SUSPENSION SYSTEM DESIGN FOR THE MAIN OPTICS FOR GEO 600

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The GEO 600 gravitational wave detector is currently under construction in Germany. To ensure that the detector sensitivity is not limited by seismic noise above 50 Hz a significant degree of isolation has to be provided for each test mass. To achieve this level of isolation each test mass, which will be made from fused silica (mass $\sim$ 6 kg), will be suspended as the final stage of a triple pendulum. The triple pendulum will incorporate two stages of cantilever springs in order to enhance the vertical isolation and will use fused silica fibres in the lower pendulum stage in order to minimise thermal noise from the pendulum modes. Details of the mechanical design and experiments carried out on a prototype suspension in Glasgow will be discussed.

1 Main mirror suspensions

1.1 Introduction

The GEO 600 (German-British) detector [1] is designed to operate down to 50 Hz. The sensitivity limit at this frequency is set by the thermal noise from the internal modes of the fused silica test masses. The strain sensitivity limit from thermal noise is expected to be $2 \times 10^{-22}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at a frequency, f, of 50 Hz. For our optical system this corresponds to a motion of each mirror of approximately $7 \times 10^{-20}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 50 Hz. The design goal for the seismic isolation system is to achieve a noise level at each test mass a factor of 10 lower than this [2,3]. A seismic noise spectrum, of the GEO 600 site near Hannover [4], of $\sim 10^{-7}/f^2\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ in all dimensions has been measured. Therefore an isolation factor of 6×10^9 at 50 Hz in the horizontal and 6×10^6 in the vertical is required for the mirror test masses if a coupling factor of 0.1 % of vertical to horizontal motion is adopted. This factor is a value which has been typically seen in the Glasgow 10 m prototype detector [5].

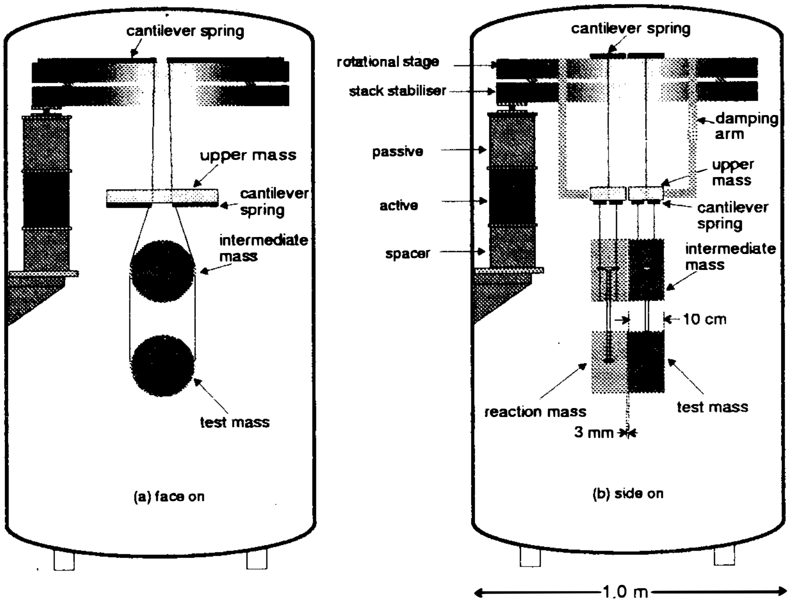

Figure 1: Schematic of main suspension: (a) face on (b) side on

We expect the isolation of each mirror to be achievable with a combination of several elements. At the bottom of each suspension system there will be three legs each consisting of a two-layer isolation stack, the lower layer of which is active and the upper layer is passive. At the top of each stack there will be a rotational flexure in order to reduce the rotational stiffness of the system, and a stack stabiliser will connect the three legs. A further structure, called the rotational stage, will interface between the stack stabiliser and the pendulum system. From the top of the rotational stage an upper mass is suspended from two cantilever springs, providing additional vertical isolation, and from the upper mass a double pendulum is suspended by a further 4 cantilever springs. Thus the suspension from the rotational stage is a triple pendulum. A schematic of the overall suspension system is shown in figure 1. The purpose of the reaction mass pendulum is to provide a seismically isolated platform for the application of overall control forces in the detector.

