REALISATION OF THE ALIGO FUSED SILICA SUSPENSION

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The planned upgrade for the LIGO gravitational wave detectors (Advanced LIGO) has been underway for a number of years. One of the most significant aspects of this upgrade is the use of all-fused-silica pendulums to reduce thermal noise. The test mass mirrors, made from fused silica, will each be suspended using four fused silica fibres from a fused silica isolation mass. The fibres are welded in place using a CO_2 laser. We describe the realisation of a working prototype suspension at the LIGO Advanced Systems Test Interferometer (LASTI) facility.

1 Introduction

The suspension design for the Advanced LIGO (aLIGO) interferometers is based on that used in the UK-German GE600 gravitational wave detector [1], but adapted to the requirements of aLIGO [2]. As shown in Figure 1, it consists of four masses, the upper two of which are made from steel and suspended by wires from maraging steel blade springs [3]. The lower two stages of the suspension consist of synthetic fused silica pieces which are 340 mm in diameter, 200 mm thick and each has a mass of 40 kg. The test mass is suspended by 4 fused silica fibres from the penultimate mass. The fibres are welded at both ends to silica attachment points (known as *ears*) that are hydroxide-catalysis bonded to the masses [4]. One can minimise thermoelastic noise caused by temperature fluctuations close to the bending point, by choosing the fibre dimensions in that region such that there is a cancellation between the noise terms originating from the thermal expansion coefficient and the combination of applied stress with the change in Young's modulus with temperature [5].

2 Fibre production

The silica fibres are drawn from 3 mm diameter fused silica stock using a laser heating method [6]. A copy of the original Glasgow designed machine was constructed at the LASTI facility at MIT

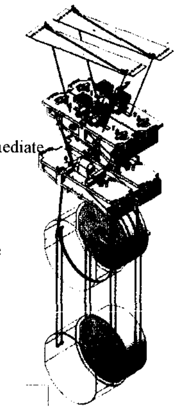

Figure 1: Schematic of the quadruple suspension showing the test mass, three isolation masses and the parallel reaction chain. The reaction chain provides a means to apply low noise control of the main suspension.

to produce fibres for the suspension. The preferred profile is one that has a 400 μm diameter along most of the fibre length but transitions to 800 μm for 20 mm near the ends and then, within a few millimetres, to 3 mm diameter. The 3 mm diameter sections allow the ends to be welded to the attachment point. The 800 μm sections are where most of the bending of the fibre takes place. The 400 μm diameter is determined by a compromise between fibre strength and the suspension vertical and fibre transverse mode frequencies. After the fibre has been pulled, its cross-sectional profile is measured using an optical non-contact method to ensure that it matches the required profile[7].

3 Welding the monolithic suspension

The development of the welding process is described in more detail elsewhere[8] . In this paper we note that before welding the fibres on the prototype suspension at LASTI, we carried out ten successful tests on a mock-up suspension that had fused silica attachment points affixed to 40 kg aluminium masses. These tests were used to determine any issues with the process and verify that the technique was robust. The welding of the fibres took place within a class 100 clean room tent. A CO_2 laser beam with up to 100 W power was used. The beam was directed to the welding head through an enclosed articulated arm as shown in Figure 2. The welding head consists of a two lens telescope, to set the beam size to the 3 mm working diameter, and two mirrors mounted on galvanometer drives, to enable the operator to direct the beam at any position on the weld. An angled mirror is placed behind the stock to allow 360^o access to the weld, as can be seen in Figure 3. Due to the high laser power involved, care must be taken to ensure that specular reflections do not escape from the working area. A number of purpose designed baffles are used to contain the beam within the working area and a thermal imaging camera was used (with the laser set at low power) to search for any beams that were not caught by these baffles. With the laser running at low power, the thermal imager easily detects the few Kelvin increase in temperature caused by the reflections. Before welding, a fibre is selected from storage and *proof-tested*, by applying a force of 150 N (150 % of nominal load) for 10

Figure 2: Welding the fibre to the penultimate mass. The picture shows the articulated arm bringing in the laser beam to the weld head. The suction tube to remove the silica vapour can also be seen.

minutes. Any fibre that has been damaged, by inadvertent touching for example, will break within 1 or 2 minutes at this tension. The tested fibre is then transferred to a *cutter*, which has been set to give the exact fibre length required. In the cutter, the excess lengths of stock are removed and the fibre is held by tweezers with zirconium dioxide tips. The tweezers are mounted on three-axis stages that are in turn mounted on an aluminium section. When released from the cutter, the fibre can then be transported to the structure that is used for holding the suspension during the welding procedure. When the fibre has been pulled, characterised and cut to length it can then be welded in position. When the suspension is complete, the fibres will stretch approximately 6 mm under load. The initial vertical position of the test mass is set with this correction applied. The fibres are welded in place one at a time. An example of a completed weld can be seen on the right-hand attachment point in Figure 3. When all 8 welds are complete, and before the test mass is released, the pitch of the test mass can be set with respect to the penultimate mass. At the same time, the tension in the fibres is set to zero. The test mass is lowered by 0.25 mm, putting a tension of 4 N on each fibre. The 4 welds at the penultimate mass are heated in turn until the silica softens and the fibre aligns itself with the tension and relaxes to reduce the tension to zero. The process is then repeated for the welds at the test mass. This time, after the mass has been lowered, the pitch alignment of the mass is set. The relaxation process is then carried out on all four lower welds. This means that before the test mass is released, the pitch is set to within 1 mrad, and all 4 fibres have nominally zero tension.

4 Post-welding

After the completion of the welds and the annealing and pitch alignment stage, the test mass is lowered until it hangs freely, to ensure that fibres and welds are strong enough. The pitch angle of the freely hanging mass was confirmed to be within 1 mrad of the expected value. After this test the two silica masses were connected to the upper part of the suspension and the full suspension was then transferred to the vacuum system. The suspended mirror formed one end

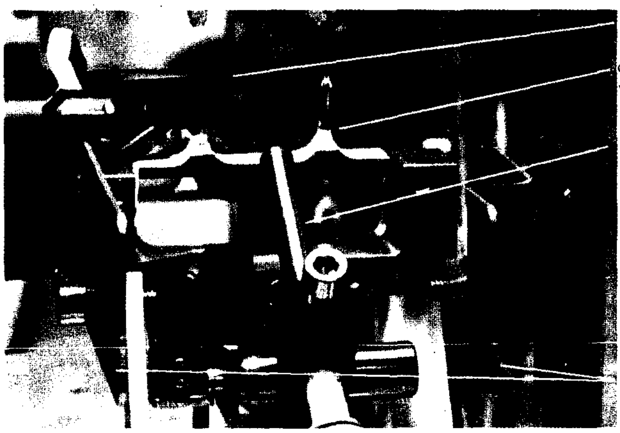

Figure 3: This picture shows two attachment points where the fibres are welded to the mass, the one on the right already has a finished weld. Weld tooling is in place on the one on the left. The long thin steel pipe is the extraction pipe to remove any silica vapour and stop deposition on the fibres or test mass during welding. The angled mirror that allows full access to the weld can be seen, as can the baffles used to catch errant beams.

of an optical cavity and the error signal from a laser that was frequency locked to this cavity, was used to measure the quality factor of test mass acoustic modes and the suspension fibres violin modes, to confirm the low mechanical loss of the monolithic suspension technique.

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