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Proof load test and vertical bounce frequency test apparatus for ITM/ETM silica suspension fibres

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Reference documents

Design documentation	
D1002067	Proof and bounce tester enclosure
D1002069	Proof and bounce tester door
D1002083	aLIGO SUS UK bounce tester
D1002082	aLIGO SUS UK proof tester
Technical documentation	
E1000366	Pulling/Welding Procedure

1 Introduction

One aspect of the monolithic suspension procedures (E1000366) for the quadruple suspension in aLIGO is characterisation and 'proof loading' of fibres used in the suspensions.

Proof loading of fibres is necessary to ensure that a fibre welded into the aLIGO quad suspension is indeed strong enough. Each fibre is therefore loaded to 15 kg (150% nominal load) for 5 minutes before welding in order to proof the fibre is strong enough for the suspension. Section 2 of technical document gives a description and manual for the proof tester.

Characterisation is undertaken to make sure the fibres meet the dynamics requirements. The baseline apparatus for this is the dimensional characterisation machine (T1000024), which measures the diameter of the fibre along its entire length. This information can then be fed into a finite element package to very accurately calculate the stiffness of the fibre and thus the bounce and violin mode frequencies. Another supplementary apparatus that is not in the baseline assembly procedures, but can help with confirming the fibre stiffness is the bounce tester. Section 3 of this technical document gives a description and user manual for the bounce tester. This apparatus shares many common components with the proof tester.

2 Proof load tester

2.1 Description of apparatus and list of parts

The proof tester consists of a transparent polycarbonate cabinet with a door in the front. The cabinet has base and roof made of aluminium sheet, with the corner verticals and door made from lengths of Bosch extrusion. The roof has a central fixture with a universal joint and fork shaped connector piece which the fuse end on one end of the fibre can be connected to. A 15 kg cylindrical aluminium mass sits on a hydraulic or electric jack. The mass can be connected to the other end of the fibre. Using the jack can be lowered such that the fibre takes the full 15 kg load. Figure 1 shows the proof tester in Glasgow with a hydraulic jack system. Drawings for the proof tester don't include the drawings for the hydraulic jack but have a suggested motorised jack, which can be bought of the shelf and is as easy to use.

