

LASER INTERFEROMETER GRAVITATIONAL
WAVE OBSERVATORY
– LIGO –

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<h2>Mirror Suspension System for the TAMA SAS</h2>		
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Abstract

Several R&D programs are ongoing to develop the next generation of the interferometric gravitational wave detectors providing the superior sensitivity desired for refined astronomical observations. In order to obtain a wide observation band at low frequencies, the optics need to be isolated from the seismic noise. The TAMA SAS (Seismic Attenuation System) has been developed within an international collaboration between TAMA, LIGO, and some European institutes, with the main objective of achieving sufficient low frequency seismic attenuation (-180 dB at 10 Hz). The system suppresses the seismic noise well below the other noise levels starting at very low frequencies above 10 Hz. It also includes an active inertial damping system to decrease the residual motion of the optics enough to allow a stable operation of the interferometer. The TAMA SAS also comprises a sophisticated mirror suspension subsystem (SUS). The SUS provides support for the optics and vibration isolation complementing the SAS performance. The SUS is equipped with a totally passive magnetic damper to suppress internal resonances without degrading the thermal noise performance. In this paper we discuss the SUS details and present prototype results.

Introduction

There are presently several ground-based gravitational wave (GW) laser interferometer detectors being developed or operated. These detectors (LIGO, TAMA, Virgo, GEO600) are designed for direct detection of the GWs; they have best sensitivity around 100 Hz, at relatively high frequencies, where many promising astronomical events are expected. To establish GW astronomy with these instruments, it is necessary to

improve their sensitivity and the frequency reach. For this purpose a new generation of detectors with higher sensitivity and lower frequency reach is being developed. The major obstacle for a ground-based laser interferometer is the seismic disturbance at low frequency. Therefore, seismic isolators with superior low frequency attenuation performance are required. The SAS (Seismic Attenuation System) has been developed to provide reliable seismic isolation starting at 100 mHz frequency which will allow robust operation of the interferometer.

The SAS (see Figure 1 and 2) can be considered as a cascade of passive mechanical filters, with active controls to suppress resonances at low frequencies [5]. TAMA SAS, was designed to fit into the vacuum chambers of the TAMA 300 interferometer. Ultra low frequency attenuation is realized with an inverted pendulum (IP), with resonant frequency of a few tens of mHz. Following it there are two stages of cascaded isolators implemented with low frequency vertical springs [4]. Below the lower filter a suspension platform hosts four vertical isolation springs for mirror suspension. A double pendulum mirror suspension is hooked from these springs.

Design Features of the New Suspension

In order to use TAMA SAS in the TAMA300 laser interferometers, it must be implemented with a suitable mirror suspension subsystem (SUS). The basic concept of the current TAMA mirror suspension was retained to design the SUS for the TAMA SAS [1] [2]. A schematic view of the new suspension system is shown in Fig. 2. The suspension consists of a double stage pendulum; both the intermediate mass and the mirror are suspended at four points by tungsten wires, with diameter of 100 μm and 50 μm respectively. In the prototype TAMA SAS/SUS, the role of the mirror is played by an

aluminum cylinder which has the same outer dimension, mass and momenta of inertia as a real fused silica mirror of the TAMA 300 interferometer. Each mirror carries four pin-shaped permanent magnets for actuation.

Although the IP has an active damping system to suppress the resonances of the SAS/SUS rigid body modes, there are some modes of the SUS which cannot be damped from it, since the active damping is obtained with local sensors and actuators on the IP [3] [6] [7]. For instance, the pitch motion of the mirror does not recoil much against the IP. To overcome this problem and suppress the r.m.s. motion of the mirror, SUS is equipped with a passive magnetic damper. Independently suspended Neodymium permanent magnets are located around the aluminum intermediate mass (a stage just above the mirror.) Eddy current on the intermediate mass induce velocity damping on the intermediate mass. The motion of the damping magnets can be cross-coupled to the mass. This effect would convert the $1/f^2$ (where f is the noise frequency) asymptotic behavior of the vibration isolation factor of the intermediate mass to a much worse $1/f$ behavior. To avoid this problem, the damping magnets are also suspended with flexible stainless steel rods and vertical springs. In this way the magnets, sufficiently isolated from the ground motion, will not introduce vibration transfer and the best $1/f^2$ attenuation on the intermediate mass will be preserved. Moreover, by choosing proper dimension and mass parameters of each stage, the mirror motion in all the degrees of freedom can be coupled to the motion of the intermediate mass and damped passively. Although the damper dissipates major amounts of energy, of the order of 10^{-7} J, in the intermediate mass, the corresponding thermal fluctuation will not transfer to the mirror because of the attenuation of the last pendulum.

To further simplify the suspension control, we implemented a coaxial recoil mass suspended from the intermediate mass. It hosts the control coils for the mirror. This configuration eliminates complicated response functions in mirror actuation. If the coils were mounted onto a structure with very different mechanical admittance than that of the mirror, there would be large asymmetry in recoil forces leaking onto the upper stages. For example, if the coils were located on a rigid frame fixed to the last attenuation filter, the mirror actuation would have complex behavior. Actuating on the mirror from a similarly suspended mass, all recoiling forces compensate and will not transmit to the upper stages. As a result, the mirror responds as a single pendulum (Fig. 3).

