LIGO Laboratory / LIGO Scientific Collaboration

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HAM SAS Inverted Pendulum Tests

Yumei Huang, Riccardo DeSalvo

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This is an internal working note
of the LIGO Project.

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 – NW17-161
175 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/

We have done both simulations and some measurements to test the HAM SAS Inverted Pendulum. The simulation is very similar to what made by Ilaria Taurasi [ref.]

First, I designed the inverted pendulum in each detail with software Solid Works, I only put one leg to software Ansys where I chose the material of each part of it.

Then we made the measurement to check that the model finds correctly the resonance frequencies.

The new measurement of interest is the measurement of the IP oscillation quality factor as a function of oscillating frequency.

1) Ansys simulations

I calculated the main resonant frequency changing the payload between 0 and 732.8Kg.I used KaleidaGraph to plot the data in fig. 1 and made a fit.

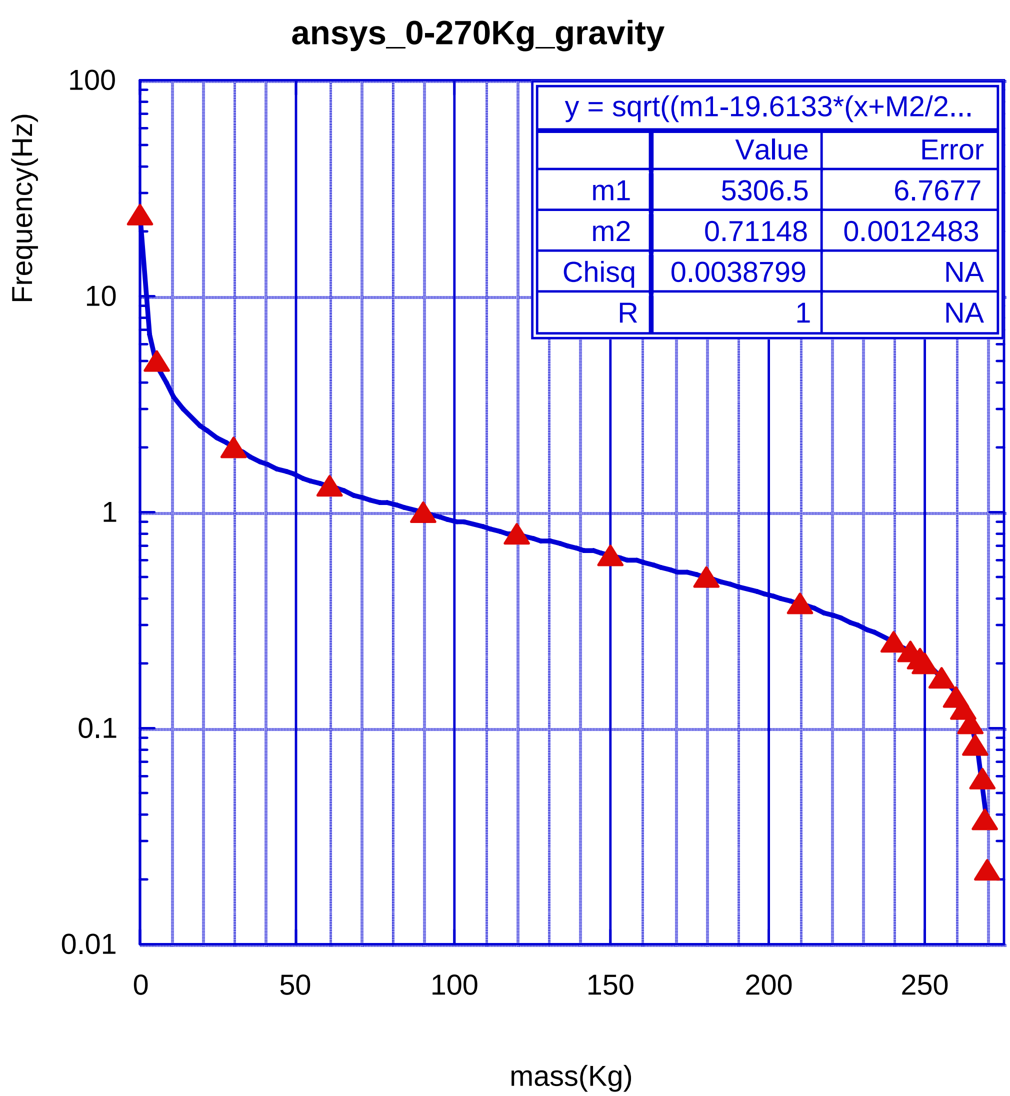


Figure 1: Simulation diagram of LIGO inverted pendulum.
Frequency (Hz) vs. Load(Kg).
The Ansys simulation was made on a single leg.

