The development of technology for high performance laser interferometer gravitational wave detectors at the UWA

C.N. Zhao, J. Winterflood, M. Taniwaki,
M. Notcutt, J. Liu, L. Ju, D.G. Blair
Department of Physics, The University of Western Australia,
Nedlands, WA 6907, Australia

Abstract

In this paper we report progress in the development of technology for high performance laser interferometer gravitational wave detectors. This includes: (a) the development of ULF pre-isolators which are expected to greatly simplify laser interferometer control systems, (b) the demonstration of successful locking of an interferometer using multistage cantilever spring vibration isolators, and (c) the design of sapphire test masses capable of achieving a 16 fold reduction in test mass thermal noise.

1. Introduction

Laser interferometer gravitational wave detectors require high performance vibration isolation to reduce seismic noise. In previous work we have shown that vibration isolation with corner frequency down to about 10 Hz is relatively easy to achieve using mass-cantilever spring isolators [1,2], and also that it is possible to achieve substantially improved interferometer performance if a single ultra low frequency (ULF) pre-isolator stage is used [3]. A local control and locking system is essential to damp the low frequency normal modes of the vibration isolator and keep the interferometer locked at dark fringe.

High performance suspension systems are also crucial for reducing thermal noise. The thermal and mechanical properties of sapphire make it an interesting material for use as test masses. The high thermal conductivity of sapphire means that thermal lensing [4] can be minimised, while the combination of its very high Young's modulus and low acoustic loss will ensure that the internal resonant modes have high frequency and low thermal noise. The recent progress on polishing and coating of sapphire mirrors [5] seems also to indicate that the material is suitable.

In this paper we report progress in all of the areas discussed above. A new two dimensional ULF isolator structure is described. The first successful locking of a fully suspended interferometer using multistage cantilever spring isolators is reported. New measurements on sapphire are also reported along with modelling results which demonstrate that an interferometer with arms of only 400 m can achieve sensitivity comparable to that predicted for VIRGO and LIGO.

2. Ultra Low Frequency Pre-isolators

It has been shown that relatively simple ultra low frequency pendulum-like structures can be cascaded in front of multistage isolators to greatly improve the seismic isolation performance in the frequency range from tens of millihertz through tens of hertz as shown in figure 1. The internal modes of these ULF structures bypass their isolation above a few tens of hertz. However the multistage low-frequency isolator provides such enormous isolation at these frequencies that this is no disadvantage. The advantage provided by pre-isolation is a large reduction in the seismic motion driving the isolator normal modes and also an extension to the low frequency end of the detection band. The normal mode motion is so reduced that damping of these resonances is not required. Indeed if viscous damping of any sort is applied with respect to a seismic reference, the normal mode motion may be worsened since even the peaks can be reduced below the seismic level.

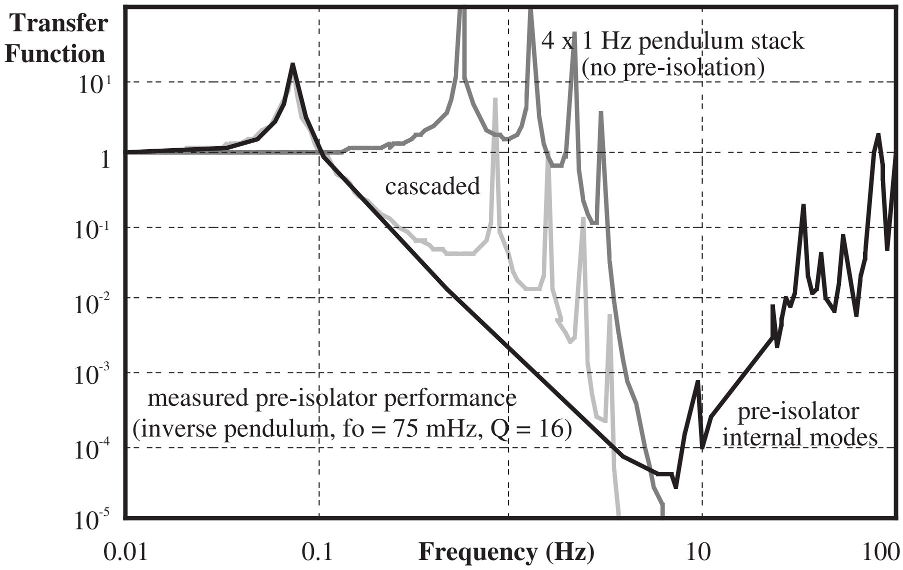

Fig. 1: Typical transfer functions of multistage isolator, pre-isolator, and the combination.