A drawback of the recoil mass is that it introduces an additional mode (the differential motion of the mirror and the recoil mass) which cannot be damped with the magnetic damper above. To fix this problem, a dedicated recoil mass magnetic damper was installed. The recoil mass damper is attached to the intermediate mass damper with a flexible rod, also to avoid vibration re-injection. Since the real mirror is made of fused silica, a non-magnetic material, damping works only on the aluminum recoil mass. The mirror is doubly isolated from the thermal fluctuation on the recoil mass due to the step up to the intermediate mass and the step down to the mirror. The thermal noise of the dampers does not harm the performance of the system.

To determine the parameters of the mechanics and to study their characteristics, several simulations were performed with commercial and custom software [8].

Experimental Results

In order to validate the design of the new mirror suspension, we characterized a SUS prototype passive isolation performance and controllability. For these measurements,

the SUS was separated from the rest of the SAS chain and located on a rigid frame fixed on a horizontal shaker. The shaker has a 2 kW voice coil actuator acting on a movable table supported and guided by oil bearings. The damping magnets on the recoil mass were not included in the system under test. The motion of each suspension stage was detected with commercial compact accelerometers above 1 Hz and with custom DC photo-position sensors below 1 Hz. Fig. 4 Top [bottom] compares the measured transfer functions in the longitudinal direction between the platform and the mirror, [and the intermediate mass] with simulated curves. The few mismatches between the two curves, and their origins, are well identified. For instance, the three bumps between 2 and 10 Hz correspond to pitch resonances of the mirror, the recoil mass, and the damping magnet holder respectively. These cross-coupling from pitch modes can be reduced by moving the wire clamps closer to the center of mass on each stage. More importantly, the best asymptotic trend of $1/f^4$ for the mirror is preserved while having the fundamental resonance at 850 mHz well damped by the magnets. The measurement was limited above a few tens of Hz by ambient acoustic noise picked up by the accelerometers.

Fig.5 shows the measured response of the mirror to the actuation force in the longitudinal direction. In this measurement, the SUS platform was suspended from the SAS lower filter with a single wire. One can clearly see the effect of acting from the recoil mass. The response of the mirror is basically simplified like that of the simplest single pendulum.

Conclusions

We have designed a mirror suspension system optimized for the TAMA SAS, a novel, low frequency seismic isolator. The main features of the suspension are a passive magnetic damping on the intermediate mass, that does not spoil the isolation performance of the double pendulum, and the use of a coaxial recoil mass pendulum to simplify the mirror controls. The advantages of these features were confirmed by the measurements with a prototype suspension.

References

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The drawings of the suspension system for the TAMA SAS and related mechanics are available at LIGO web site with the following document code.

