x$ component of the calculated load-cell response to an applied load of 135 lb along the x-axis with a Buna o-ring installed. The data collection rate of this data set was 1000Hz with a sample rate of 16; meaning that the output data is a running average over 16 samples. Thus the overall sample rate (OSR) is calculated according to;

$$\text{OSR} = \frac{\text{Data Collection Rate}}{\text{Sample Rate}} = \frac{1000\text{Hz}}{16} = 62.5\text{Hz}. \quad (2.3.1)$$

Ideally, the result of equation (2.3.1) would produce a straight line along 135 lb. However, the damping contribution in this case is highly unstable due to the high overall sample rate causing the instability in the derivative function, which effectively increases the bandwidth of the response curve. This instability is directly attributed to the noise in the voltage data causing rapid changes in the slope of the voltage curve.
For the case shown in Figure 2.3.1, the voltage and derivative functions are shown below. Considering this is a static loading case with linear damping, it would be expected to see a voltage curve that started low and ended high with no abrupt changes in slope. However, with a high sample rate of 62.5Hz, there are several abrupt changes in the slope of the voltage curve shown in Figure 2.3.2 making the derivative function unstable as shown in Figure 2.3.3.

Figure 2.3.2: Output voltage data from channel 0 (V0) with applied load of 135 lb along the x-axis and overall sample rate of 62.5Hz.
Figure 2.3.3: Calculated derivative of output voltage from channel 0 (or 1 or 2, etc.) with applied load of 135 lb along the x-axis and overall sample rate of 62.5 Hz.

The effect of increasing the sample rate is shown in Figure 2.3.4. The sample rates for the plots are increased from the original 16 to 96 and 256 resulting in overall sample rates of 62.5 Hz, 10.42 Hz, and 3.91 Hz respectively.
Figure 2.3.4: Calculated derivative of output voltage with applied load of 135 lb along the x-axis and overall sample rates of 62.5 Hz, 10.42 Hz, and 3.91 Hz.

The 3.91 Hz curve in Figure 2.3.4 contains an acceptable amount of noise for the derivative function and provides a significantly smoother and more stable curve. This results in a smoother and more accurate damping contribution calculation than the higher overall sample rate curves as shown in the next Figure 2.3.5.
Figure 2.3.5 shows the results of the damping contribution for the lowered overall sample rate of 3.91 Hz. Although this particular damping function is inaccurate due to remaining instabilities that will be analyzed later, the result of decreasing the sample rate is clearly illustrated by the near stabilized damping contribution and significantly reduced bandwidth of the response curve. For this research, the data collection rate remained at 1000 Hz and the sample rate was increased to 250. This results in a time of 0.25 seconds between readings or an overall data collection rate of 4 Hz.
Now that a stable sample rate has been defined, a more accurate damping matrix can be generated from the new data. Figure 2.3.6 shows the results of collecting data at an overall sample rate of 4Hz. This data generates more accurate damping constants and stable derivative function, which increases the accuracy of the resolved force data or response curve.

![Graph showing calculated Fx component of load-cell response](image)

Figure 2.3.6: Calculated Fx component of load-cell Response with an applied load of 120 lb along the X-axis and a reduced overall sampling rate of 3.91 Hz.
Further accuracy and decreased bandwidth of the response curve can be achieved by calculating a running average of the derivative function. Figure 2.3.6 also shows the response of collecting data at 4Hz and calculating a running average of the derivative function over four samples. Running averages have the effect of smoothing or filtering noise without the effect of slowing the data output speed.

Because Equation 2.3.3 is only valid for the interval;

\[ 0 < t < (t @ [F - V_k = 0]) \]

It is necessary to define a value for \((F - V_k)\) near the equilibrium point where \(F - V_k \neq 0\) that can be used in all cases. Intuitively, for complex modeling, the more data that can accurately be collected helps to negate the contributions of outliers and other anomalies such as noise and insufficient filtering. However, there are limitations in the resolution of the data stream that invalidate the data near the equilibrium point for use in the generation of the damping matrix. The bandwidth of the stiffness contribution from \(t = 0\) to the equilibrium point should also be considered. For loading cases considered in this research, that bandwidth is only 2.5 lbs in some cases. Therefore, the point at which \(F - V_k \neq 0\) was arbitrarily chosen to be \(F - V_k = 0.5\) lbs. Because a constant data acquisition rate is being used, the time to reach equilibrium, where
F - V_k = 0, is a good indication of the quantity of data collected. For each loading case and o-ring type, as listed in Table 1.3.2, there is a minimum of 76 seconds of data collection for loading cases above 20 lbs. Given the OSR being used, there are several hundred data points collected between t = 0 and F – V_k = 0.5 lbs. Therefore, this time interval is deemed sufficient to generate an accurate damping matrix. The damping matrices for the 20 lb cases will still be calculated and compared to support trends and for further analysis.
Chapter 3  
Results and Analysis

This chapter presents the static and dynamic effects of o-ring type on the Delta IP68 load cell with a known static load applied along the x-axis. The magnitudes of constants that primarily contribute to the predicted load calculation in the Fx columns of the stiffness and damping matrices will be isolated for comparison. This will be followed by the evaluation of the assumption of constant damping through the comparison of the stiffness only and the stiffness with damping models.

