LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T0900316-v1 *ADVANCED LIGO* 30 June 2009

Preliminary Design Review for Blade Test Facility

Robert Giglio

Distribution of this document:
LIGO Scientific Collaboration

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1 Introduction

The purpose of this paper is to demonstrate the feasibility of constructing a device to measure the characteristics of blade springs in order to match a set of springs with the same performance.

2 Application

When the blade springs are used in the assembly, they are loaded by wire at a specific angle. In order to keep the suspended parts below level, the springs must be matched very precisely to one another. Another quality that the blades exhibit is the linear relationship between vertical force and displacement. Because each blade has a unique initial offset, deflection under stress, and linearity, all blades must be tested to ensure that they fall within error bounds and are able to be correctly paired with a similar blade.

3 Technical Requirements

Several requirements for the blade testing must be met. Not meeting any of the following requirements will be considered a red flag and a redesign will be required.

1. The total accuracy for the measurement of the blades must be within .02 inches
2. The machine must be clean-room safe to avoid contaminating the blades
3. A data collection system must be in place to collect and analyze the data

4 Engineering Requirements

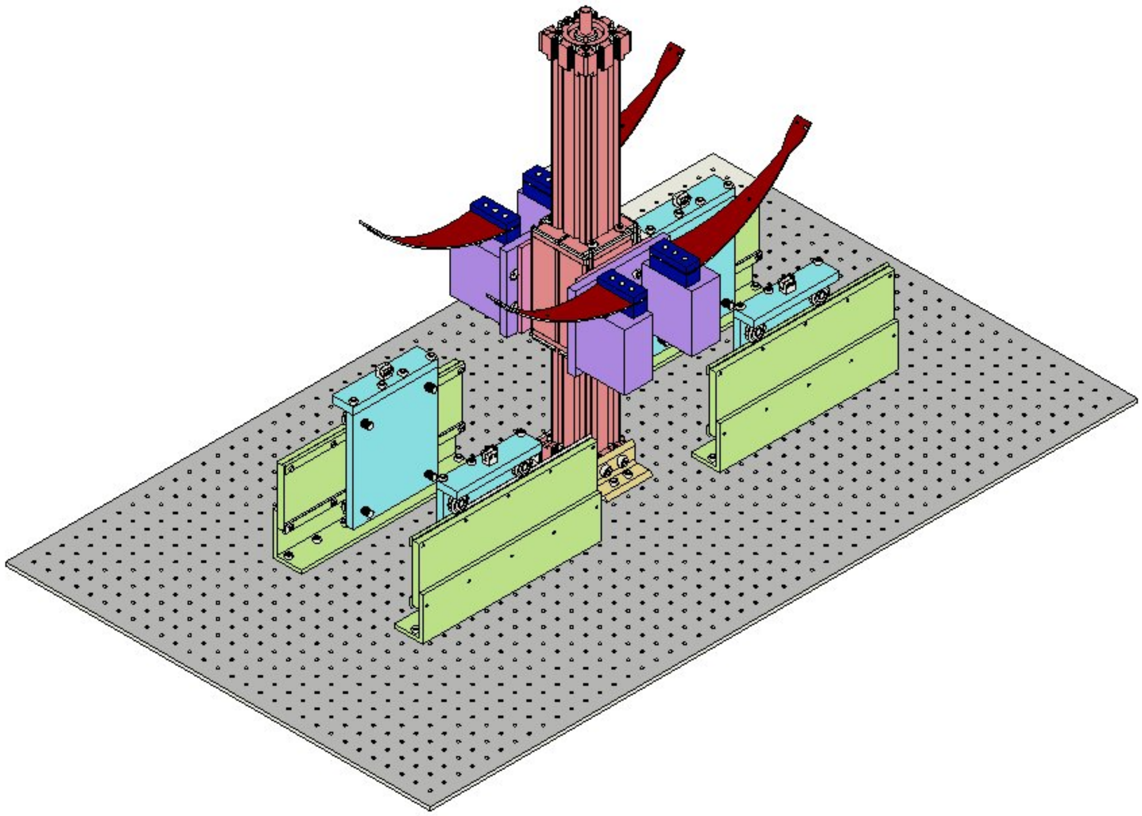
As for the scope of this paper, the engineering requirements are not as severe as the Technical Requirements, but are nonetheless important from the design aspect of this project.