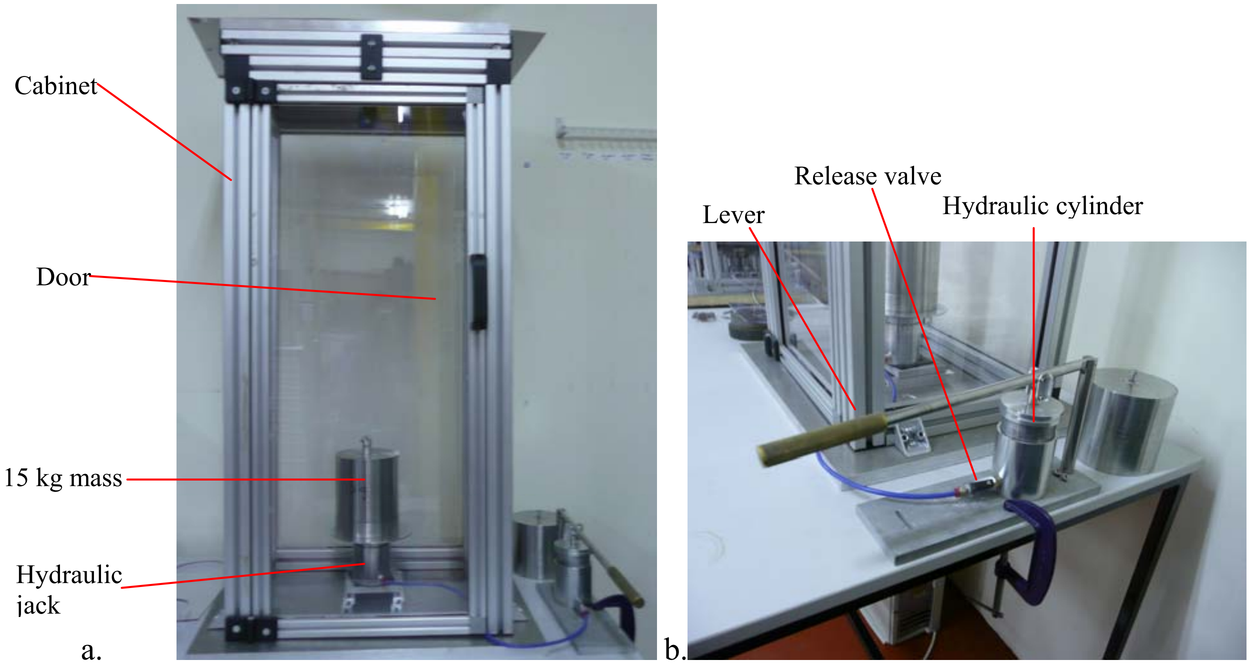


Figure 1a. Proof tester cabinet with the 15 kg mass sitting on the hydraulic table with the blue tube leading to the jack. b. Close-up of hydraulic jack.

The bill of materials for the cabinet can be found in the following drawings:

Drawing no.	**Description**
D1002067	Proof and bounce tester enclosure
D1002069	Proof and bounce tester door

The bill of materials for the jack and mass can be found in:

Drawing no.	**Description**
D1002082	aLIGO SUS UK proof tester

2.2 Working principle and manual

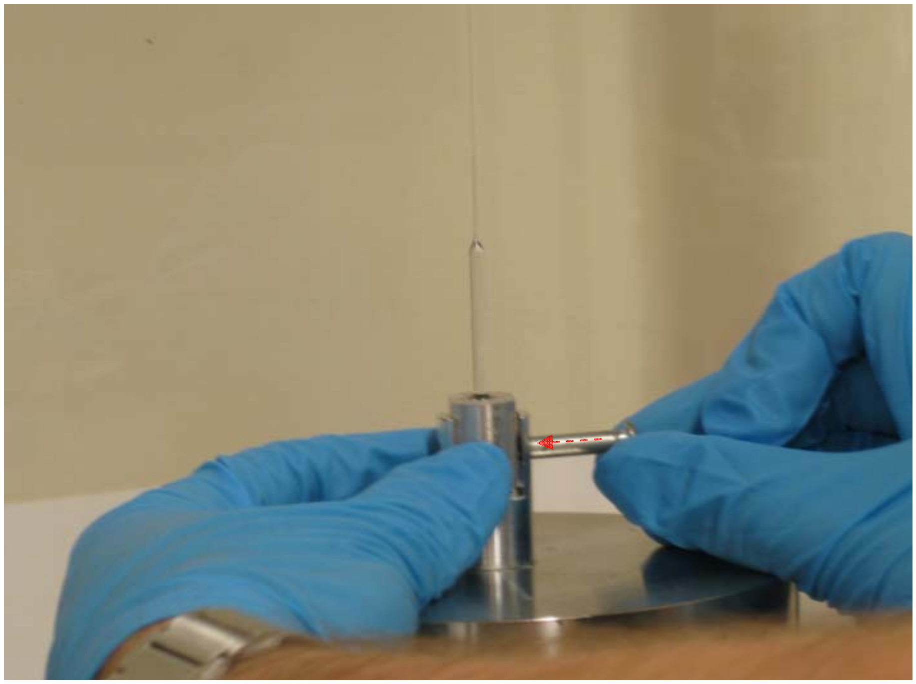
By loading each fibre with 15 kg, the fibre gets 150% of its nominal load in the fibre suspension which is 10 kg. The overload test is done for 5 min to make ensure that any microcracks that could have been introduced due to a fibre touch have time to propagate though the fibre and develop a fracture. Heptonstall et al. report an average strength of aLIGO fibres of 4.4 GPa in P1000080, which is equivalent to a load of 55 kg. In G0900875 he also reports that all fibres measured that have been flame polished for longer than a total of 20 minutes before pulling held a load of between 30 and 70 kg.