3.1 Effect of O-ring type on Deflection and Stiffness

Prior to considering the effect of the o-ring type on the dynamic response of the load-cell, we first investigate their effect on the static stiffness of the load-cell. This effect is evaluated as a function of the hardness and modulus of the o-ring material. It might be expected that as the modulus and hardness of the o-ring increases, the relative deflection between the plates would decrease. Figure 3.1.1 shows a plot of the distance, measured by hand with a caliper, between the inside edges of the plates as loads are applied along the x-axis.
To give a better understanding of the hardness values listed for the o-ring materials, a typical rubber band has a Shore-A hardness of 65 where a pencil eraser has a Shore-A hardness of 70. As can be seen, the FEP-encapsulated silicone o-ring allows the least amount of deflection for all loading cases followed by the silicone, buna, and viton o-rings respectively. The measurements were taken at the gap between the plates located at 180 degrees from the direction of the load. Therefore, as the load is applied, the gap increases.

![Figure 3.1.1: Plot of distance between the inside edges of the MAP and TAP plates as a result of loading along the x-axis.](image-url)
Figure 3.1.1 demonstrates that there is no a direct correlation between the hardness or modulus of the o-ring material and relative deflection of the MAP and TAP plates. However, a high precision measurement of the gap distance between the plates was not possible with the hand caliper. Therefore, to confirm these findings, Table 3.1.1 lists the o-ring property values along with the load cell voltage output response to a 120 lb force applied along the x-axis. Because of the linear relationship between the deflection of the plates and voltage, a direct comparison can be done between the voltage values to determine the relative deflections that occur as a result of the 120lb load. In this case, the larger the voltage values the more the deflection between the plates at the gap measured in Figure 3.1.1.
Table 3.1.1: Load cell response at equilibrium compared to the hardness and modulus of o-ring material types installed between the MAP and TAP for 120 lb load applied along the x-axis.

<table>
<thead>
<tr>
<th>O-ring type</th>
<th>Hardness (Shore-A)</th>
<th>Modulus of Elasticity$^{12}$ [13, 14] (psi)</th>
<th>Voltage Outputs in Response to the Loads After Equilibrium (volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FEP-Encapsulated Silicone (silicone) 740</td>
<td>V0  V1  V2  V3  V4  V5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50e3 (FEP)</td>
<td>2.63  -0.01  -1.34  -2.58  -1.25  2.59</td>
</tr>
<tr>
<td>FEP-Encapsulate Silicone</td>
<td>85</td>
<td>740</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silicone</td>
<td>70</td>
<td>2.87  -0.06  -1.53  -2.95  -1.35  3.10</td>
</tr>
<tr>
<td></td>
<td>Buna</td>
<td>65</td>
<td>2.91  -0.10  -1.57  -3.03  -1.38  3.13</td>
</tr>
<tr>
<td></td>
<td>Viton</td>
<td>75</td>
<td>2.94  -0.10  -1.59  -3.08  -1.39  3.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>950</td>
<td></td>
</tr>
</tbody>
</table>

$^{1}$ The modulus of the FEP-Encapsulated Silicone o-ring is not known. The FEP makes up 50% of the cross sectional area of the o-ring. Because this material has a much higher modulus than the surrounding Silicone, it is expected that the modulus of the composite would be greater than the silicone itself.

$^{2}$ The modulus for polymers is affected by temperature, fabrication methods, and post processing. These values are best guess estimates for comparison only and are not considered to be exact.
Table 3.1.1 lists the o-rings in order from the least amount of measured deflection at the top of the table to the most deflection at the bottom. As expected from the previous data, the hardest o-ring with a Shore-A hardness of 85 and largest expected modulus allows the least amount of deflection. The viton o-ring allows the most deflection but has higher values for the hardness and modulus than the silicone and buna o-rings respectively. This is evidence that these properties of the o-rings do not contribute significantly to the overall deflection between the plates. Considering the stiffness of materials in general is a function of the modulus, it is surprising to see no relationship between the two for this data set. This lack of a correlation between the modulus and stiffness may be the result of the deformations introduced in the o-ring due to the geometry the o-ring resides in. The o-rings are in a square groove on the TAP side and press against a flat surface on the MAP side to provide a seal between the surfaces. As the plates come closer together, the circular cross section of the o-ring conforms to the square geometry of the groove on one side of the plate and relaxes on the opposing side.

Figure 3.1.1 provides evidence that there is a clear contribution to the static stiffness of the load-cell based on the type of o-ring used. Therefore, it is necessary to generate separate calibrated stiffness matrices for each o-ring installed in the load cell. The procedure for the generation of the calibrated stiffness matrix was outlined in section 2.2. Six loading cases were used to generate these matrices for this research: 20 lb, 40 lb, 60 lb, 80 lb, 100 lb, and 120lb along the x-axis.
These loading cases provide the minimum number of equations necessary to determine a stiffness matrix accurate for applied loads $F_x$ and will therefore only have non-zero values in those columns. As will be seen in the data, it was not possible to eliminate a slight offset in the application of the force resulting in a relatively small applied $T_y$, therefore non-zero coefficients also appear in the stiffness matrix for this component.

The voltage data used to generate the $V$ matrix was collected after equilibrium was reached to prevent errors caused by damping. The first stiffness matrix to be determined by applying equation 2.2.7 is shown in Table 3.1.2 and was determined with the o-ring removed.