1. Precise linear actuators must be used to measure displacement
2. Load cells will measure the force applied to the springs
3. All pieces must exhibit minimal deflection when placed under load
4. The machine must be safe so as to avoid harming either the blades or operators

5 Design

In this section I will attempt to break down the design and fully explain the function of each piece as well as providing information regarding why the specific parts were chosen.

The basic idea behind the design is to raise the clamped end of the blade with a linear actuator while measuring the force required to fix the end of the blade at the same height. Also, to compensate for the lateral elongation of the blade, the force sensor is attached to a track which allows the force to remain vertical at all times.



As you can see from the above image, the actuator (pictured in peach) moves the clamped end of the blades (pictured in red) up and down. The load cell (not pictured) attaches to the top of the wheel carriage (aqua) which rolls along the track (green) which attaches to the optics table or other type of base (in gray). The baseplate (in pink) attaches the adapter (purple) to the actuator. The blade clamp at the end of the blade (not pictured) attaches with a wire to a clamp that is threaded into the load cell. The actuator is mounted to the table by the Actuator Mount (yellow).

5.1 Actuator

The actuator from Nook Industries was chosen for several reasons. Firstly, because we are testing blade springs, there will be a strong moment applied to the actuator. This moment would cause wear on the ball screw and would eventually produce particulate matter, making it not clean-room safe. This actuator, however, has a wrap-around carriage which allows for a more balanced load. Secondly, the actuator is very precise (as detailed in the Error Analysis section). Thirdly, the actuator is very efficient (upwards of 90%). All of these factors are necessities when choosing an actuator and I was unable to find such a suitable actuator from any other manufacturer.

5.2 Wheel Track Plate (Green)

The wheel track plate and carriage are present to ensure that the force is always directed vertically on the end of the spring. The specific design for the track plate was chosen to ensure all forces act along a center line. The actual track itself is supplied by BWC (the same manufacturer as the wheels, which will be detailed presently). As shown in the above image, the track mounts to the top and bottom of the plate with the ends pointing opposite each other. Directly below this, the track is bolted to the table. This ensures that the force is along a direct line of action, reducing stresses and moments which could cause unwanted deflections. The angle piece is mounted to the plate with the same set of bolts that mount the track to the plate. The plate has through holes and the angle is threaded. This was done for several reasons. Firstly, the plate only comes in 6061 and the angle comes in 6063. Secondly, welding would greatly reduce the strength of the metal and subject it to more deflection when loaded. Thirdly, it is a far simpler design that also allows the space between the two parts to be cleaned thoroughly before entering the clean room.

5.3 Wheel Carriage and Load Cell (Aqua)

The purpose of the wheel carriage is to roll along the track mounted to the Wheel Track Plate. The design involves two pieces of aluminum plate that are bolted together at right angles. On the shorter piece is mounted the load cell to measure force in the string. In the other, larger piece are the wheels supplied by BWC. A detailed error analysis of this part can be found in the Error Analysis section. The design of this as two separate parts was decided for many of the same reasons that the Wheel Track Plate was broken into multiple parts. The risk of fatigue due to stresses, deflection, and cleanliness warranted the separation into multiple parts.

The wheels from BWC are actually two different types of wheels. The two top wheels are "eccentric wheels", meaning that their bushings are slightly offset from the center of the wheel. The purpose of this is to be able to tension the wheels to the desired tightness to ensure that there is no "wiggle" on the carriage. The bottom wheels, intended to carry the load, are "concentric wheels" which, as expected, hold a bushing in the very center of the wheel.

5.4 Adapter (Purple)

Because we are testing multiple blades which come in multiple clamp sizes, we must have a way to attach them to the actuator without too many parts. The adapter accomplishes this by drilling three sets of holes, each for a different blade type, into the 2x4 aluminum pieces called the "adapter arms". These arms horizontally align the blades with the wheel carriage to ensure that the force is vertical. The arms are attached to a backplate with countersunk bolts from the back of the plate. The reason for doing so was for reasons similar to the Wheel Carriage and the Track plate: cleanliness, stress/fatigue, and deflection.

As shown in the above image, the blades attach to the arms with blade clamps (dark blue) which are bolted into the helicoil taps in the arms. Helicoils were chosen because the aluminum threads could eventually wear or gall from the repeated insertion and removal of bolts. A detailed error analysis of the surface of the arms is presented in the Error Analysis section.

5.5 Baseplate (Pink)

The baseplate provides a consistent way for the Adapter to mount to the actuator. Because the adapter will have to be removed from time to time to flip it upside down to access the holes drilled on the bottom, it would be unreasonable to have to re-adjust its height on the actuator. Therefore, the baseplate attaches at the desired, carefully measured height and never needs to be moved again. The Adapter simply bolts on top through Helicoil holes in the baseplate.