When using the proof tester, please use the following guidelines. Some pictures are shown in to support the guidelines in **Error! Reference source not found.**:

1. Fully lower the jack and mass.

2. Insert the fibre at the top and fix the top fuse end to the top fork holster with a pin:

3. Raise the jack such that the distance between the pin connections on the 15 kg mass and the ceiling is 5 to 10 mm shorter than the distance between the holes of the fuse ends on the fibre when the fibre is straight. Lock the jack.
4. Fix the fibre into place on the mass fork holster:



5. Close the cabinet door.
6. Unlock the jack and lower the jack slowly until the table is no longer touching the mass. The fibre will typically stretch by ~6-7mm during this unloading process, and this is normal.

7. Leave the mass to hang on the fibre for 5 minutes.

8. When the fibre has successfully passed the test, slowly jack up the table again until the fibre is no longer under any tension.
9. Remove the bottom retaining pin to release the fibre.
10. Hold the fuse end at the top and remove the retaining pin, allowing the fibre to be extracted and taken to the next characterisation step.

3 The vertical bounce tester

3.1 Description of apparatus and list of parts

A schematic overview of the bounce tester set-up is given in Figure 2. The containing cabinet is of the same design as used in the proof load tester. The fibre is suspended from the ceiling of the cabinet via a universal joint and upper holder. The fibre connects using a locking pin. A mass is suspended off the bottom of the fibre.