We have investigated several approaches. Inverted pendulum [6] or counter-sprung structures are mechanically the simplest. However in order to get low resonant frequencies, there has to be a large cancellation of gravitational force with elastic spring constant. For instance to tune a 1 metre inverted pendulum to 30 mHz resonant frequency requires a 99.6% cancellation of forces. At this level time dependent and non-linear effects begin to dominate [7] and the temperature dependence of the elastic spring constant becomes prominent. This system is also inconveniently sensitive to mass loading.

A more suitable approach for horizontal isolation is to use a linkage structure carefully aligned with gravity which simulates the motion of a very long radius pendulum [8,9], some examples of which are shown in figure 2. Ideally all joints should be perfectly flexible and the structure perfectly rigid. This would make the stability and resonant frequency independent of temperature and mass load. In practice the stiffness of the flexures and the limited rigidity of the mechanical structure are both significant at the 30 mHz level. However these non-ideal elastic spring constants have comparable magnitudes to the required residual restoring force so the balance is very stable with temperature and time and is only slightly sensitive to the suspended mass.

The folded pendulum or Watt's linkage (Fig. 2a) is one of many linkages which simulate a long radius pendulum in one dimension. Using this structure we have demonstrated 16 mHz corner frequency and isolation exceeding 100 dB at 10 Hz [8]. A few long-radius linkages may be generalised to cylindrical symmetry to mimic a very long *conical* pendulum achieving x–y isolation in a single stage. One such is the Scott-Russel linkage shown in figure 2b. It consists of a normal pendulum of length r joined near the mid-point of a beam of length $a + b$. The normal pendulum is under tension and supports the entire weight of the structure and suspended mass. The top section of the beam supports the suspended mass under compression (and bending). The lower end of the beam is merely constrained to move in a vertical line directly under the main support. This is shown as a sliding joint but in practice taut wire guidance functions acceptably as the vertical motion is extremely small.

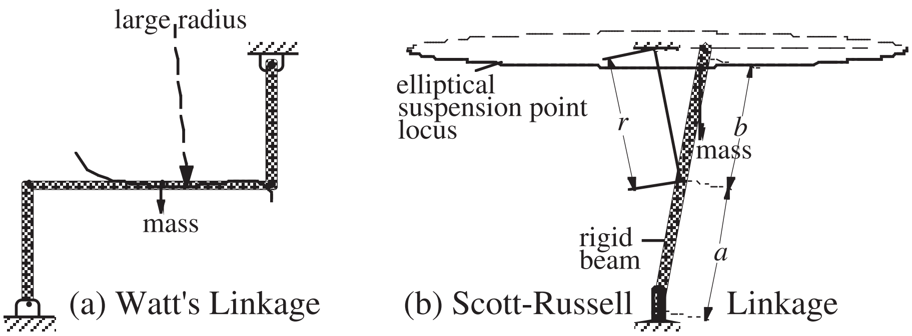

Fig. 2: Linkages simulating the large radius of a very long pendulum.

If length a is made equal to r then the upper section of the beam b may be considered as an inverted pendulum which is constrained to follow the same angle of deflection as the normal pendulum a. If b is also equal to r then the effect of the normal and inverted pendulums cancel and the suspension point follows a straight horizontal line. If a slightly lower suspension point is chosen, then the suspension point follows an elliptical path as shown which may in principle be set to any large radius for small displacements. This linkage may be given cylindrical symmetry to produce spherical motion. There are some spatial conflicts between supports and suspended masses but these are readily overcome with a little ingenuity. We have tested a small model with very encouraging results [10]. A full sized pre-isolator for our existing isolators is under construction.

3. The 8 m Interferometer and Its Control System

Multistage low frequency isolators based on the cantilever spring-mass isolation elements have been developed at UWA and described elsewhere [1]. Four isolator stages of about 90 kg each support an 11 kg compound pendulum test mass suspended with a thin membrane [11]. The isolator system has four vertical modes (1.3, 3.2, 4.5, and

6.5 Hz), four horizontal modes (0.47, 1.8, 1.9 and 2.5 Hz), four rocking modes (below 1.2 Hz) and four low frequency torsional modes (below 0.4 Hz). The high frequency performance of the isolator has been tested using a sapphire transducer [12]. The vertical and horizontal response of the isolator at high frequencies (above the transducer mechanical resonance of about 60 Hz) reaches the noise floor of the sapphire transducer of 3×10^{-15} m $/\sqrt{\text{Hz}}$ [1].