I imported one leg from Solid Works to Ansys where I applied the Standard Earth Gravity, I chose the boundary conditions and I controlled the contacts. The software solved the model and found the frequencies. Analyzing the first 6 modes, I only use the first modes to compare with the measurements.

I changed the mass on the top of the leg in a range between 0 Kg and 269.5 Kg.

The data was fit with the formula: $f \cong \frac{1}{2\pi}\sqrt{\frac{k - \frac{g}{L}(M_{Load} + \frac{m_{LegEff}}{2})}{M_{Load} + \frac{m_{LegEff}}{3}}}$

Where $f = \frac{1}{2\pi}\omega$, ω is the radial frequency. M_{Load} is the mass of the payload, m_{LegEff} is the effective leg mass.

From the figure, we can see that when the M_{Load} beyond 250 Kg, the frequency get down rapidly.

2) Measurements

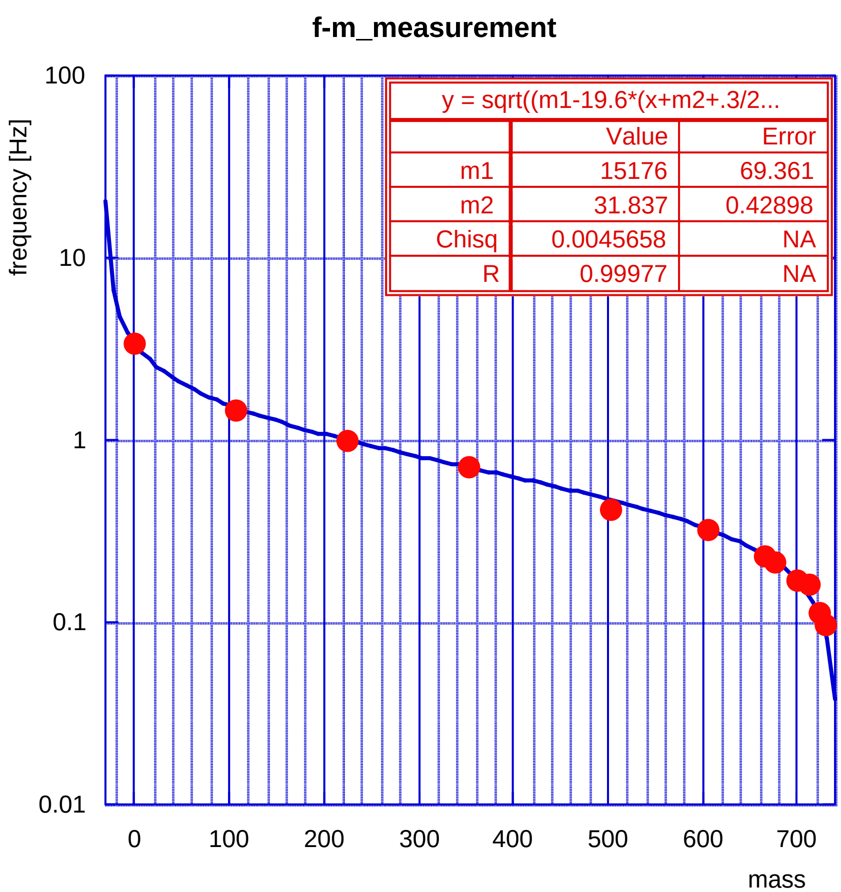


Figure 2: Measurement diagram of the 3-leg inverted pendulum.

The aim of the measurements is to cross check the Ansys result and to measure the behavior of the oscillation Quality factors as a function of the frequency.

For the measurements we used an existing three legs prototype IP table with full size HAM SAS legs and flex joints, but no counterweights.

To record the movement we mounted an IP LVDT position sensor [ref.] below the table. We acquired the ring-down measurement on a Digital Oscilloscope.

To start the measurement, we need to give the table a push in the sensitivity direction of the LVDT and start the Oscilloscope after setting the scale to let the curve fit the screen.

The data was then transferred to a computer for fitting the resonant frequency and the ring-down. The method was good to get information on the Frequency and Amplitude. It turned out though that the digital oscilloscope was not capable to store data sets longer than 100 s and did not allow adequate measurement of the oscillation lifetime τ.

To measure the τ , we set the oscilloscope to 1 second per division (10 second screen length) and used the peak to peak function of the oscilloscope to estimate the instantaneous signal amplitude. I then recorded the data by hand with a stopwatch writing down the average every 10 seconds until the signal amplitude got comparable with the signal noise, typically for 15 to 30 minutes.

This measurement procedure was repeated for increasing IP loadings with steps of ~100 Kg

When the load mass was beyond 600 Kg, we added the mass with smaller steps because the frequency gets down rapidly.