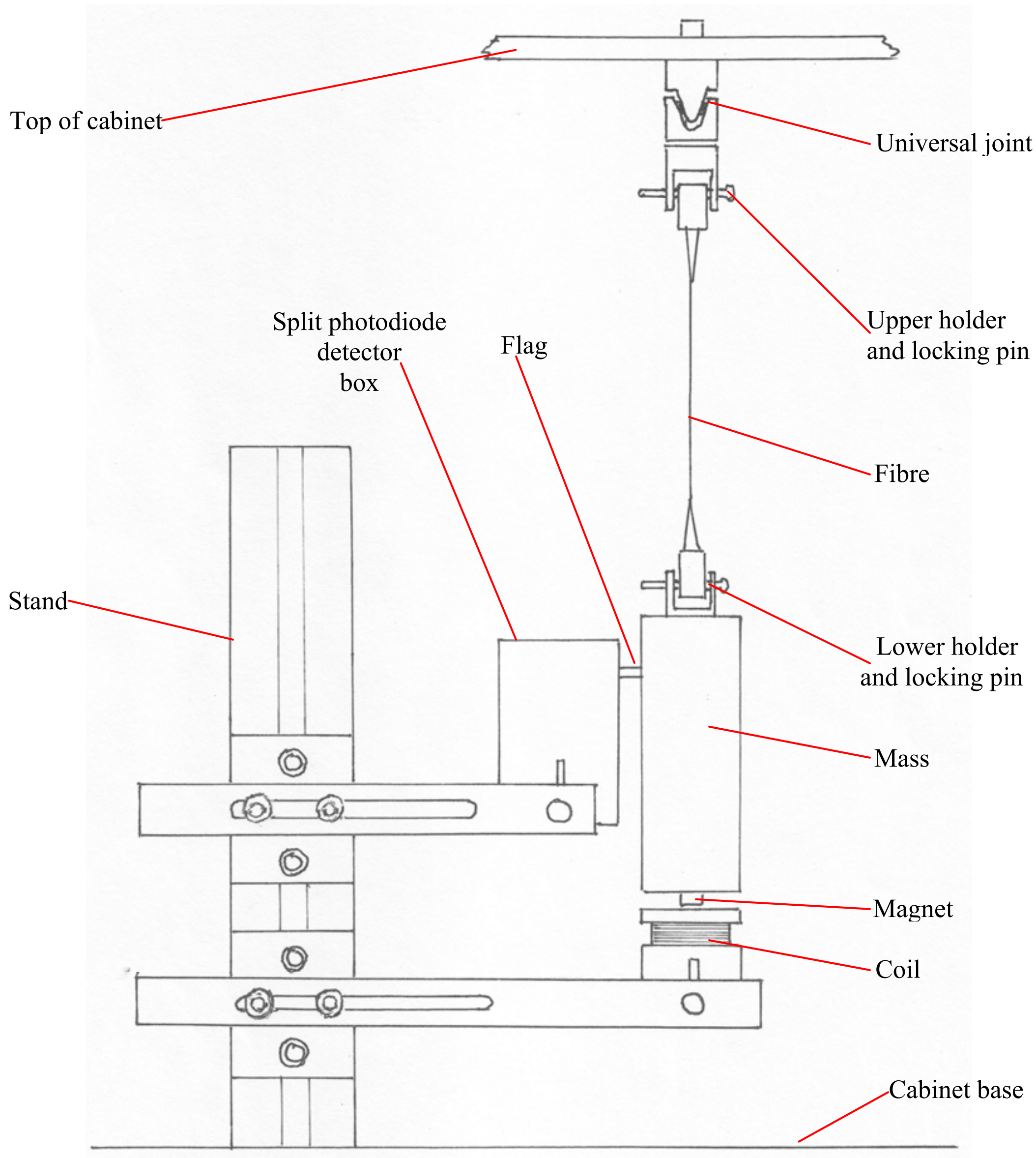


Figure 2 Schematic overview of the bounce tester set-up. Additional parts: Dual 12 V power supply; Oscilloscope; Spectrum Analyser.

Vertical motion of the mass is induced by the interaction of the coil with the magnet. The current in the coil is supplied by the "source" terminal of the spectrum analyser, or an independent function generator. Two photodiodes and associated electronics in the detector box convert vertical motion of the flag on the mass into voltage for the spectrum analyser.

3.2 Working principle

Figure 3 shows the bounce tester set-up.

The fibre under test suspends a 1.1 kg mass and the measured resonance frequency is scaled to that of a 10 kg load. The fibre is attached to a universal joint at the top so that it hangs freely along the local vertical. A coil below the mass and a button magnet on the mass base is used to apply a vertical oscillating force to the mass, the frequency of which is controlled by a function generator. The flag connected to the top of the mass interrupts the light from an LED falling on a split photodiode. The amplified output from this is shown on an oscilloscope and the frequency of the signal generator is adjusted for maximum amplitude on the oscilloscope and therefore resonance of the mass – fibre system.

