Experimental Testing of LIGO Vibration Isolation System

by

Alexander G Krull

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

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Signature of Author .................................................................

Department of Mechanical Engineering

May 11, 2007

Certified by .................................................................

Nergis Mavalvala
Assistant Professor
Thesis Supervisor

Accepted by .................................................................

John H. Lienhard V
Undergraduate Officer, Department of Mechanical Engineering
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Abstract

The LIGO (Laser Interferometer Gravitational-wave Observatory) project is designed to detect gravitational waves using precision interferometry. The detection from astrophysical sources has the potential to test Einstein's Theory of General Relativity, and additionally open a new window into the universe and its origin. The Initial LIGO detectors are currently operating at a strain sensitivity of $10^{-21}$ Hz, or equivalently $10^{18} m/\sqrt{Hz}$ at 100 Hz. In order to attain improved sensitivity required for guaranteed detection of astrophysical sources, e.g. coalescing neutron star binaries and black holes, pulsars, and supernovae collapses, improvements of the strain sensitivity must be achieved. Next generation detectors such as Advanced LIGO are under development, which aims to improve the sensitivity by more than a factor of 10 at all frequencies, compared to initial LIGO. This improvement in sensitivity will be achieved in part by improved seismic isolation one component of which is an active vibration isolation platform.

Currently, research and development is being conducted at MIT on a prototype of this vibration isolation system. The work described in this thesis focuses on the Internal Seismic Isolation (ISI) system under development for Advanced LIGO. This system consists of a three-stage in-vacuum seismic isolation system which is supported by an external hydraulic actuation stage known as the Hydraulic External Pre-Isolation (HEPI) stages of the active vibration control system. HEPI uses forces generated by hydraulic
pressure to cancel low frequency seismic noise, primarily due to forces from ground vibration. The ISI is an actively controlled platform, in which each stage is supported by three maraging steel blade springs. The vibration is sensed in six degrees of freedom and reduced by applying forces through a control feedback loop.

In order for the feedback loop to function properly, it is important to know and be able to predict the position of the ISI stages to within a few thousandths of an inch. Since the load being applied to the spring blades is known, the compliance of each spring along with various shim thicknesses will determine the final position of the stages.

Although compliance is a material and geometric property, and should remain constant from spring to spring, due to imperfections of the fabrication process and variation in the material properties, small variations in the long and short spring compliance value were detected using a Spring Tester. The blades were designed based on their resonant frequencies and the load which they would be supporting – more specifically, their geometry (length, width, and thickness) were defined such that the load each supported brought them to a 1/3 of their failure stress.

For my undergraduate thesis, I determined the compliance of multiple long and short springs was determined using a specially designed apparatus – the "Spring Tester." Ideally, three blade springs of identical compliance should be used to eliminate system imbalance, but to variation during fabrication may be difficult to achieve.

Using the Spring Tester the mean values for each set of long and short spring linear compliance data were found to be \(0.729 \pm 0.008\) mils/lb and \(0.670 \pm 0.027\) mils/lb, respectively, while the means for the long and short angular compliance data were \(0.078 \pm 0.001\) mrad/lb and \(0.089 \pm 0.003\) mrad/lb, respectively.

Thesis Advisor: Nergis Mavalvala
Title: Assistant Physics Professor
Acknowledgements

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I would also like to thank Myron McInnis and Ken Mason for their instruction and assistance with anything mechanical during the setup and operation of my thesis experiments. Much thanks also goes to my thesis advisor Dr. Nergis Mavalvala for her dedication to the successful completion of my report. The sense of urgency she instilled in me as the thesis deadline approached was a major driving factor in the completion of this thesis.

Finally, I would like to thank all the individuals in the LASTI laboratory who provided me with their support with regard to the experimental testing process. Fabrice Matichard and Ricardo DeSalvo were valuable in helping me to understand the functionality of the Spring Tester, and an effective testing.
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Chapter 1

Introduction

This introduction provides a look into the nature of gravitational waves and the methods employed by LIGO to detect them. It then describes the goals of this thesis and their relevance to the improvement of LIGO as a whole.

Beyond the introduction, Chapter 2 describes the subsystems which make up LIGO's Internal Seismic Isolation (ISI) system. Chapter 3 discusses both the mechanical aspects of the ISI, and details of the Spring Tester experiment. Chapter 4 sets forth and analyzes the experimental results. Chapter 5 provides insight into the future work on the ISI and potential improvement to the Spring Tester experiment.