<table>
<thead>
<tr>
<th>V0</th>
<th>-0.104</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>49.791</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>0.065</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1.741</td>
<td>0</td>
</tr>
<tr>
<td>V2</td>
<td>0.289</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-25.666</td>
<td>0</td>
</tr>
<tr>
<td>V3</td>
<td>-18.304</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17.710</td>
<td>0</td>
</tr>
<tr>
<td>V4</td>
<td>0.370</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-24.981</td>
<td>0</td>
</tr>
<tr>
<td>V5</td>
<td>17.608</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-15.736</td>
<td>0</td>
</tr>
</tbody>
</table>
As expected from the load-cell geometry described in section 2.2, the V3 and V5 values contribute the most to the measured $F_x$ load component. For the $T_y$ column, it would be expected that the magnitude of the V2 and V4 values are approximately half that of the V0 values which is in fact the case. The same method was used to generate the other four stiffness matrices for the load cell with each of the four o-ring types installed.

To quantitatively compare the stiffness contribution of each o-ring, Table 3.1.3 shows the resulting magnitudes of the $F_x$ and $T_y$ columns for the stiffness matrices generated with the different o-rings installed including the matrix generated with no o-ring installed.

Table 3.1.3: Effect of o-ring type on the magnitude of the $F_x$ of the stiffness matrix.

<table>
<thead>
<tr>
<th>O-ring type</th>
<th>Hardness (Shore-A)</th>
<th>Modulus of Elasticity$^{12, 13, 14}$ (psi)</th>
<th>$\sqrt{V_0^2 + V_1^2 + V_2^2 + V_3^2 + V_4^2 + V_5^2}$ (lbs / volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No O-ring</td>
<td>N/A</td>
<td>N/A</td>
<td>25</td>
</tr>
<tr>
<td>Viton</td>
<td>75</td>
<td>950</td>
<td>71</td>
</tr>
<tr>
<td>Silicone</td>
<td>70</td>
<td>740</td>
<td>95</td>
</tr>
<tr>
<td>FEP-Encapsulated Silicone</td>
<td>85</td>
<td>740 (silicone)</td>
<td>183</td>
</tr>
<tr>
<td>Buna</td>
<td>65</td>
<td>430</td>
<td>2208</td>
</tr>
</tbody>
</table>
The previous results suggested that the ranking of the o-rings from higher to lower stiffness contributions was FEP-Encapsulated Silicone, Silicone, Buna, and finally Viton. This data suggests the stiffer o-ring is the Buna by several magnitudes followed by the FEP-Encapsulated Silicone, Silicone, and finally Viton. The results for all three comparisons agree accept for the Buna o-ring. Later results will show that the Buna o-ring is quite different than the others in the damping contribution as well.
3.2 Effect of Damping Constants Generated in Damping Matrix

As described in section 2.3, the damping matrix is of the form,

\[
\begin{bmatrix}
F_x & F_y & F_z & T_x & T_y & T_z \\
\frac{dV}{C_{11}} & . & . & . & . & . \\
\frac{dV}{C_{16}} & . & . & . & . & . \\
\frac{dV}{C_{61}} & . & . & . & . & . \\
\frac{dV}{C_{66}} & . & . & . & . & . \\
\end{bmatrix}
\]

(3.2.1)

where the notation \( \frac{dV}{t} \) will be used to mean \( \frac{d}{dt} (V) \). Similar to the calibrated stiffness matrix discussed in the previous section, non-zero constants will populate the \( F_x \) and \( T_y \) columns while the rest of the matrix will be populated with zeros. If the damping contribution from the o-ring is constant with position and time, the damping matrix values will be independent of the applied loads. However, if the damping is not constant, it will be apparent in the difference between the values generated for each loading case for the same o-ring. This disagreement will also be apparent in the plots of the new system model with the added damping contribution since the constant damping matrix is generated by a least squares fit to the data throughout the measured time interval. Therefore, if the damping varies, there will be points along the damping response curve that will be over or under damped and the effect will be proportional to the difference between the applied value and the true value of the damping constant.
The same six loading cases \( F_x = 20 \text{ lbs}, 40 \text{ lbs}, 60 \text{ lbs}, 80 \text{ lbs}, 100 \text{ lbs}, 120 \text{ lbs} \) were used to generate six damping matrices for each o-ring type using only the data from one loading case for each matrix. It is expected that because the V3 and V5 voltages are the primary contributors to the \( F_x \) voltage matrix column for a force in the x-axis direction, the \( \text{dV3} \) and \( \text{dV5} \) will be the primary contributors to the \( F_x \) column of the damping matrix for a force in the x-axis direction. This is important to verify since if certain voltage outputs do not significantly contribute to the damping effect, i.e. they are primarily noise, including them in the analysis of the variation of damping constants with time may contribute to false conclusions of the model being considered. Therefore, we will first look at the individual contributions to the damping matrix to see if some of the terms can be isolated for comparison.

The first loading case to be modeled was the 120 lb case with the Buna o-ring installed in the load cell. A damping matrix was calculated with this data and entered into Equation 2.3.1. Figure 3.2.1 shows the result of applying the damping matrix to the model for a static load of 120 lb on the x-axis. The stiffness contribution is plotted as well to compare the accuracy of the two models. The initial over damped response followed by the under damped response is a clear indication that the damping is not constant.
The next several figures show the result of applying the calibrated damping matrix to the 120 lb loading data (Equation 2.3.1) with the exception of removing the effects of certain voltage outputs by zeroing the respective rows corresponding to the individual output voltages.