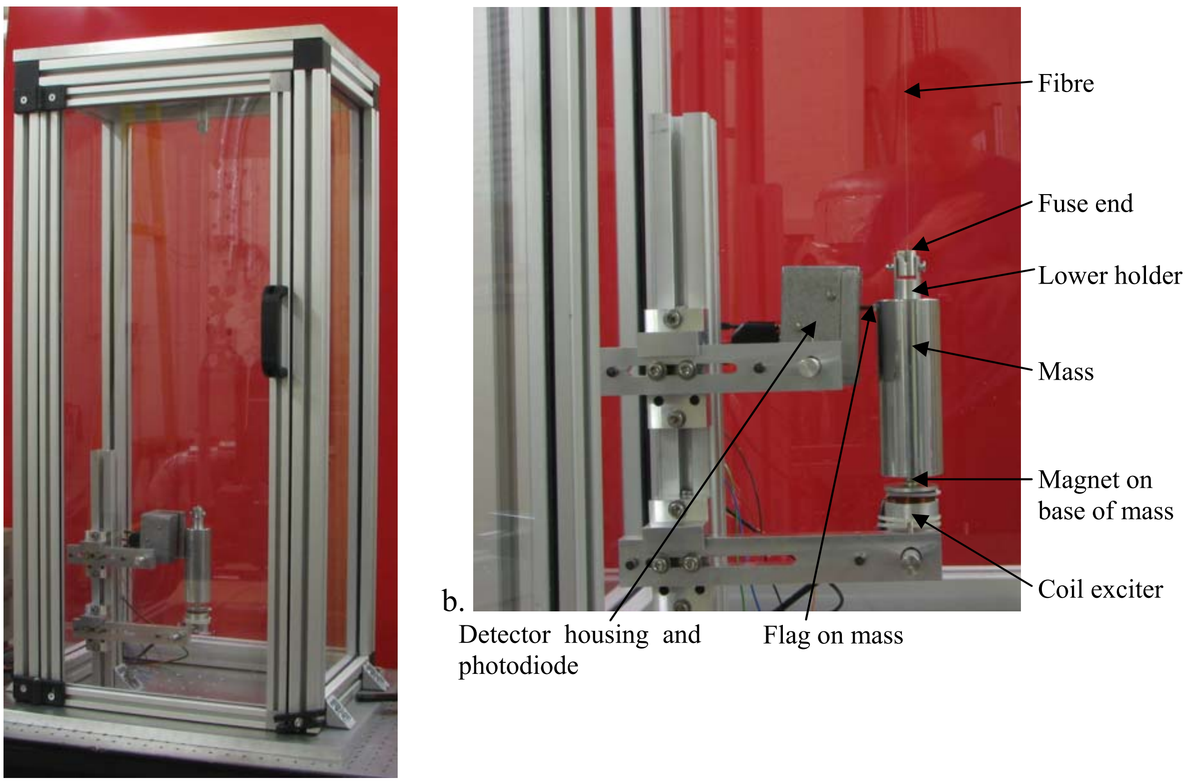


Figure 3 a. Proof tester, b. Close up of mass, detector and exciter

Assuming an ideal fibre with a constant diameter along its entire length the bounce frequency is related to the fibre dimensions and the mass suspended on it, through equation 1:

$$f = \frac{1}{2\pi}\sqrt{\frac{E\pi d^2}{4lm}}, \quad (1)$$

where f is the bounce frequency; E is Young's modulus; d is the diameter of the fibre; l the fibre length and m is the suspended mass.

3.3 Electronics

Referring to the circuit diagram in Figure , the photodiodes are operating in photovoltaic mode. The shadow of the flag moves from one photodiode to the other and back again when the mass undergoes vertical oscillations, producing an alternating voltage which inputs an alternating current to the inverting input of the op-amp. This is matched by the feedback current in the 100 kΩ resistor due to the value of the output voltage of the op-amp. The circuit is thus a current to voltage converter giving 0.1 V per μA.