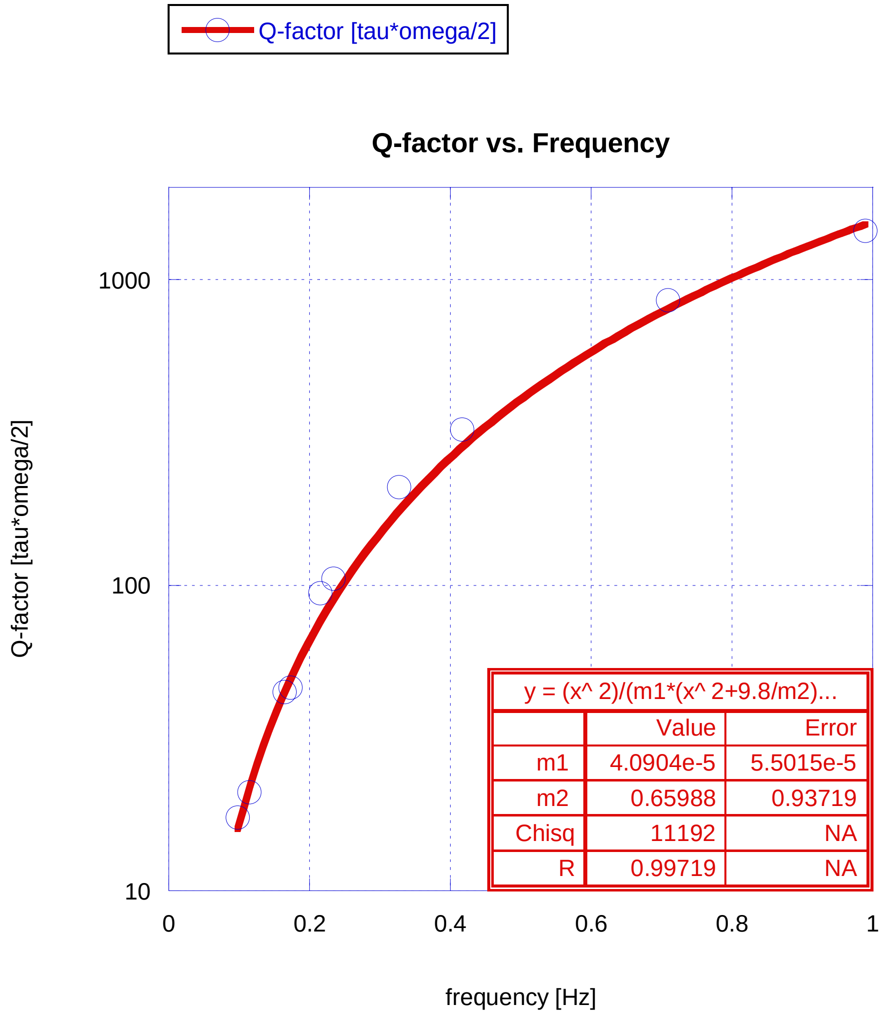
At the start of the measurement we leveled the IP table with a small bubble level. As we loaded the table, it naturally became more and more tilt sensitive. At every loading steps we monitored the equilibrium position, and when the equilibrium position changed by more than 3-4 mm we re-leveled the table by means of a small hydraulic jack and shims. Leveling does not compensate for imperfections in the leg flex joint alignments, which introduces a torque, which becomes increasingly visible as the table is loaded. We used soft parasitic springs to compensate for the internal torque that rotated the table when we put more mass on it. We used two correction springs diametrically mounted at the periphery of the IP table to compensate the rotational movement. A few Nm were sufficient to stabilize the table.

For the last few measurements, instead of leveling, we used a radial parasitic spring to compensate for the residual tilt.

We know the function between the frequency and mass,

$$f \cong \frac{1}{2\pi}\sqrt{\frac{k-\frac{g}{L}(M_{Load}+\frac{m_{LegEff}}{2})}{M_{Load}+\frac{m_{LegEff}}{3}}}$$

The fit is basically the same as our measurement. In the fit we introduced the known leg weight and length. In both figure 1 and 2 the parameter M1 is the leg's elastic constant k, (N/m), the parameter m2 is the mass of the table and the position sensor and other un-removable payloads, which were unknown at the time of the measurement. At the end of the measurements we weighted the table and all other un-removable payloads. Their actual mass turned out to be 28.8 kg, in good agreement with the 31 kg of the fit.



$$Q \cong \frac{1}{\Phi}\frac{\omega^2}{\omega^2+\frac{g}{L}}\ ,\ Q=\tau\omega/2\ ,\ \tau$$

3) Comparison of simulations and measurement data

The parameters of the fits on Ansys simulations are about 1/3 of the fit parameters for the measurement data, because the in Ansys I only input one leg and no table, while the prototype has three legs. We find good agreement between simulation and the model.

The Q-factor measurement shows the expected quadratic behavior with frequency. It confirms that when operated at sufficiently low frequency the IP table will need no Q-factor damping.