There are three outcomes of interest to consider. The first is if a given row is not a contributor to the damping response, one would observe little or no difference in the damping contribution as compared to the original matrix. The second is if the given row is a significant contributor to the damping response, one would observe a damping plus stiffness response curve that is closer to the applied force curve.

Figure 3.2.1: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis and the Buna O-ring installed using calibrated stiffness and damping matrices.
The final outcome of interest would be if the stiffness and damping response becomes unstable as a result of zeroing the respective column. An explanation for this occurrence is that the respective row may be acting as a balance to another contributing or non-contributing row that once removed, no longer stabilizes the damping response. Figure 3.2.2 shows a reduced timeline of the plot in Figure 3.2.1 for comparison of these effects with later plots.

<table>
<thead>
<tr>
<th>Stiffness Contribution</th>
<th>Stiffness and Damping</th>
<th>Applied Load</th>
</tr>
</thead>
</table>

**Figure 3.2.2**: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis and the Buna O-ring installed using calibrated stiffness and damping matrices from 0 to 10 seconds.
The first voltage output to be removed is the dV0 output. The calculated x-axis force component is plotted in Figure 3.2.3 with the dV0 row zeroed shows a better response than the original plot in Figure 3.2.2. This is a strong indication that not only is row dV0 not a contributor to the damping response but also a contributor to the error. Figures 3.2.4 and 3.2.5 plot the calculated stiffness and damping response with the dV1 and dV2 rows zeroed respectively. In each case the damping contribution becomes unstable which is a sign that these two output voltages may or may not be significant contributors. Since we already know that dV0 is not a contributor to the damping effect, we can plot the response of zeroing the dV0, dV1, and dV2 rows from the matrix to determine if dV1 and dV2 are mutual stabilizers or if they contribute to the damping.
Zeroing the dV1 and dV2 rows, as shown in Figure 3.2.6, causes more of an over damping response in the beginning and a more unstable response overall. However, the general trend in the damping response is similar to the original plot in Figure 3.2.2, which suggests that they do not contribute significantly to the damping effect.

Figure 3.2.4: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with row dV1 zeroed.
Figure 3.2.5: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with row dV2 zeroed.

Figure 3.2.6: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with rows dV0, dV1, and dV2 zeroed.
Figure 3.2.7: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with row dV3 zeroed.

Figure 3.2.7 plots the calculated stiffness and damping response of after zeroing the dV3 row in the damping matrix. The overall damping response is much closer to the response of the system to stiffness alone. This is a strong indication that the dV3 row is a significant contributor to the damping effect. Figure 3.2.8 plots the calculated stiffness and damping contribution of the dV3 row alone. This curve verifies the conclusion that dV3 is a significant contributor. Zeroing row dV4, as shown in Figure 3.2.9, causes the damping to become unstable but generally follow the stiffness response. This is an indication that the dV4 row may simply be another stabilizing row with or without a significant contribution. Figure 3.2.10 plots the effect of zeroing all rows except dV3 and dV5. Removing the dV4 row stabilizes the response and closely matches a stabilized response from Figure 3.2.6, which is the plot of the response of removing dV0, dV1, and dV2.
This is evidence that the dV1, dV2 and dV3 rows simply stabilize each other and have no contribution to the damping. Zeroing the dV5 row, as shown in Figure 3.2.11 shows a response that closely matches the stiffness response. This is a strong indication that this row contributes significantly to the damping as well. Figure 3.2.12 shows the damping response applying only the terms of the dV5 row alone. This response does not match up as closely with the original plot in Figure 3.2.1 as the dV3 row contribution but the similarity is apparent. Also, looking back at Figure 3.2.9, we can see that the response of the dV3 and dV5 rows is nearly identical to the original response with all the values in the matrix. Therefore, the primary contributing rows to the damping response for loads applied in the x-axis direction are confirmed to be dV3 and dV5. This response was the same for the damping matrices generated with the other o-rings installed as well, although to these graphs are not presented in this section for brevity.
Figure 3.2.8: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with all rows except dV3 zeroed.

Figure 3.2.9: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with row dV4 zeroed.
Figure 3.2.10: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with rows dV1, dV2, dV3, and dV4 zeroed.

Figure 3.2.11: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with row dV5 zeroed.
Figure 3.2.12: Calculated stiffness and damping response for load cell with 120 lb applied load along the x-axis using calibrated stiffness and damping matrices with all rows except dV5 zeroed.
3.3 Effect of Applied Static Load and O-ring Type on Damping Constants

The results of the previous section have demonstrated that the damping effect due to the Buna O-ring is not constant in time. In order to evaluate the variance of the damping constants for a single applied loading case, multiple damping matrices were calculated over 60 data points for a total of 15 seconds of data for each matrix. The first matrix was calculated over the interval \(0 < t < 15\) seconds, the second matrix over the interval \(0.25 < t < 15.25\) and so on until equilibrium was reached (see Table 1.3.2) for each loading case and o-ring type. The magnitude of the \(F_x\) column was then calculated for comparison. Only the \(dV_3\) and \(dV_5\) terms were included in the magnitude calculation to avoid unexpected contributions of the other voltages.