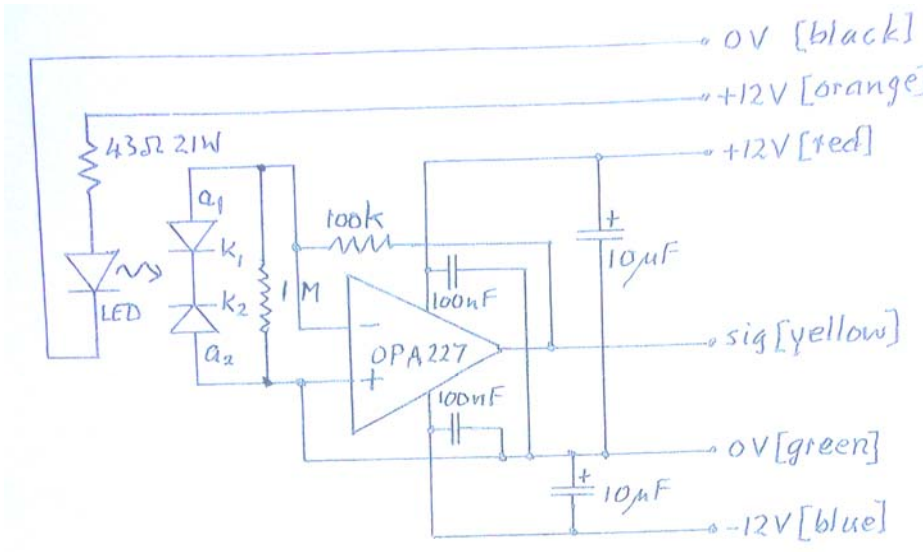


Figure 4 Circuit diagram for the flag photodiode sensor and circuit board layout

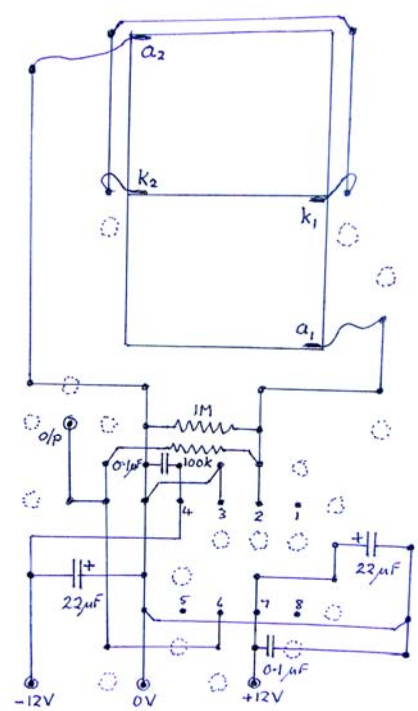


Figure 6 Schematic of circuit for installation onto breadboard.

It has been discovered that the op-amp can go into saturation and it is believed that the large source impedance of the photodiodes causes the inverting pin to charge up since the effect can be cured by placing a 1 MΩ resistor across the photodiodes.

3.4 Calibration and testing measurements

The calculation of theoretical bounce frequencies assumes that the clamp and supporting structure are completely rigid, which is not the case in practice.

It is therefore necessary to calibrate the apparatus. Instead of a fibre, a steel wire of uniform circular cross-section (193 µm diameter) was used to suspend the mass. Measurements were taken first with the wire held in pin-vices then with the universal joint included and finally with fuse-end clamps attached with Araldite 2012.

Table 1 shows the comparison between the theoretical and experimental bounce frequencies for each configuration. The difference of 2.5% for the third case was taken as the calibration and applied to subsequent ribbon measurements.

Table 1 Bounce testing of steel suspension wire

Configuration	**Theoretical bounce frequency (Hz)**	**Measured bounce frequency (Hz)**
1. Using rigid pin vice clamps	16.3	15.9 ± 0.1
2. Including universal joint	16.3	15.8 ± 0.1
3. Including universal joint, fuse end and glue (wire shortened by 10 mm)	16.5	16.1 ± 0.1

The results shown in Table 2 were obtained with three aLIGO fibres of length 600 mm. The peaks were consistent over many data runs and were narrow with a width of 0.25 Hz at half amplitude. The three specimens are very similar considering that no special steps were taken to match them.

The measured bounce frequency in the third column can then be converted to the predicted bounce frequency of the suspension, by first correcting the frequency with the 2.5% error and correcting for the actual mass in the suspension which is 10 kg per fibre. The results are shown in the fourth column. The frequencies for a 10 kg load have to be scaled up by √2 for the predicted aLIGO frequencies since in the aLIGO suspension the tops of the fibres will be attached to an upper mass which is free to move. These frequencies are shown in the fifth column.

Table 2 Results found for 3 fibres of length 60 centimeters

Fibre	Mass [kg]	Bounce Frequency [Hz]	Predicted bounce frequency in aLIGO suspension with PUM fixed [Hz]	Predicted bounce frequency in aLIGO suspension with PUM suspended [Hz]
A	1.102	19.1094	6.50	9.19
B	1.102	19.1719	6.52	9.22
C	1.102	19.0469	6.48	9.16
A	0.538	27.125	6.45	9.12