1.1 Gravitational Waves

In 1916, Einstein predicted the existence of gravitational waves (GWs) in his Theory of General Relativity [1]. The theory broke down conventional notions of space and time, claiming the cause of gravitational effects to be the curvature of space due to massive objects. According to the theory, the greater an object’s mass, the greater the curvature in the fabric of space-time it would cause. Conceptually, these curvatures, or depressions, in space-time should cause less massive objects to orbit, or “fall” into, the more massive bodies, explaining the orbits we observe in the universe today.

GWs are ripples of the space-time fabric, caused by accelerations of massive objects [2]. Einstein’s theory states that like electromagnetic radiation, GWs travel at the speed of light and behave in an oscillatory nature. Unlike electromagnetic radiation, GWs pass through most matter undisturbed, and are emitted from accelerating objects or systems of objects, causing fluctuations in space-time, compressing an object in one axis while simultaneously stretching it in the orthogonal direction (Figure 1.1). Therefore, if a GW were to come in contact with the Earth, it would stretch and compress everything in its path in an oscillatory nature until it completely passed. The wave characteristics of
GWs depend on the energy of the body from which it is emitted. The larger the acceleration of an object, the greater the energy of the emitted gravitational wave, and the greater its amplitude.

The GWs emitted from objects with small masses relative to the sun, for instance, are impossible to detect with current measurement techniques. The strongest GWs will therefore be emitted by high energy cosmic events such as coalescing neutron stars or black holes, pulsars, and collapsing supernovae [3]. Theoretical estimates predict that GWs should arrive at the earth with a strain of $10^{-19}$ – roughly one thousand times smaller than the diameter of a proton, and one thousand billion times smaller than the diameter of a human hair.

1.2 LIGO Overview

The Laser Interferometer Gravitational-wave Observatory (LIGO) is a joint research project, funded by the National Science Foundation, between researchers at MIT and Caltech [3]. The goal of LIGO is to directly detect GWs. LIGO uses laser interferometry, an extremely accurate and precise technique for measuring small distances, in the attempt to detect GWs. Three laser interferometers, that function based on principles of the Michelson interferometer (Figure 1.2), have been constructed in Livingston, Louisiana and in Hanford, Washington (Figure 1.3). The two observatories are separated by 3,002 km – the approximated predicted distance traveled by a GW in ten-thousandths of a second. Detection by LIGO’s three interferometers to within one ten-thousandth of a second offset would confirm the passing of a GW.
1.2.1 LIGO Gravitational Wave Detection

LIGO uses light from a high-powered laser to detect GWs. The light is passed through a semi-transparent mirror, known as a beamsplitter, where it is separated into waveforms of equal power, phase, and frequency and redirected down two precisely measured four-kilometer arms, oriented perpendicular to one another [4]. The optics are kept under vacuum conditions in order to isolate them from noise sources such as air pressure or sound vibration. The light beams reflect off mirrors, polished to extremely high precisions, at the ends of each arm, and travel back toward the beamsplitter where they are recombined. A photodetector registers the relative phase difference of the two beams.

When the light in each arm interferes the resultant wave characteristics can be determined by superposition. The superimposed image of two interacting waves depends on the frequency, amplitude, and relative phase of the two light waves. Constructive
interference occurs when the crest of one or more waves are aligned resulting in a wave with even greater amplitude. Destructive interference occurs when the crest of one wave meets the trough of another [2]. The effects of constructive and destructive interference are illustrated in Figure 1.4 below.

![Figure 1.4: Constructive interference (left); Deconstructive Interference (right)](image)

LIGO is designed such that without any disturbances, the two laser beams should recombine out of phase, and an interference pattern of total deconstructive interference should be registered by the photodetector. In the case that a gravitational wave passes through the interferometers, the arm lengths would be affected by fluctuations in the curvature of space-time, and one of the four-kilometer arms would compress while the other stretched in an oscillatory nature until the gravitational wave completely passed [2]. As the length of each of the interferometer's arms change, so does the relative phase difference of the two recombined beams.