Taking a closer look at Equation 2.2.3, we can see that as \(|F - V_k|\) approaches zero, the \(dV\) term also approaches zero making the second part of the left hand side very small. Theoretically, this is balanced by the inverse of the \(dV\) terms becoming very large in the first part of the left hand side. However, there are limitations in the resolution of the data that cause inaccuracies in the calculation of the damping matrix near the equilibrium point. Figures 3.3.1 and 3.3.2 show the \(V_5\) voltage output and the \(F_x\) stiffness response respectively for the load cell long after equilibrium is reached.
Figure 3.3.1: V5 Voltage output after equilibrium is reached for 120 lb load with Buna o-ring installed.

Figure 3.3.2: Calculated response of $F_x$ component after equilibrium is reached for 120 lb load with Buna o-ring installed considering only the stiffness matrix.
The overall noise in the voltage data as a result of the resolution of the system is similar to the noise in the V3 voltage output, shown in Figure 3.3.1. Presumably, this noise causes the variance in the stiffness calculation, shown in Figure 3.3.2. These are typical values for load cells of this type. The Delta IP68-10m is rated to have an allowable error 1.25% of FS, which corresponds to 1.88 lbs. These limitations in the resolution of the voltage outputs, errors in the stiffness matrix, errors in loading, and other unforeseen contributions cause the data collected near the equilibrium point to be unreliable in calculating an accurate derivative of the voltage matrix. Figure 3.3.3 plots the magnitude of the $F_x$ column (see Table 3.1.3) of the multiple damping matrices calculated with the 120 lb applied loading data.

Figure 3.3.3: Variance in the magnitude of the $F_x$ column of the damping matrix calculated with the 120 lb applied load data and the Buna o-ring installed.
The peak that is seen to occur near the 15 second mark in Figure 3.3.3 is inherent to the Buna o-ring and not observed for the other o-ring materials. This same peak is apparent in Figures 3.3.4 and 3.3.5, which are plots of the magnitudes of the $F_x$ columns of the multiple damping matrices calculated with the applied 100 lb and 80 lb loading data respectively. This peak becomes less apparent in the damping matrix calculated with the 40 lb data as shown in Figure 3.3.6. The magnitudes of the $F_x$ columns of the Buna o-ring matrices all have a trend that approaches zero with a range or bandwidth near 18k lb-s/V. All of the other o-rings have increasing trends that vary in range or bandwidth from 20k lb-s/V to 250k lb-s/V. The 120lb loading case for the FEP-Encapsulated o-ring, shown in Figure 3.3.7, is a representative sample of the other o-ring plots.

![Figure 3.3.4: Variance in the magnitude of the $F_x$ column of the damping matrix calculated with the 100 lb applied load data and the Buna o-ring installed.](image-url)
Figure 3.3.5: Variance in the magnitude of the $F_x$ column of the damping matrix calculated with the 80 lb applied load data and the Buna o-ring installed.

Figure 3.3.6: Variance in the magnitude of the $F_x$ column of the damping matrix calculated with the 40 lb applied load data and the Buna o-ring installed.
The variance of the magnitude of the $F_x$ column for the FEP-Encapsulated Silicone of 50k to 350k lb-s/V is ten times greater than the variance of the magnitude of the $F_x$ column for the Buna o-ring. This large difference in the bandwidth of the magnitudes is apparent in all the applied load cases for this o-ring as well as all the loading cases for the Silicone and Viton o-rings. The Silicone and Viton o-rings have bandwidths of 10k to 70k lb-s/V and 2k to 30k lb-s/V respectively. With the best-fit constant effect of the least squares method, it would be expected to see the damping constants be higher for large bandwidths than for lower bandwidths.
Hence, the FEP-Encapsulated Silicone o-ring would be expected to have the largest constants followed by the Silicone, Viton, and Buna o-rings respectively. Figures 3.3.8 and 3.3.9 show the values of the dV3 and dV5 damping constants in the Fx column of the damping matrix. In Figure 3.3.8, the value of the dV3 damping constant for the Viton o-ring is 3 lb-s/V and is too small show up on the plot. The damping constant for the 20lb loading case of the Buna o-ring was very high at 16000 lb-s/V which skewed the data, so the 20lb loading cases for all the o-rings were left out of the plots for clarity.

![Figure 3.3.8: Value of dV3 damping constant in Fx column of damping matrix for each o-ring material and loading case.](image-url)

Figure 3.3.8: Value of dV3 damping constant in Fx column of damping matrix for each o-ring material and loading case.
Given the previous assumption relating the bandwidths of the multiple matrices to the least squares prediction of the damping constants, the Buna values are surprisingly large compared to the others. The Buna values also vary much more than the others with a difference of over 3000 lb-s/V between the 80lb and 40lb cases. The cause of the variance in the magnitudes of the damping matrices is most likely attributed to the material properties and deformations of the o-rings as the plates move relative to one another. The linearity of the magnitude and lower variance of the calculated constants for all but the Buna o-ring suggests there is a more consistent deformation of those materials as the plates move relative to one another.