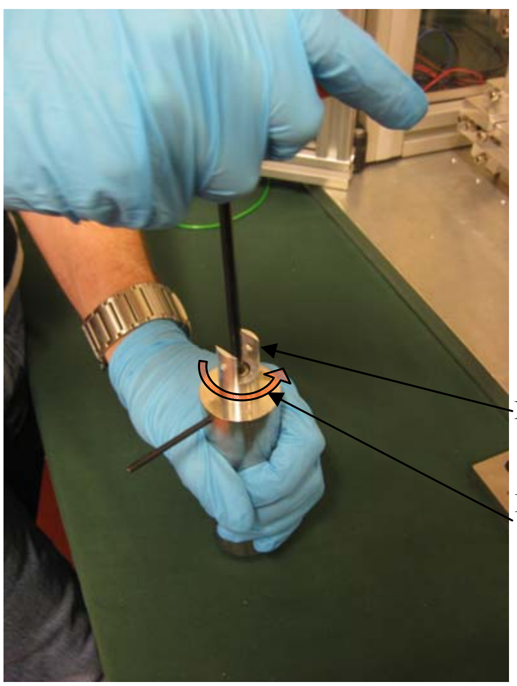
B	0.538	27.250	6.48	9.16
C	0.538	27.062	6.44	9.10

3.5 User procedure manual

3.5.1 Installing the fibre

1. Move the detector box toward the stand to make room for the mass.
2. Lower the drive coil assembly to the base.
3. The fibre is carried vertically by a fuse-end which is inserted into the top holder and held by the locking pin, in a similar manner to the proof tester.
4. The mass is held vertically and the lower fuse-end inserted in the holder on the top of the mass where it too is locked by a pin.

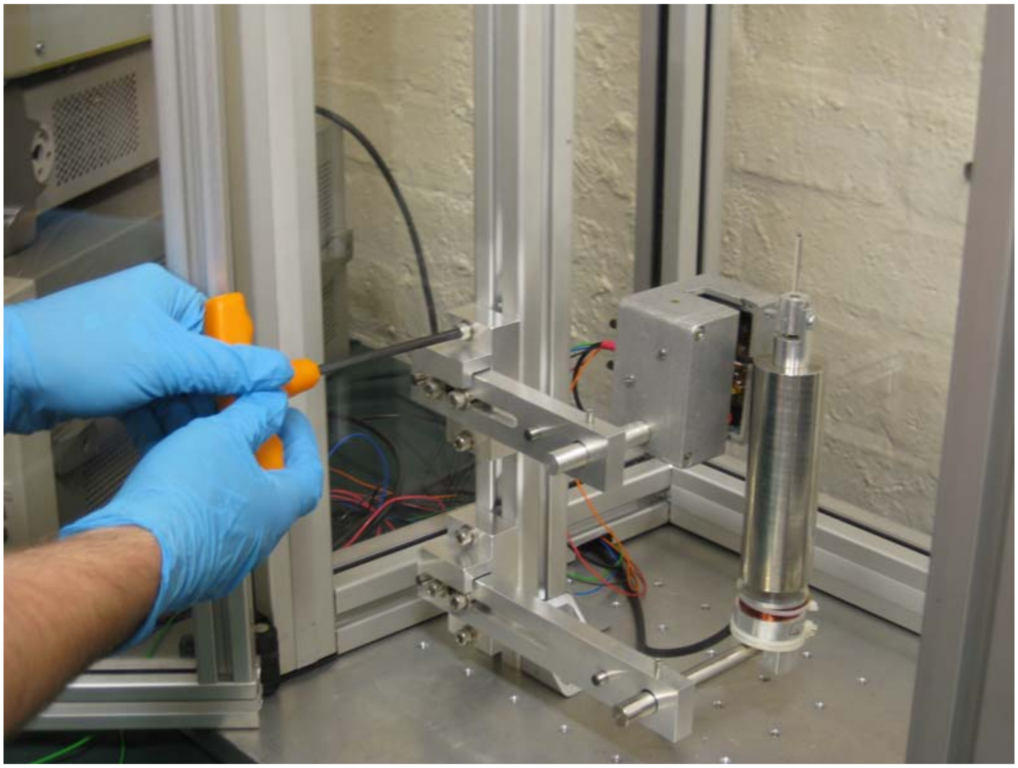
5. It may be found that the fuse-ends are not aligned and that the flag does not meet with the slot in the detector box. If so remove the mass from the fibre and loosen the attachment screw on the top of the mass that allows the upper holder to be rotated until the flag is aligned with the slot and tighten the adjustment screw.