1.2 Isolation stack

As described above, each isolation stack consists of two layers, the lower layer of which is active and the upper layer is passive. In the active layer feed forward will be used to control the effects of the micro-seismic peak and feedback will be used to improve the isolation at higher frequencies. The passive layer behaves like a mass on a spring. In our stack the masses are steel blocks and the springs are pieces of graphite loaded silicone rubber (RTV 615)[6]. The RTV will be encapsulated in stainless steel bellows in order to meet the GEO 600 vacuum specification. The overall transfer function of one layer is similar to a pendulum. However typically the quality factor, Q, is chosen to be small (~ 10) so as to reduce the amplitude of the seismic noise at the resonances of the stack. A single passive layer can be designed to have a vertical frequency at 15 Hz, with a 20-kg load. Experiments at Glasgow have shown an attenuation of ~ 20 dB at 50 Hz can be achieved with this single passive layer.

1.3 *Cantilever blades*

In order to enhance the vertical isolation two vertical spring stages will be included in the triple pendulum. Two relatively long upper blades with uncoupled vertical frequency [a] 1.9 Hz are attached to the rotational stage and support an upper mass. Four shorter blades with uncoupled vertical frequency 3 Hz then suspend a double pendulum from the upper mass. The blades are constructed from maraging (precipitation hardened) steel, which is low carbon steel with a high tensile stress, in a design adapted from that used by the VIRGO group [7]. Several aspects have to be considered in the design of each blade [8]. Firstly the frequency of the bending mode must be chosen in order to obtain the required level of vertical isolation. Secondly the maximum stress for the blade is set at approximately half of the elastic limit of the maraging steel to minimise the effect of long term creep.

1.4 *Triple pendulum*

A theoretical model of the triple pendulum was required to allow us to predict all of its resonant mode frequencies. Two different techniques were used, firstly writing down the differential equations of motion using Newton's second law and secondly calculating the kinetic and potential energy in order to utilise Lagrange's equations. The first technique was used in modelling by C.Torrie and the second technique was adopted by M. Husman. We were able to confirm that our models were consistent [9].

There are several constraints already in place for the triple pendulum suspension, which have to be taken into account before finalising the design and calculating the mode frequencies. Firstly the intermediate and test mass main optics will be made from fused silica (Suprasil 1) with four vertical fibres of fused silica between them. This design has been chosen to minimise the effects of thermal noise [10]. Secondly the low frequency resonant modes of the triple pendulum require to be damped in a way that does not introduce excess noise at the test mass. Modelling of local control servo systems indicates that the various low frequency modes can be actively damped by applying signals to the upper mass using six actuators [5,11], providing the modes lie in a narrow band of frequencies with an upper limit of less than 5 Hz. Applying the active damping at the upper mass ensures that any extra motion caused by electronic noise in the feedback system is filtered by the double pendulum below and therefore does not affect the test mass. The active damping system uses co-located damping; a sensor is used to detect the motion of the pendulum and then a coil/magnet transducer [12] applies a feedback force at the point of sensing to counter the motion. The coils are mounted on damping arms attached to the rotational stage, see figure 1. In order to be able to apply orientation control from the actuators on the upper mass, there must be four wires between the upper and intermediate mass.

The frequencies can be made to lie within the specified range apart from the vertical and roll frequencies of the final stage which lie between 20 and 40 Hz. These frequencies are left undamped in the present set-up as they occur too near the gravitational wave band for sufficient attenuation of electronic noise. The final stage of suspension is on fused silica fibres to minimise thermal noise effects [13,14]. It therefore does not incorporate cantilever blades as used in the upper two stages to give low vertical frequencies.

2 Glasgow prototype suspension

2.1 *Introduction*

A prototype triple pendulum suspension was constructed in Glasgow but without reaction masses. Aluminium masses of the same mass and outer dimensions as the fused silica masses

[a]The frequency observed for a spring in a particular stage supporting only the mass of that stage.

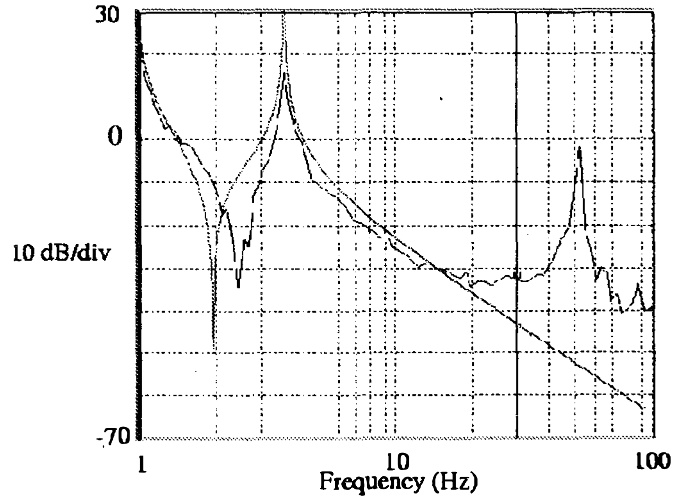

Figure 2: Vertical transfer function of upper cantilever blades.