Figure 3.3.9: Value of $dV_5$ damping constant in $F_x$ column of damping matrix for each o-ring material and loading case.
Considering the least squares method of calculating the best fit constant for the damping values, it is expected that assuming constant damping values will produce more accurate results in the model for the other o-rings compared to the Buna.
3.4 Effect of Applied Static Load and O-ring Type on the Accuracy of the Damping Matrix

Accuracy is typically reported as a percentage of the full scale (%FS) loading for the axis being considered. In this work, the stiffness matrix for each of the load cells was calculated with only six applied loads. Therefore, the error generated from the stiffness contribution is greater than if more loading cases were used, as is typically done in practice. However, the purpose of this research is to study the relative accuracy between the stiffness and stiffness with damping models. The same stiffness matrix used in Equation 2.2.3 will be used to calculate the stiffness contribution used for the comparison. Therefore, the damping contribution should not be affected by errors in the stiffness matrix.

Figure 3.4.1 shows the response of the stiffness model and stiffness with damping model for a 20 lb load applied in the x-axis direction using a damping matrix calculated from the 120lb loading data. By inspection, the model with the damping contribution is more accurate than the model with the stiffness contribution alone. Figure 3.4.2 shows a plot of the %FS error for the same case. The maximum allowed load in the x-axis direction for this load cell is 150 lb as shown in Table 1.3.1. As expected, the error for the stiffness with damping model is less than the error for the stiffness model alone. The initial damping response is good with a decreased error of more than 2%FS and quickly falling to a difference near 0.5%FS as the o-ring deforms and under damping becomes apparent. Figure 3.4.3 and 3.4.4 shows similar plots for the Silicon o-ring.
Figure 3.4.1: Calculated stiffness and damping response for load cell with the Buna o-ring installed and with 20 lb applied load along the x-axis using the damping Matrix calculated with the 120 lb applied load data.

Figure 3.4.2: Percent FS error for calculated stiffness and damping response for load cell with the Buna o-ring installed and with 20 lb applied load along the x-axis using the damping Matrix calculated with the 120 lb applied load data.
Figure 3.4.3: Calculated stiffness and damping response with the silicon o-ring installed and with 20 lb applied load along the x-axis using the damping Matrix calculated with the 120 lb applied load data.

Figure 3.4.4: Percent FS error for calculated stiffness and damping response for load cell with the silicon o-ring installed and with 20 lb applied load along the x-axis using the damping Matrix calculated with the 120 lb applied load data.
The error is much less for this case overall as compared to the data for the Buna o-ring. Taking a look at higher loading cases, Figure 3.4.5 shows the error from Figure 3.3.1, which is the 120 lb applied load case for the Buna o-ring. Although the response is unstable and the substantial overall error would be unacceptable in the practice, the improvement in the accuracy of the model with the damping contribution is apparent. The difference in the errors starts near 12%FS and gradually falls near 4%FS with the damping model remaining more accurate.

Figure 3.4.5: Percent FS error for calculated stiffness and damping response for load cell with the Buna o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
For the Buna o-ring, the trend of large variations in the %FS errors continues for the damping matrices calculated with all loads. This is apparent in Figures 3.4.6, 3.4.7, and 3.4.8. Each case has a damping matrix calculated from the 40lb, 80lb, and 120lb loading data respectively. The 80 lb data was then used to calculate the response of the load cell with the stiffness and stiffness with damping models. Notice how the initial damping and stiffness contribution vary more with the lower loading used to calculate the damping matrix.

![Graph showing percent FS error](image)

**Figure 3.4.6:** Percent FS error for calculated stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.
Figure 3.4.7: Percent FS error for calculated stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.

Figure 3.4.8: Percent FS error for calculated stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
The large initial over damping effect of the 40lb damping matrix may be due to the peaks noticed in the magnitudes of the $F_x$ columns in section 3.3. Due to the large variations and instability of the damping contribution the Buna o-ring exhibits in all loading cases, there does not appear to be any significant evidence that shows which loading case or cases would be optimal in calculating the damping matrix. Furthermore, the low frequency oscillations in the damping and stiffness response may be attributed to the o-ring. The weights are hung on a hanger that is nearly three feet long with the weights placed at the distal end from the load cell. The weights are steadied by hand and some cycling of no more than a tenth of an inch is present on the distal end. Looking back at the stiffness response, the calculated load varies by up to 5 lbs. It is unlikely that fluctuations in the steadied hanger would have such a dramatic effect considering the small angle and maximum load of 120 lbs. Considering that the other o-rings do not exhibit this response, the cyclic behavior is likely attributed to the Buna o-ring and not the loading. Furthermore, this cyclic behavior of the damping contribution is not likely due to the o-ring slipping between the plates. If slipping were to occur, the static friction would hold the o-ring in place and the body would momentarily become stiffer. This would show up as a valley in the damping response and a flat spot in the stiffness contribution as the value of the derivative function decreased and the voltages stabilized. This behavior would be followed by an over damped response and a spike in the stiffness response as both the values and the time derivative of the output voltages and would suddenly increase as the result of the o-ring slipping once the friction was overcome.
Making the same comparison with the silicon o-ring we have more accurate and stable results as shown in Figures 3.4.9, 3.4.10, and 3.4.11 without the large fluctuations in the calculated force.

Figure 3.4.9: Percent FS error for calculated stiffness and damping response for load cell with the silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.
Figure 3.4.10: Percent FS error for calculated stiffness and damping response for load cell with the silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 90 lb applied load data.