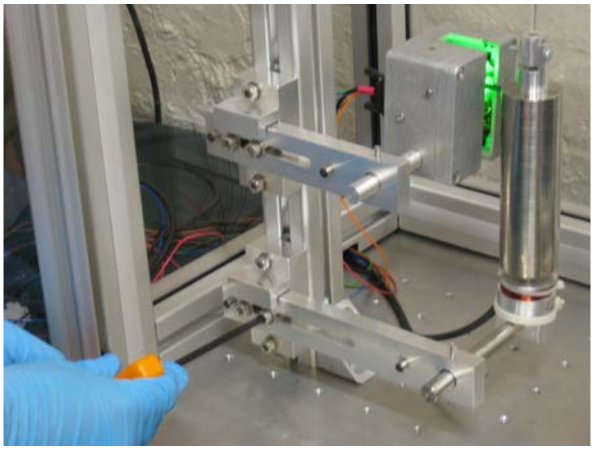
Setting up the electronics

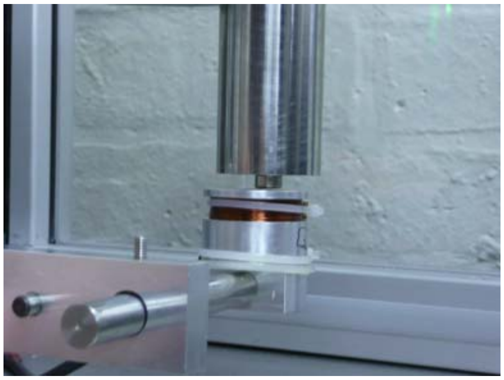
1. Connect the power supply to the box (+12 V, -12 V, 0 V) and switch on. The light of the LED will be seen through the slot.

2. Move the detector box horizontally so that the flag enters the slot. The shadow of the flag on the photodiodes can be seen through the slot in the top of the box.



3. Move the box vertically until the shadow lies on the division between the flat square faces of the photodiodes.
4. Move the drive coil assembly upward until the bottom of the magnet is level with the upper surface of the coil holder and adjust the position of the coil so that it is not touching the magnet (see bottom row **Error! Reference source not found.**).





3.5.2 Setting up the Spectrum Analyser

1. Connect the output of the box to the input of the spectrum analyser and the "source" output of the analyser to the drive coil. Set the source output voltage to somewhere between 300 mV and 2 V.
2. Set the frequency to "Periodic Chirp" or a "Sine-sweep" with a starting frequency and span to cover the expected bounce frequency, predicted by equation 1.
3. Set the vertical scale to "Autoscale".
4. After a data run, the analyser should now produce a narrow peak, showing the bounce frequency. With the oscilloscope set to ac, the output voltage can be monitored during the frequency scan and should show a maximum amplitude at the bounce frequency (Figure 5).

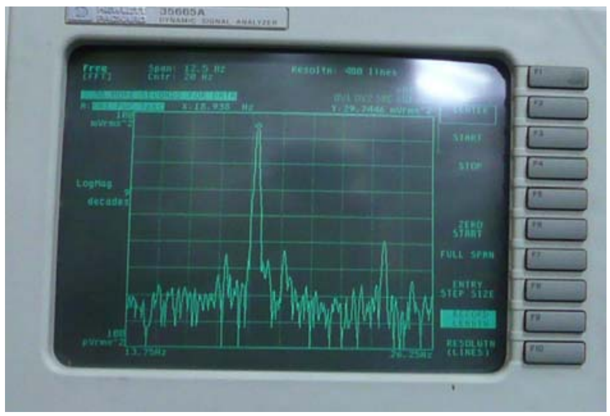


Figure 5 Narrow peak on the Spectrum analyser screen at the bounce frequency

Once the electronics and spectrum analyser have been set-up for the first fibre, all should be in place to measure other fibres of the same length much more quickly.

3.6 List of components

The bill of materials for the cabinet is the same as for the proof tester.

The bill of materials detector assembly and mass can be found in:

Drawing no.	**Description**
D1002083	aLIGO SUS UK bounce tester