5.6 Actuator Mount (Yellow)

This piece is by far the least complicated part in the assembly; it experiences very little moment or force and really only serves to ensure that the actuator remains vertical throughout the testing.

5.7 Step Motor (Not Pictured)

The step motor is mounted on top of the actuator. A motor mount supplied by Nook connects the shaft of the actuator (shown extruding from the top) and the shaft of the step motor. The motor by Lin Engineering was chosen for its low cost, versatility, and their great customer support. Using their system, it was very clear what parts were needed to properly use the step motor in this setup.

6 Error Analysis

This is perhaps the most complicated part of the design. Because our scientific requirement demands that our precision be within .02 inches (about half a millimeter), the combined error must not exceed this for any blade.

6.1 Adapter Plate

The adapter plate is where the blade clamp is attached to the actuator. Because of the design, this piece will be subjected to a strong moment which it must withstand. Running a simulation in Ansys, it has been determined that the maximum deflection angle caused by the moment is .0003 radians under load by the largest blade we will test (this corresponds to a .0003" deflection at the tip). Given this, the adapter plate is well within error tolerance for all springs

6.2 Load Cell

The load cell measures the force exerted by the spring. Unfortunately, ultimate precision over the entire range of forces is impossible due to nonlinearity inherent to the design of load cells. The load cell chosen has a nonlinearity of +/-.03% of the full scale reading (in this case, 25lbs). This corresponds to a total error of 3.4 grams. While this may not seem significant, remember that the total force to cause a deflection in the smallest blade is 1.435 Kg. Because the springs are linear with force, it is possible to determine the absolute error measured in deflection. For the purpose of this document, the blade we will consider in depth will be the spring that has the largest error. The remaining errors will be tabulated at the end of this document.

The blade with the largest error (D080761) has a deflection of 3.09 inches at 1.435Kg. Using proportions, it is trivial to solve for the deflection to the corresponding force of 3.4 grams. After calculation, the result is .007 inches. While this may seem high, remember that this is the maximum error that will be experienced with any of our blades. As shown in our requirements, this is within our error tolerance.

In addition to reading errors, load cells present another type of error. Because they are based on strain-gage technology, they must deflect some under load. The total deflection of the load cell at capacity is .01 inches. While this is within error bounds, it is possible to eliminate the error. Load cells deflect linearly with force, so knowing the force, we can easily compensate for the deflection to increase our accuracy.

6.3 Linear Actuator

The linear actuator chosen is a very precise machine. As per the data sheet, the error is .05mm for 300mm of travel with an end-play of .02mm. Both of these are well within our error tolerance.

As far as the motor driving the actuator, it has a step of .0157 radians (or, 400 steps for a full circle). This corresponds to a step size of 12.5 microns for the linear actuator, well within tolerance.

6.4 Wheel Carraige Assembly

The wheel carriage assembly has to withstand a maximum force of around 20Kg. It has been designed in such a way that minimizes the moment exerted on the piece. Thus, the total error associated with the wheel/track assembly is, according to an Ansys simulation, less than .0001 inches. This is two orders of magnitude more precise than is necessary and thus complies with our technical requirement.

There is, however, a more important type of error associated with this piece: friction. If the wheels have too much friction, the wire would not pull straight down. Instead, it would pull backwards at an angle, producing non-vertical force. Knowing nothing but the maximum allowable vertical deflection and the string length, it is possible to calculate the tolerable friction in the wheels.

Let ʎ be a small angle by which the string deviates from vertical. Also, let the length of the string be 6 inches. The maximum deflection, as per the technical requirements, is .02 inches. Thus, the shortest allowable distance between the top of the load cell and the top of the blade is 5.98 inches.