Figure 3.4.11: Percent FS error for calculated stiffness and damping response for load cell with the silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
Overall, each of the three matrices used in Figures 3.4.9 – 3.4.11 provides more accurate calculations of the predicted load with the 80lb matrix being slightly better with smaller overall error. Figure 3.4.12 shows the response of the 120lb matrix with a 120lb applied load. The initial response indicates the slipping as described earlier with the sudden peaks and valleys of the damping contribution but there do not appear to be any flat spots in the stiffness curve. This may be attributed to the stiffness matrix containing all the V0 through V5 stiffness contributors and the damping matrix only containing the dV3 and dV5 contributors. Figure 3.4.13 shows the plot of the damping response using all the calibrated values in the damping matrix. There is an obvious stabilization that occurs with increased accuracy and less fluctuation of the predicted load.
This is a strong indication that isolating the dV3 and dV5 terms will not produce the best results. Both the Viton and FEP-Encapsulated Silicone o-ring had similar accuracies and stability as the Silicone o-ring, including more stable and accurate load predictions when all the damping constants were used. Unlike the Buna o-ring, the other three o-rings showed lower noise and less overall fluctuations in the predicted load with the damping matrices generated with the higher loading data. This makes sense considering the linear damping constant trend shown in section 3.2.

Figure 3.4.12: Stiffness and damping response for load cell with the silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
Figure 3.4.13: Stiffness and damping response for load cell with the silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data using all voltage time derivative outputs.

All of the loading cases shown so far have been applied as close to the origin as possible.

Figure 3.4.14 and 3.4.15 show the results of the stiffness and stiffness with damping model applied to the load cell with the Buna and Viton o-rings respectively. The damping matrices for each case were generated from the 120lb loading data for that type of o-ring. The overall response of the system is unstable but hovers around the applied load.
This suggests that the damping contributions for the cases above are only valid for loads applied near the origin. However, it may also suggest that additional loading cases need to be considered in the calculation of the damping constants to stabilize the damping contribution. Figures 3.4.16 and 3.4.17 are plots of the stiffness response to loading in the x-axis direction 4 inches from the origin using a complete and incomplete data set respectively to generate the stiffness matrix.

Figure 3.4.14: Stiffness and damping response of load cell with Buna o-ring and 100 lb applied load along the x-axis using full Damping matrix calculated with the 120 lb applied load data.
Figure 3.4.15: Stiffness and damping response of load cell with Viton o-ring and 100 lb applied load along the x-axis using full Damping matrix calculated with the 120 lb applied load data.

Figure 3.4.16: Stiffness response of load cell with Buna o-ring and 100 lb applied load along the x-axis using complete stiffness matrix.
The stiffness matrix for Figure 3.4.16 is calculated using the six voltage responses from the equilibrium state of the 20 lb, 40 lb 80 lb, 100 lb and 120 lb loading cases with an additional row added for the 100 lb loading case along the x-axis, applied 4 inches from the origin (i.e. a combined $F_x$ and $T_y$ loading case). Although the predicted load is inaccurate, it is stable and reaches a steady state. The stiffness matrix used in Figure 3.4.17 was generated from the original six loading cases only. Although the response is more accurate, the response is unstable and does not reach a steady state. This is an indication that the damping matrices may experience the same phenomena as the stiffness matrices and stabilize with additional loading cases.
Chapter 4

Conclusions

The experimental work presented in this thesis provides general guidelines and calibration procedures to accurately model and improve the response time of submersible 6-axis load-cells based on multiple beam configurations sealed with compressible o-rings. This objective is achieved by adding a damping contribution to the existing stiffness model through an appropriate time derivative of the output voltages.

The data acquisition rate of 4Hz proved to be sufficient to calculate the time derivative of the voltage outputs while combining this with an additional running average over four samples of the time derivative proved to be sufficient to calculate the force response of the load cell. The typical maximum data acquisition rates for load cells available today are in the range of 4-10Hz depending on application and hardware [1,4]. Refinement of the sample rate was not done in this research beyond the determination of a sufficient rate to calculate the derivative function. However, the 4Hz rate with the additional averaging of the derivative function was shown to generate slightly more noise than the stiffness contribution alone, which suggests that it is very close to the optimal data acquisition rate.
Each o-ring was shown to have significant contributions to the overall stiffness of the system with large variations in the magnitudes of the $F_x$ columns of the different stiffness matrices generated from the six loading cases. The hardness of the o-rings was found to have no contribution to the stiffness or damping properties of the o-rings. Each stiffness matrix was determined with the minimum six loading cases due to time constraints, whereas in standard practice, many loading cases are used to negate the effects of manufacturing errors in the transducer and mounting errors in the strain gauges. The negative effects of using minimal loading cases was apparent in the application of the stiffness matrix generated for the load cell incorporating a Buna o-ring.