Since demonstrating the performance of the individual isolators, we have concentrated on demonstrating that this isolator structure along with membrane suspended compound pendulum test masses can be used in a practical interferometer. To suppress the normal mode amplitudes sufficiently to be able to achieve locking of the interferometer output to a dark fringe we have used a computer controlled PID servo system [13]. Shadow sensors are used to sense the normal mode motion of the translation of the control mass and the tilt of the test mass. Rotational motion is monitored using an optical lever arm. In each case the signals are fed back to coil/magnet actuators which apply forces to the control mass and test mass to damp the normal modes and control them. The servo signal from the global locking interferometer is also fed back to the test mass actuators.

We have established an 8 m suspended simple Michelson interferometer illuminated by a 58 mW Nd:YAG laser. The fringe contrast of the interferometer is 0.98. It has been successfully locked to the dark fringe using the internal modulation technique [14] with a modulator in one arm. We are particularly pleased to have been able to show that there is no apparent problem in terms of control of the low frequency multistage cantilever spring isolators, nor the compound pendulum test mass suspension. Locking up is easy. We can see some excess noise around 1.5 kHz which we are currently investigating and noise introduced by the control system below 1 kHz.

4. Sapphire Test Masses

Sapphire with its high Q–factor, high sound velocity, high thermal conductivity and low absorption is a very attractive material for use as beamsplitters and test masses. For a cylindrical sapphire test mass with diameter of $d = 200$ mm, thickness of $H = 200$ mm ($\sim$ 25 kg) and a beam size of 2 cm, the internal resonances are higher than 22 kHz [17]. The high internal resonant frequencies in the sapphire test mass are very important in reducing their thermal noise contribution. Integrating the thermal noise over the first 200 normal modes, taking into account that the Q–factor of sapphire is about 43 times greater than that of silica [15,16] and comparing the results with that of a silica test mass of the same dimensions, the thermal noise amplitude of this sapphire test mass will be a factor 16 times better than that of a silica test mass with the same dimensions [17].

Optical absorption of test masses and mirrors causes thermal lensing which limits the maximum optical power in interferometers. Sapphire, with high thermal conductivity about 17 times higher than silica, produces less thermal lesing. The distortion is determined by the ratio $\mathrm{d}u/\mathrm{d}t/K$ and this is 30 times less for sapphire than for silica. Recent measurements [18] have shown that the optical absorption coefficient of sapphire can be as low as 3.5 ppm/cm at 1 μm wavelength. This is superior to most samples of fused silica, although a silica sample with 1 ppm/cm loss has recently been demonstrated [19].

The intrinsic birefringence of sapphire is a disadvantage. However analysis has shown [17] that in a well controlled interferometer with misalignment angles less than 100 μrad, the loss due to birefringence will be significantly less than other loss sources such as mirror losses and curvature mismatch. Test masses are normally controlled to 100 μrad [2] in prototype instruments and even better in long baseline designs, so this aspect of birefringence seems to be tolerable, although accurate metrology is required to define the crystal axis of optical components.

On the other hand, inhomogeneity and localised stress can cause inhomogeneous birefringence. The birefringence of a small sapphire sample has been investigated [17]. The sample shows stable performance in the central region but is degraded at the corners where machining has created high stress. For a large sapphire test mass, it is expected that stress associated with machining will be greatly reduced. The inhomogeneous birefringence of the small sapphire sample is estimated to be less than 0.04°/cm. It is of great importance that further more accurate measurements on large sapphire samples be made to obtain definite results.

5. Test Mass Suspension

To fully benefit from the low thermal noise acoustic properties of sapphire it is essential to develop greatly improved suspension systems. For this reason there is great interest in the development of “monolithic” suspension systems. The bonding of a niobium flexure to sapphire seems quite promising. We have calculated that niobium flexure bonded to sapphire test masses can allow pendulum Q–factors as high as 10^{10} and vertical mode Q–factors $\geq 3 \times 10^8$. This requires strength low acoustic loss bonding of niobium and sapphire. A preliminary bonding test using Incusil-ABA sheet between niobium and sapphire showed a bonding strength > 150 MPa. The effect of the bonded flexure on the internal Q–factor of the sapphire will be investigated.

6. Conclusion

We have shown that pre-isolators can greatly improve isolator performance and that two-dimensional isolator structures are well suited to use in interferometers. Progress in the study of sapphire test masses leads to the expectation that thermal noise can be reduced by about one order of magnitude compared with previous estimates. The locking of the 8 m suspended laser interferometer has shown the practicality of multistage cantilever spring isolators. The results on the prototype interferometer system at UWA combined with the above modelling lead to a prediction [11] that the mid-baseline laser interferometer AIGO 400 using multistage cantilever spring isolators and sapphire test masses should be capable of approaching the sensitivity level of stage one long baseline (3$\sim$4 km) instruments over a bandwidth of a few hundred Hertz.

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