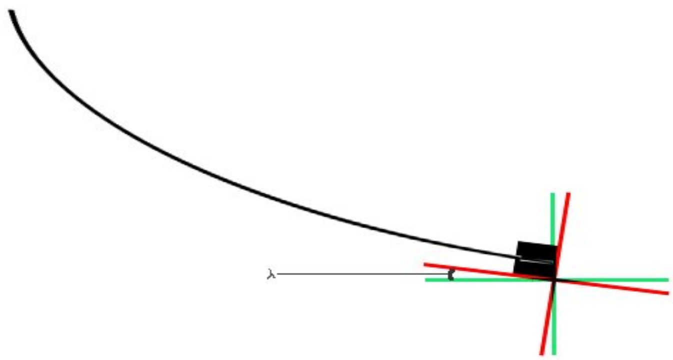
From this, we can construct a triangle. Solving for ʎ, we find that the angle is .08 radians. Also, we solve for the horizontal displacement, X= .5 inches. Because the force is always pointed along this line, we know that the coefficient of friction must be .5/5.98 or .08. This may seem like an unobtainable number, but in fact the wheels that will be used have a coefficient of friction of .0005-.02. The upper limit friction cited by the supplier corresponds to a deflection of .0012 inches, which is well within our error tolerance.

6.5 Error Tolerance

A critical part of this design is precision. Because we are measuring such small quantities, we must ensure that all parts do not cause enough error to throw off the measurements. Here I will detail parts of the assembly in which error could be induced.

6.5.1 Adapter Plate

This piece is one of the most critical of the entire assembly. Because the blades themselves rest on this part, they are not only subjected to large moments, but they must also be very level. In order to properly assess how level the surface to which the blade mounts must be, we need to characterize the way blades are loaded when offset by a small angle (ʎ).



At full flatness, the blade, therefore, will deflect by the following equation: D = tan(ʎ)*length

However, because the tip of the blade is initially elevated, it will not be elevated by the same amount. Therefore, this is a potential source of error. To figure out the allowable angle, we must make the assumption that the blade is linear even at the small angle ʎ. Also, we know that the blade tip will deflect vertically by its initial height at its rated load. In the following derived equation, we denote E as our error, US as the unloaded length, UH as unloaded height, and SL as the fully loaded length.

0 = sqrt(US^2+UH^2)*sin(arctan(UH/US)+ʎ)-sin(ʎ)*SL-UH-E

Solving the equation for ʎ for the D080018 blade with an E=.005 yields an angle of .05 degrees. From this, knowing that the adapter is 2 inches wide, it is trivial to show that the maximum difference from one side to another is .0017 inches. Therefore, the flatness has been called out to .001 inches to ensure that it falls within error requirements.

Another area of concern may be that the adapter plate is actually made of three pieces and that they could perhaps not be bolted on level. However, minute adjustments are possible (and probably will be necessary) in order to get the piece to within .05 degrees. This, however, will be easily accomplished.

6.6 Statistical Error Reduction

Certain types of uncertainties can be reduced by applying statistics. For our purposes, only the error introduced by the load cell is reducible because it is the device making the measurements. Because we know both the range of error and because the error is different each time, we can model it as a Gaussian distribution. The uncertainty equation is:

E = Error/sqrt(samples)

Therefore, if four samples were averaged, their error would be cut in half. Similarly, with 9 samples, the error is 1/3 of the original. Because we intend to test the blades more than once, we can easily measure the force on both the way up and on the way down to increase the samples and drive down our error. Tests should be performed on the load cells to find the true uncertainty rather than using the supplied uncertainty as all load cells are slightly different.

6.7 Error Budget

(units in inches)	Adapter	Load Cell	Actuator	Wheels	Total
D080761	.0003	.007	.003	.0012	+/-.0115
D080019	.0003	.002	.003	.0012	+/-.0065
D020617	.0003	.0015	.003	.0012	+/-.006
D020615	.0003	.001	.003	.0012	+/-.0055
D080018	.0003	.0045	.003	.0012	+/-.009
D020205	.0003	.004	.003	.0012	+/-.0085
D020201	.0003	.0045	.003	.0012	+/-.009

Note that these errors are very pessimistic and are probably significantly higher than they would appear in real life. Rather than calculating the deflection in the adapter for each blade, I used the maximum that it can experience, and rather than measuring the friction in the wheels, I used its maximum rated friction (with an unrealistically long wire). Also not taken into account is that the error of the load cell can be minimized using statistics (taking the average of 4 samples cuts the error in half). Thus, it has been shown that the results will, in fact, land well within our error tolerance of .02 inches for the measurements.

7 Data Acquisition (DAQ)

This section will attempt to explain the method of control and data acquisition for both the load cell and the step motor (and thus the actuator). Our setup includes the data acquisition board by AdLink.