From prior testing done by myself and other ATI staff, the maximum %FS errors typically seen in this type of load cell produced by ATI incorporating a Buna o-ring (US 150-600 calibration) and a standard stiffness matrix (without considering damping effects) is in the range of 3%FS. The plots generated with the limited loading cases in this thesis produced errors much greater than 3%FS, which suggests the magnitudes of the constants in the $F_x$ columns of the stiffness matrices would be improved by more accurate generation of the stiffness matrix. The effects of this additional accuracy on the generation of the damping constants are unknown, however one expects similar results.
Each o-ring was shown to have significant damping contributions with large and small variations in the magnitudes of the $F_x$ columns of the different damping matrices generated from the six loading cases for the different o-rings. The model of the system including damping was shown to increase the overall accuracy of the predicted force for static loads on the Delta IP68 model force/torque load cell with accuracies increasing by 0.05%FS up to more than 10%FS in some cases. The dV3 and dV5 damping constants were shown to be the primary contributors to the damping for forces along the x-axis. There was also evidence of the remaining constants acting as signal conditioners or noise filters, which increased the accuracy and decreased the noise generated by the damping contribution for loads applied close to the origin. A stiffness response was illustrated in figures 3.4.14 and 3.4.15 with a complete and an incomplete stiffness matrix respectively being used. The response showed that using the complete matrix caused a significantly more stable response of the stiffness matrix suggesting that the same phenomena may occur with the damping matrices if multiple loads are used to in the calculations. The damping matrices were also shown to be much less accurate for loads farther from the origin due to the fact that all six loading cases used to generate the matrices were close to the origin. This effectively decreased the accuracy of the coefficients influenced by the $T_y$ component of the loading. Multiple load calculations may improve this response as well.
A comparison of the magnitudes of the $F_x$ columns of the damping matrix was done in an attempt to define the stability of the damping contribution through the variation of the magnitudes of the damping constants calculated due to different loadings. The Buna o-ring showed the largest variance of 2000 lb-s/V whereas the variations in the magnitudes for the other o-rings were on the order of 100 lb-s/V, 300 lb-s/V, and 500 lb-s/V for the Viton, FEP-Encapsulated Silicone, and Silicone o-rings respectively.

The much larger variation in the data from the load cell with the Buna o-ring was proven to have negative consequences on the accuracy of the predicted forces with the damping contribution as well as the accuracy of the stiffness matrix. This suggests that preliminary testing of this type can be done during the design phase of a similar load cell to eliminate the materials that have these effects. The remaining three o-rings proved to be modeled well by applying damping effects, resulting in improved accuracy and response time for all static loading and unloading cases. The performance of all three o-rings was similar which suggests that the least squares approximation method of calculating the damping matrix can be applied with confidence for certain these choices of o-ring materials.
Future research should include the optimization of the sample rate for different loading cases to find potential relationships between the type of loading, o-ring material type, and optimal data rate. Dynamic loading should also be done to test the response of the contribution of the damping matrix to varying loads. This could first be tested by loading along a single axis and allowing the system to reach equilibrium and maximum deformation of the o-ring, then apply an immediate opposing load and compare the response to the stiffness contribution.

Multiple loading test cases should be used in an attempt to generate a more accurate calibrated damping matrix that would also compensate for torques or bending moments more accurately. This particular study will inevitably raise the question of the contribution of cross talk and modeling to minimize its effects on the derivative function. It has already been shown that adding a single loading case to the stiffness matrix increases its stability. To streamline the data collection for this concept, an automatic data acquisition protocol would have to be developed that would define when and when not to include data in the least squares calculation.
This would most likely be done with the help of an additional input during data acquisition that would define the beginning point of the data collection, such as a contact switch to send a signal that the applied loads are free from support and 100% of the load is on the load cell. The stopping point can then be limited by some defined percent difference in the derivative function with respect to the applied load.

The modulus of polymers used to make o-rings is greatly affected by temperature. Thermal cycling that causes the transducer body expansion and contraction is currently successfully compensated for. Studying how thermal cycling can affect the stiffness and damping effects of the o-ring should certainly be studied as well. The lack of a relationship between the stiffness and the modulus is something that should be explored as well. The geometry the o-ring resides in as well as the relative deflection between the plates are likely to play key roles in the stiffness contribution.
References


Appendices
Figure A.1: Stiffness and damping response for load cell with the viton o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.

Figure A.2: Stiffness and damping response for load cell with the viton o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
Figure A.3: Stiffness and damping response for load cell with the viton o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.

Figure A.4: Stiffness and damping response for load cell with the viton o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.
Figure A.5: Stiffness and damping response for load cell with the viton o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.

Figure A.6: Stiffness and damping response for load cell with the viton o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.
Figure A.7: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.

Figure A.8: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
Figure A.9: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.

Figure A.10: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.
Figure A.11: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.

Figure A.12: Stiffness and damping response for load cell with the FEP-Encapsulated Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.
Figure A.13: Stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.

Figure A.14: Stiffness and damping response for load cell with the Buna o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.
Figure A.15: Stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.

Figure A.16: Stiffness and damping response for load cell with the Buna o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.
Figure A.17: Stiffness and damping response for load cell with the Buna o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.

Figure A.18: Stiffness and damping response for load cell with the Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 120 lb applied load data.
Figure A.19: Stiffness and damping response for load cell with the Silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.

Figure A.20: Stiffness and damping response for load cell with the Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 80 lb applied load data.
Figure A.21: Stiffness and damping response for load cell with the Silicone o-ring installed and with 120 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.

Figure A.22: Stiffness and damping response for load cell with the Silicone o-ring installed and with 80 lb applied load along the x-axis using the damping matrix calculated with the 40 lb applied load data.