### 1.3.2 LIGO Seismic Noise Sensitivity

Due to the extraordinary sensitivity necessary for the detection of GWs, even seemingly insignificant sources of external noise have the potential to disrupt the measurement process. For LIGO to reliably detect GWs, any noise with the potential to disrupt the measurement system must be removed [5]. This means that the mirrors responsible for deflecting the laser beam should be quiet enough to detect GWs, i.e. the mirrors should not move more than the GW signal. LIGO uses a combination of cancellation and filtration techniques in order to reduce seismic noise.
Seismic noise can be caused by a variety or sources, including ground vibration generated from events such as earthquakes, volcanoes, wind storms, and tidal motion, or noise from human activity such as vehicle traffic or other major city disturbances [4]. In Livingston for instance, human logging activity produces significant seismic noise which must be damped out by LIGO’s seismic isolation system.

Initial LIGO, is currently operating at a strain sensitivity of $10^{-21}$ Hz, or $10^{18}$ m/$\sqrt{\text{Hz}}$, at 100 Hz. Currently, an improved system, known as Advanced LIGO [6], is under development, which aims to improve the sensitivity by more than a factor of 10 at all frequencies, compared with initial LIGO.

The changes involved to achieve the increased sensitivity proposed for Advanced LIGO involve significant improvement and replacement of many aspects of the system. The increased sensitivity of the Advanced LIGO system is significant in that it will allow scientists to gather more data in less time, increasing the potential for significant discovery.

1.4 Thesis Motivation

The work in this thesis focuses on the seismic isolation system for Advanced LIGO. Advanced LIGO will use three stages of seismic isolation. The first two stages will focus on the reduction of low frequency noise using active vibration control, while the third stage will use passive filtering to reduce high frequency noise.

LIGO Advanced System Test Interferometer (LASTI) is a facility located at MIT. LASTI is equipped with full sized prototypes of the Advanced LIGO system, which allows for system testing and debugging before final installation at the Hanford and Livingston observatories [8]. LASTI focuses on testing of mechanical structures, electronics, and control methods.

Advanced LIGO uses three levels of isolation in order to achieve successful noise filtration [9]. The Hydraulic-External Pre-Isolation (HEPI) system is responsible for low frequency control and is external to the vacuum. A quadruple pendulum system provides passive isolation above a few hertz [5]. A three-stage in-vacuum vibration isolation platform, known as the Internal Seismic Isolation (ISI) system, is designed to give a
factor of 1000 attenuation at 10 Hz. This thesis focuses on the ISI, which utilizes six maraging steel blade springs, supporting two stages, to achieve passive isolation and compliance.

The compliance of the maraging steel springs will determine various geometric spring mount parameters (Figure 1.5) and the stainless steel shim size, which will determine each spring’s deflection and final position of the ISI stages upon which the interferometer mirrors are mounted.

Material imperfections during fabrication can induce slight variation in the compliance of each spring blade. In this thesis, the compliance of LIGO’s long and short springs was determined. In addition, the precision with which a Spring Tester measures the compliance of the blade springs was quantified in order to assess the quality of the results.
Chapter 2
Internal Seismic Isolation for Advanced LIGO

The Internal Seismic Isolation (ISI) system (Figure 2.1), under development for Advanced LIGO, consists of a three-stage in-vacuum active seismic isolation system that is supported by an external hydraulic actuation stage – the Hydraulic-External-Pre-Isolation (HEPI) system. The entire ISI system for Advanced LIGO is designed to fit into the existing LIGO vacuum system and mate to the existing HEPI support structures. Active seismic isolation is a control method aimed at reducing undesired motion of the approximately 1800 lb payload, whose bottom stage suspends the LIGO test masses (interferometer mirrors) in a quadruple pendulum configuration [6].

![Figure 2.1: ISI fully assembled at the LASTI facility](image)

Three long and three short triangular blade springs, secured by steel shoulder screws provide vertical system compliance and support the ISI stages 1 and 2, respectively (Figure 2.2) [9]. Previous LIGO blade springs were machined with a radius so that when fully loaded the curvature was eliminated from the spring's profile. Based
on an initial cost analysis, the springs were redesigned "flat," so that they became curved under a load. Although the actual savings based on this design are debatable, these "flat" springs are currently used in the system [5].