7.1 Data Acquisition Board

The PCI-9524 board by AdLink has a great number of inputs and outputs for strain gauges, digital inputs, step motors, and analog inputs. For our purposes, only the I/O for the strain gauges and the step motor will be used. On the board, pins 53-68 are reserved for strain gauges. This breaks down into four inputs with four pins each (pin1 is input, pin2 is excitation+, pin3 is excitation-, pin4 is ground). These inputs plug directly into our load cells. All other requirements (such as impedance, excitation voltage, output voltage) match between the load cell and the DAQ board.

Pins 32-34 are allotted to step motor output. There are also outputs for 2 more step motors, but this is not a requirement of ours. The outputs are PulseA+, PulseB+, and 5V. Depending upon the way the driver board for the step motor is set up, the PulseA and PulseB outputs can be set to different types of output. For our purposes, they will be set to Step/Direction mode.

7.2 Step Motor Driver

The step motor driver supplied by Lin Engineering is a relatively simple, but versatile piece of equipment. It has three inputs: direction, step, and 5v reference (these are the same outputs mentioned above in the DAQ board section). Other inputs are for +24V and ground. The outputs are what one would expect for a step motor driver (StepA-, StepA+, StepB-, and StepB+). There are still two more pins which must be bridged by a resister to set the run current of the motor. The type of resister has not been discussed with anyone, but it is my belief that this should be a potentiometer to adjust it based on how much current is required to prevent unnecessary heating in the motor.

7.3 Software

The drivers for the AdLink data acquisition board are available for Linux and, since this is the environment I am most familiar with (and because of its superb stability), I will be programming on the Fedora 9 distribution. The program will probably be mostly written in Python to simplify the coding/upkeep and there will be helper functions written in C. The language choice is subject to change as I begin to program the board and see which language will be easier to maintain.

7.3.1 Configurability

The program will parse an XML file containing specific instructions for each type of blade. The file will be user-editable and will be very versatile. The user can specify movement and reading options the way they want the machine to run. The file will probably not need to be edited much, but if the operator finds that, for example, the blades are still experiencing plastic deformation after the second full deflection, he/she will be able to tell the program to fully deflect the blades twice before collecting data.

7.3.2 Interface

The interface will be a simple GUI with manual actuator controls and places to enter information about the blades (such as initial height, part and serial numbers). When the user runs the program, he/she may step away as it runs, as no user interaction is required. If he/she desires, a real-time plot of the force-displacement can be generated.

7.4 Data Analysis

The data analysis will be done entirely by the computer using algorithms I have already developed. They are detailed below:

7.4.1 Offset

Before we can begin to characterize the blades, we must know where the data itself begins (that is to say, where the blade just begins to load). The algorithm samples data from the load cell and does a time average. If the data “spikes” or deviates a certain percentage above this average, then the blade has begun loading. The percentage cutoff will have to be experimentally determined, as it is impossible to say right now how much noise will be present due to external factors (magnetic fields, load cell error, DAQ board error, etc).

7.4.2 Linearity

Once we have the offset and have thrown away the meaningless data, we can fit a line to it. From this, we can calculate the linearity of the line fit using traditional equations.

7.4.3 Reduction in Height on Overload

We need to know if the blade plastically deformed in the overload test. This is a trivial task; the start height is simply compared to the end height after the test and the difference is saved.

7.4.4 Force to Flat

Because the user will have entered an initial height of the spring, we can very easily calculate the amount of force required to make the blade flat. Another idea that could be implemented later is to use a laser/dial indicator mounted on a track overhead to measure the blade and ensure that it is indeed perfectly flat at the calculated value. The actuator could make adjustments until the blade's flatness was optimal and then save that number.

7.4.5 Graph

The picture of the graph will be saved in a specified directory (and named as "serial.jpg" where serial is the blade's serial number). The graph will be generated with GNUPlot, a free and open-source graph plot program.

7.4.6 Raw Data

The raw data itself will be saved in a series of files inside the same directory as the graph image. They will be titled "serial-run.jpg" where run denotes the number of the data collection cycle. The data is being saved as a backup in the event that the server containing the database crashes.

7.4.7 Data Storage

The data will be stored in a MySQL database on the computer. This is to simplify and streamline the storage and prevent accidental removal of data. The database can also be synced across multiple computers for redundancy.

7.4.8 Data Presentation

I had the good fortune of programming an extensive web application whose sole purpose was to present large amounts of data. The program (called WebDisplay) has been open sourced with the blessing of my boss (Dr. Blaise Bourdin of the LSU Math Department). The WebDisplay interface will allow searching, filtering, and ordering of the blades in order to find the ones that match most closely. To see the system in action, visit http://nas.schur.math.lsu.edu/index.php?experiment=quenching