to be used in the final design were used for the intermediate and test masses. Steel wires were used to suspend each stage. The two stages of cantilever springs outlined in section 1.3 were also used. The purpose of this prototype was to test the predicted performance of both stages of cantilevers, to test the theoretical mode frequencies and to test the performance of the damped triple pendulum in the longitudinal direction. The results are outlined below.

2.2 Vertical transfer function

On the full triple pendulum model the theoretical response of the upper stage, which is suspended from two cantilever blades, was obtained using MATLAB [15], and shows a $1/f^2$ fall off above the coupled frequency of the blade, see figure 2. This simple model assumes that the blade acts as a massless spring. A vertical transfer function from the rotational stage to the upper mass of the triple pendulum was obtained. The pendulum was driven by a shaker constructed from piezoelectric elements and the response measured using accelerometers. The experimental trace is shown in figure 2. The flattening of the response above $\sim$ 20 Hz is consistent with measurements carried out by the VIRGO group [7]. The flattening is due to the fact that the blades have a finite mass, and that the attachment point of the wires is not at the centre of percussion of the blade. The first internal mode at 55 Hz is also shown in figure 2. The upper blade has since been re-designed so that the first internal mode is above 100 Hz.

A transfer function of the lower blades was also obtained. An attenuation of $\sim$ 55 dB at 50 Hz was measured with the blades behaving ideally up to a frequency of $\sim$ 80 Hz. The first internal mode of the lower blades was measured at 220 Hz.

2.3 Impulse response

As already mentioned, the resonant modes of the triple pendulum will be actively damped from the upper mass. Modelling of the local control servo indicates that all the modes can be damped with a Q value less than 5 except the vertical and roll frequencies associated with the final stage. The theoretical and experimental response of the two longitudinal actuators are shown in figure 3. An impulse was applied to both of the longitudinal actuators and the response was measured. The experimental plots fit closely with the theoretical prediction (dotted line).

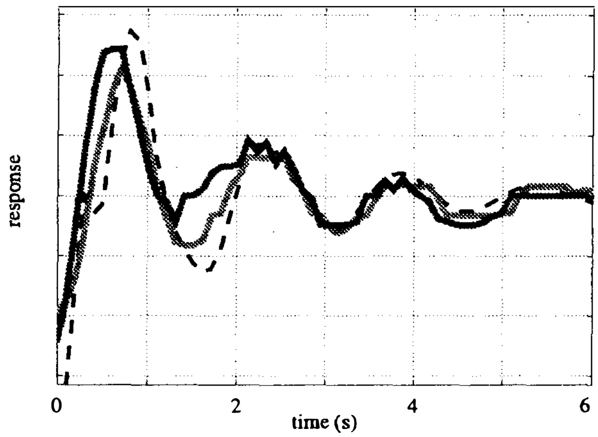

Figure 3: Longitudinal impulse response

Table 1: Prototype mode frequencies (Hz)

	theoretical	experimental
tilt / longitudinal	3.6, 2.7, 2.4 1.35, 0.5, 0.6	3.5, 2.6, 2.2 1.35, 0.6
roll / sideways	52, 3.3,2.5 1.35, 0.9, 0.6	1.37, 1.0, 0.6
rotational	3.1, 1.6, 0.4	3.1, 1.55
vertical	36, 3.8, 1.0	37, 3.7, 1.0

2.4 Mode frequencies

The resonant frequencies were obtained by exciting the triple pendulum and measuring the response from an accelerometer attached to the upper mass, with a spectrum analyser. Both the theoretical predictions and experimental results for the prototype triple pendulum are given in table 1. It can be seen that for those frequencies which have been observed there is good agreement with the theoretical predictions.

3 Conclusions

Various aspects of the design of the seismic isolation system for GEO 600 have been discussed. The design involves an isolation stack and a triple pendulum incorporating two sets of vertical cantilever blades. Experiments on the individual stages of the Glasgow prototype suspension indicate that a seismic noise level which is a factor of ~ 4.5 lower than the thermal noise level at 50 Hz should be achievable with the current design [16].

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