Stainless steel flexure rods with cylindrical heads on either end attach to the blade springs’ tips and suspend ISI stages 1 and 2 (Figure 2.3). These flexures are responsible for horizontal system compliance. Stainless steel shims are used in conjunction with the flexures, and determine the final resting position of each ISI stage. The shim dimensions are defined by the compliance of each blade spring.
The purpose of the shims is to place the lower bending point of the system, which is close to the lower bending point of the flexure, in the plane of the actuators so as to minimize rotation produced by a horizontal force [5]. This rotation is known as tilt coupling, and it decreases the performance of the vibration isolation system.

Each of the ISI stages senses motion in six degrees of freedom. The first stage uses signals from three sensors for each degree of freedom in order to reduce sensed vibration. A seismometer (Streckeisen STS-2) is used for low frequency control under 1 Hz to measure seismic activity, a short period geophone (L-4C) is used for high frequency control above 1 Hz to measure absolute velocity of the payload, and a relative position sensor is used for DC positioning to measure the difference between actuator plate and ground position. The second stage uses only two sensors per degree of freedom: a low-noise geophone (Geotech Instruments GS-13) and a relative position sensor. Electromagnetic non-contacting forcers act as the actuators for each stage and apply forces in feedback loops to reduce sensed noise.
Chapter 3
Spring Tester

3.1 Introduction to Experiment

Low frequency noise filtration is accomplished using a two stage system supported by maraging steel blade springs. Springs with different compliances will create an imbalance in the system and increase tilt coupling, a phenomenon which results in undesired motion in directions other than that in which the force was applied [10]. Increased tilt coupling is undesirable because it makes the system control loop more complex and increasingly difficult to design.

Ideally, three long and three short springs of equal compliance should be used in order to achieve most effective seismic noise isolation. Prior to assembly of the ISI system at the LASTI facility in Cambridge, a Finite Element Analysis (FEA) was performed in SolidWorks to characterize the blade spring compliances (Figure 3.1). The long spring prediction yielded linear compliance value of 0.787 mils/lb and an angular compliance of 0.088 mrad/in, while the short spring yielded a linear compliance value of 0.662 mils/lb and an angular compliance of 0.096 mrad/in [14]. After assembly of the ISI system, based on deflection data of the spring, it was determined that the actual compliance of the springs compared to the FEA model was approximately 5% softer.

Figure 3.1: Long spring FEA model. Flexure rod cylindrical head illustrated in blue, shim in orange
Precise understanding of the blade springs' compliances is important to ensure effective seismic isolation performance; therefore, a spring testing device was designed and manufactured in order to experimentally verify the compliance of each long and short blade spring.

### 3.2 Blade Spring Characteristics

![Figure 3.2: Short blade spring SolidWorks model](image)

Each long spring blade is 14.25 in. long, 0.620 in. thick, and designed to support a 2721 lb load. Each short spring is 12.75 in. long, 0.531 in. thick, and designed to support a 2020 lb load [12]. The blade springs were designed triangular in shape in order to achieve a uniform stress distribution throughout their length. The springs were fabricated using maraging steel for the material’s good yield properties and high strength compared to standard steels (Figure 3.2). Maraging steel has a high resistance to crack propagation in bending due to its grain structure. Due to its failure mode, this means that instead of cracking and risking potential damage to the system, the maraging steel blade springs will first plastically deform.

### 3.3 Spring Tester Experiment

#### 3.3.1 Measurement Techniques

A load cell is a transducer that converts a force into a measurable electric signal using strain gauges. An electric current is passed through the strain gauges, so that when a force is applied to a load cell and its strain gauges deform, they cause a change in electrical resistance, directly related to the applied force.
In this experiment, a stainless steel load cell with bonded foil strain gauges and maximum capacity of 2500 lbs was used to measure the force applied to the spring blade tip. The load cell was coupled to the blade spring tip by a steel cylindrical rod, known as the link load cell (Figure 3.3), oriented at the same angle as the load cell and through which force was applied to the spring blade tip.

Attached to the blade spring tip is a slender aluminum beam, 4.5 in. long and 0.5 in. wide (Figure 3.3), used as the platform on which displacement measurements were taken using two Starrett dial indicators. The dial indicators, with graduations of 0.001 in., were mounted to the Spring Tester side walls and contacted the aluminum beam at right angles under zero load conditions. A digital force meter displayed the load applied to the blade tip as determined by the load cell.

3.3.2 Spring Tester Mechanical System

A SolidWorks Computer Aided Design (CAD) model of the Spring Tester is shown in Figure 3.3 below.
Advanced LIGO’s ISI system is designed such that the force applied to each blade spring is perpendicular to its tips. To simulate this behavior in the experiment, a level was used to orient the link load cell perpendicular to the blade spring tip under zero load. The link load cell’s orthogonality relative to the spring blade tip was maintained by a pivoting lead screw drive system located at the front of the Spring Tester.

Once properly aligned, force was transmitted from the link load cell to the spring blade tip using a second pivoting lead screw drive system (Figure 3.4). As the lead screw rotated, two arms in parallel planes, coupled to the link load cell, applied a force to the bottom of the load cell which transmitted the force to the blade spring.

![Lead Screw](image)

Figure 3.4: Pivoting lead screw drive system for spring loading

Due to the size differences between the long and short blade springs, different mechanical setups were required for testing. For the long spring, aluminum spacers to increase the Spring Tester rotating arm length, as well as larger mount fixtures to accommodate its increased base dimensions were required for proper experimental setup. The aluminum spacers were designed so that the force could be applied perpendicular to the blade tip for different lengths of blade spring. Prior to experimentation, in order to ensure accuracy, all bolts were sufficiently tightened and moving parts aligned.
3.3.3 Load Cell Calibration

Load cell calibration is important to ensure accurate and repeatable results. Defining a reference point, i.e. zero load condition, as well as a conversion factor for the digital force meter were each part of the calibration process. The load cell was calibrated prior to experimentation, and also during experimentation.

Zero load was defined when the washers securing the link load cell to the spring blade tip were completely hand tightened. Calibration of the load cell was accomplished by suspending a known mass from the load cell and comparing it to the reading registered by the digital force meter. The known load was 396.6 lbs, and its weight according to the load cell was 252 lbs, giving a conversion factor of 1.57. The load cell was designed to have a linear relationship between actual load and that registered by the load cell; therefore, one measurement was sufficient in order to characterize this conversion factor.

3.3.4 Experimental Test Procedure

Force was applied to the spring blade tip at 100 lbs intervals up to approximately 3000 lbs for the long spring and approximately 2500 lbs for the short spring through a maximum angle of 12.5 degrees for the short spring and 13.5 degrees for the long spring. A change in the calibration of the load cell during experimentation resulted in overloading both the long and short springs throughout experimentation. Despite overloading, no adverse affects to the spring were detected during experimentation.

For the long springs, three loading cycles were conducted for each of two dial indicator mount positions. For each mount position, the dial indicators were maintained at the same position, and the digital force meter calibration parameters were maintained at a constant setting; i.e., the device was not reset between loading cycles. This procedure was used for the long spring test in order to confirm the functionality of the load cell and digital force meter.

For the short springs, due to time constraints, two loading cycles were conducted for each of two dial indicator mount position. In an effort to quantify the effect of human error on the experimental process, after each loading and unloading cycle, the spring was remounted, dial indicators reoriented, and load cell re-zeroed.
3.7 Calculations

In this section, calculations for linear and angular blade spring compliance as well as precision uncertainty for each set of blade spring measurements are detailed.

3.7.1 Compliance

Hooke's law provides a relationship between the force, \( F \), necessary to achieve a given deflection, \( x \). The force and deflection are related by a material property known as the spring constant, or stiffness, \( k \). Hooke's law is written,

\[ F = kx \]  

Compliance is the inverse of stiffness; therefore, by rearranging equation (1) above, the equation for compliance can be written,

\[ \text{Compliance} = \frac{1}{k} = \frac{x}{F} \]  

The angle of the blade spring tip was determined using the distance between the dial indicators in the \( x \)- and \( y \)-directions. The \( x \)-distance was obtained using calipers, and the \( y \)-distance was obtained by subtracting the distance registered by dial indicator 2 from that of dial indicator 1. Using trigonometry, the angle of the blade spring tip was found to be,
\[ \theta = \tan^{-1}\left( \frac{b}{a} \right) \]  

(3)

Where \( a \) and \( b \) are the \( x \)- and \( y \)-distances mentioned above, and \( \theta \) is the spring tip angle (Figure 3.5). Angular blade spring compliance was calculated by finding the average slope of the force vs. spring tip angle plot.

3.7.2 Precision Uncertainty

Two different analysis methods were used to quantify the quality of the compliance and angle measurements: precision and discrepancy between the measured and expected values. The precision of a set of measurements refers to their repeatability; statistical errors in the experimental process decrease the precision of a set of measurements. Discrepancy refers to the difference between measured values and their expected values.

In this experiment these are two “expected values” with which to compare the measured values: the FEA and ISI predicted compliance values. Systematic errors during the experimental process lead to increased discrepancy.

Due to the relatively small sample size of the short and long spring measurement data, the t-statistic method [13] was used to determine the precision uncertainty of the measured mean values for spring compliance measurements. Taking the sample standard deviation of the measurements helps to quantify their distribution,

\[ S_x = \sqrt{\frac{\sum_{i=0}^{n-1} (x_i - \bar{x})^2}{n-1}} , \]  

(4)

where \( x_i \) represents each measurement, \( \bar{x} \) the mean measurement, and \( n \) the number of measurements taken. The 95% uncertainty in the measurements was obtained using,

\[ P_x = t \frac{S_x}{\sqrt{n}} , \]  

(5)

where \( t \) is a correction factor dependent on the number of measurements taken. Based on the t-statistic method, in theory, 95% of the measurements should fall within \( P_x \) of the mean of a given set of measurements.
Chapter 4
Results and Conclusion

Table 4.1 below shows linear and angular compliance data for the measured (Spring Tester) and expected (FEA and ISI) values. The measured compliance data indicates that the short blade spring is 4% stiffer than ISI measurements and 1% softer than the FEA model, while the long spring is 12% stiffer than the ISI measurement and 7% stiffer than the FEA model. A material with greater stiffness, ie less compliance, will deflect less for a given force, while the opposite is true for a material that is less stiff, or softer.

<table>
<thead>
<tr>
<th></th>
<th>Linear Compliance (mils/lb)</th>
<th>Angular Compliance (mrad/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>short long</td>
<td>short long</td>
</tr>
<tr>
<td>FEA</td>
<td>0.662 0.787</td>
<td>0.0964 0.0882</td>
</tr>
<tr>
<td>ISI</td>
<td>0.6951 0.82635</td>
<td>0.10122 0.09261</td>
</tr>
<tr>
<td>Spring Tester</td>
<td>0.67 0.729</td>
<td>0.089 0.078</td>
</tr>
</tbody>
</table>

Table 4.1: Long and short spring compliance data determined by FEA model, ISI assembly, and Spring Tester experimentation [11]

The long and short blade springs are labeled LA to LD and SA to SD, respectively. Table 4.2 quantifies the precision uncertainty of the long and short blade spring measurements. This is important to assess the consistency and repeatability of the results. Provided in the tables are the mean blade linear and angular compliance measurement, the corresponding uncertainty, and the percentage that the uncertainty is of the mean. The means for the long and short spring linear compliance measurements are 0.729 ± 0.008 mils/lb and 0.670 ± 0.027 mils/lb, respectively, while the means for the long and short angular compliance measurements are 0.078 ± 0.001 mrad/lb and 0.089 ± 0.003 mrad/lb, respectively.

The uncertainty estimates represent the range in which approximately 95% of the measurements taken lie. The precision uncertainty for all spring data, with the exception of spring LD, is low. This shows that the measurements are consistent and repeatable. The uncertainty estimates for spring LD are significantly higher than that of the other
springs. This difference is most likely due to human error during testing. Once trial loading cycles had been completed, spring LD was the first spring tested. In addition, unlike the other long springs, after each run, the dial indicators were reoriented. The combination of being the first spring tested along with varying the testing procedure led to increased human error and uncertainty.

<table>
<thead>
<tr>
<th>Linear Compliance:</th>
<th>Angular Compliance:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spring</strong></td>
<td><strong>Mean</strong></td>
</tr>
<tr>
<td>SA</td>
<td>0.68</td>
</tr>
<tr>
<td>SB</td>
<td>0.703</td>
</tr>
<tr>
<td>SC</td>
<td>0.643</td>
</tr>
<tr>
<td>SD</td>
<td>0.651</td>
</tr>
<tr>
<td>All short</td>
<td>0.67</td>
</tr>
<tr>
<td>LA</td>
<td>0.726</td>
</tr>
<tr>
<td>LB</td>
<td>0.727</td>
</tr>
<tr>
<td>LC</td>
<td>0.731</td>
</tr>
<tr>
<td>LD</td>
<td>0.732</td>
</tr>
<tr>
<td>All long</td>
<td>0.729</td>
</tr>
</tbody>
</table>

Table 4.2: Mean, precision uncertainty, and percent precision uncertainty is of the mean for each set of spring measurements.

Figure 4.1 on page 23, shows graphical representations of the mean compliance measurements along with their upper and lower bounds as defined by the uncertainty analysis in Table 4.2.
Understanding the differences in long and short spring uncertainty estimates is important in order to analyze aspects of the testing process. For the overall long and short compliance measurements, the long spring uncertainty was consistently a factor of three less than the corresponding short spring uncertainty. Plotting normal distributions (Figure 4.2) for each set of spring compliance measurements, and comparing the uncertainties of each independent long spring dial indicator mount position shows that this difference can be accounted for in the experimental test procedures.

The histograms in Figure 4.2 have been created to show the distribution of compliance measurements for long and short spring tests. In the short spring experimental testing procedure, prior to each test, the spring was reloaded, dial indicators remounted, and digital force meter re-zeroed. Therefore, each short spring loading cycle was essentially a “new” run, providing a good distribution of data. In contrast for the long spring test, three loading cycles for each of the two locations were run consecutively, without changing any of the parameters as in the short spring test. This
was done to confirm the load cell and digital force meter functionality. Since each of the three long spring loading cycles were run without changing any conditions, it was more like taking only two sets of data – one per mount position.

![Long Spring Compliance and Angular Compliance](image)

![Short Spring Compliance and Angular Compliance](image)

Figure 4.2: Histograms illustrating distribution of long and short spring compliance data

Figure 4.3 below confirms this theory, and shows the combined compliance uncertainty compared with the uncertainty for each dial indicator mount position for the long spring tests. The uncertainties for each independent mount position are extremely low compared to the overall long spring uncertainties, illustrating the consequences of different testing procedures.
A similar analysis was not conducted for the short spring compliance measurement because only two measurements per mount orientation were available; with such a small sample size, the conversion factor used in the t-statistic 95% precision uncertainty estimate for small sample sets was very large, skewing the uncertainty numbers and providing inaccurate results.

The analysis provided in this section shows that the collected spring test measurements are consistent, and therefore give a good indication of the spring blade linear and angular compliance. In addition, the precision of the Spring Tester in the presence of human error has been confirmed.
Chapter 5
Further Research

5.1 Internal Seismic Isolation

During the summer of 2007, the ISI will be fully assembled at the LASTI facility and tested with an actual payload to ensure that the system meets performance requirements. Part of this analysis will include monitoring of the blade springs. If significant tilt coupling occurs due to blade spring compliance variation, the system control loop will be increasingly difficult to design, and reanalysis of the allowable spring compliance variation will take place [5].

5.2 Spring Tester Experimental Procedure

Improvements to the spring test experimental process would be beneficial to future tests that require high precision. The improvements are related to measurement sample size as well as aspects of the testing process prone to human error.

Load cell calibration was carried out using only one measurement value relating the actual load to that displayed by the digital force meter. It is a good assumption that this relationship is linear, but taking additional measurements with a variety of weights would only increase the accuracy of the load cell-force meter conversion factor. Likewise, analyzing a larger set of spring compliance data would give a better distribution of data from which to draw conclusions.

Human error and environment affect the repeatability of a set of measurements, and should be limited in order to guarantee effective testing. For instance, orientation of the dial indicators perpendicular to the blade spring tip using parallels, zeroing of the load cell by hand-tightening steel bolts, and orientation of the spring blade tip perpendicular to the applied force using a level each affected the consistency of the results due to their subjective nature. In addition, the variability in placement of the dial indicator measuring
tip was also a source of human error. Placement of the dial indicator was off by a maximum of ¼ in. per trial, which gives a potential human error of 1.8% and 2.0% for the long (14.25 in.) and short (12.25 in.) blade springs.

This study achieved consistent results with low precision uncertainties, but in the future measures to limit systematic errors should be a priority. Automation of the process would eliminate much of the error. Additionally, precision digital measurement devices could be used to ensure proper positioning of the Spring Tester components.
Bibliography

[5] Personal communication with Richard Mittleman