[11] LIGO-D-010249-00-R

[12] LIGO-D-010250-00-R

[13] LIGO-T-10132-00-R

Figures and Captions

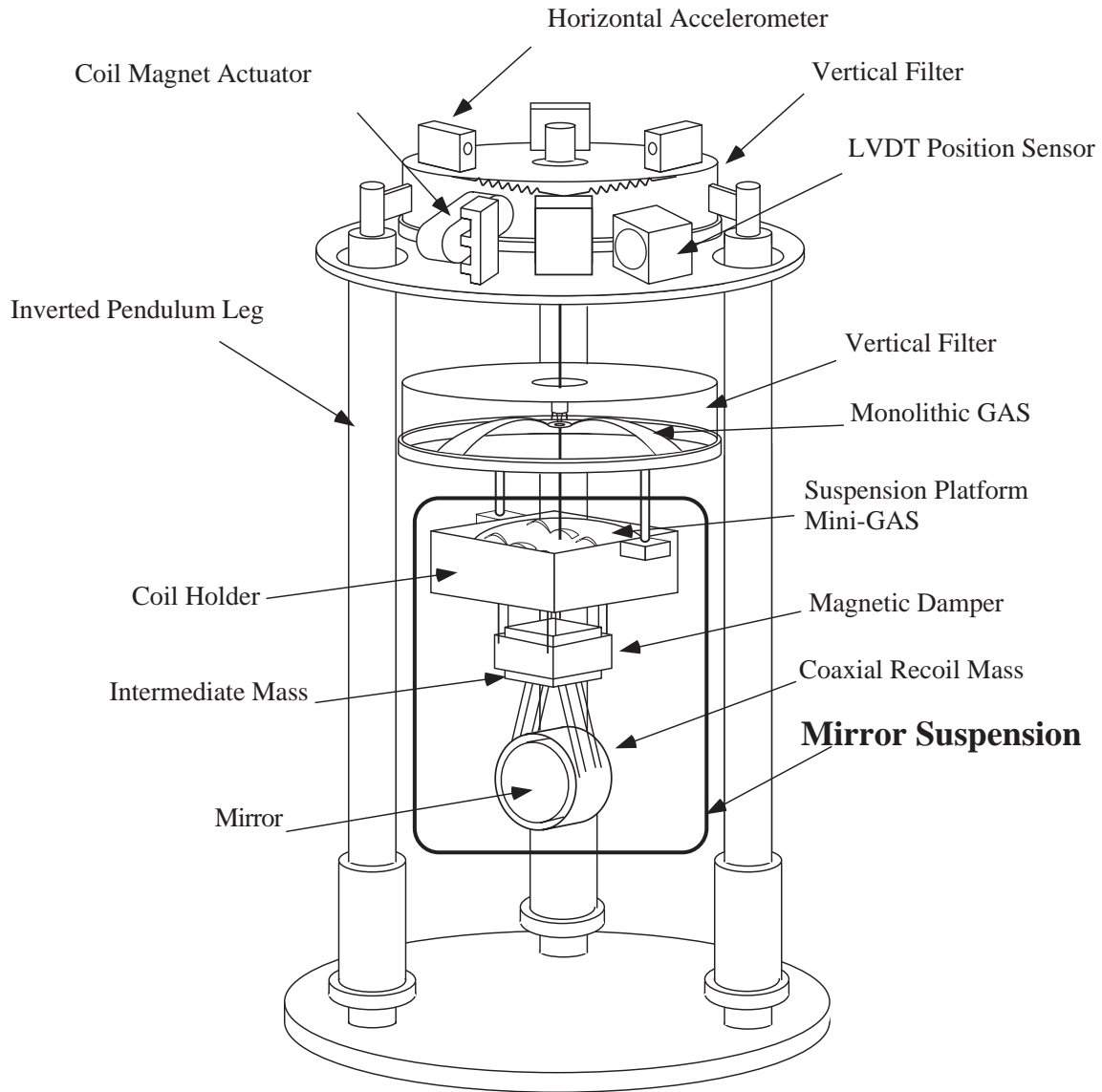


Fig.1 Schematic view of the TAMA SAS/SUS. An inverted pendulum hosts two stages of vertical isolators and the mirror suspension subsystem. The SUS part is further detailed in figure 2.

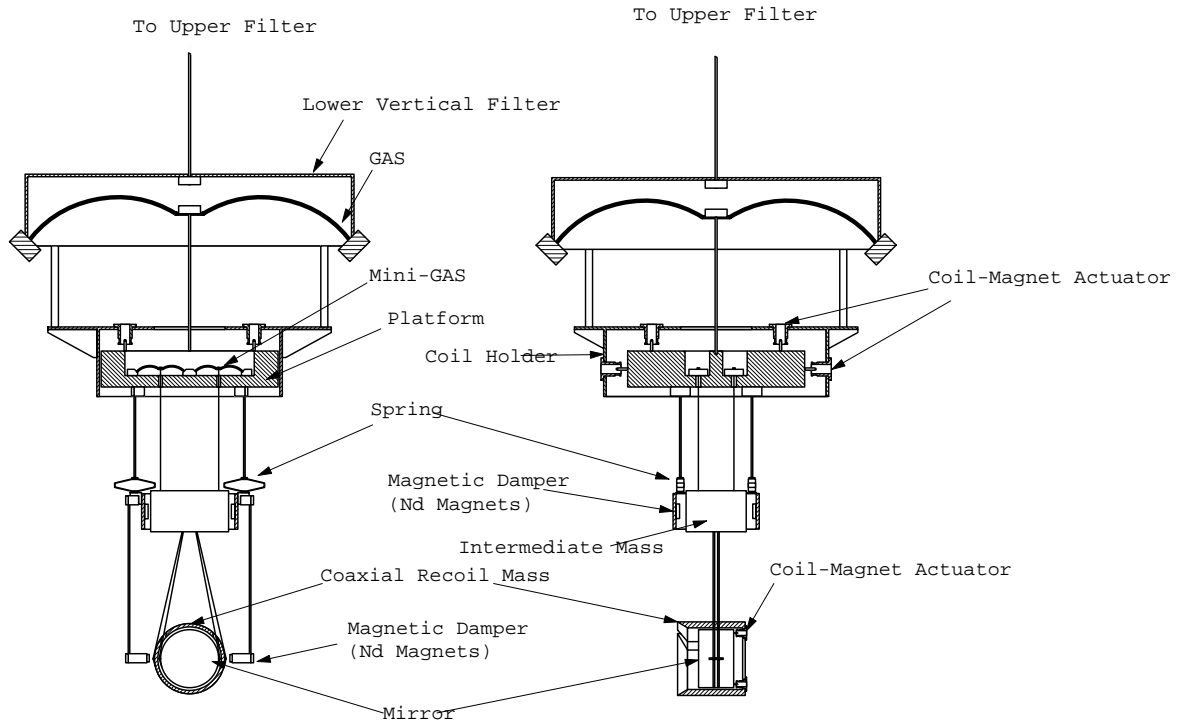


Fig.2 A schematic view of the mirror suspension subsystem (SUS). The system has a double pendulum construction and there is a passive magnetic damper around the intermediate stage. The mirror is co-located with a coaxial recoil mass for control purposes which is also provided with a dedicated suspended damping device.

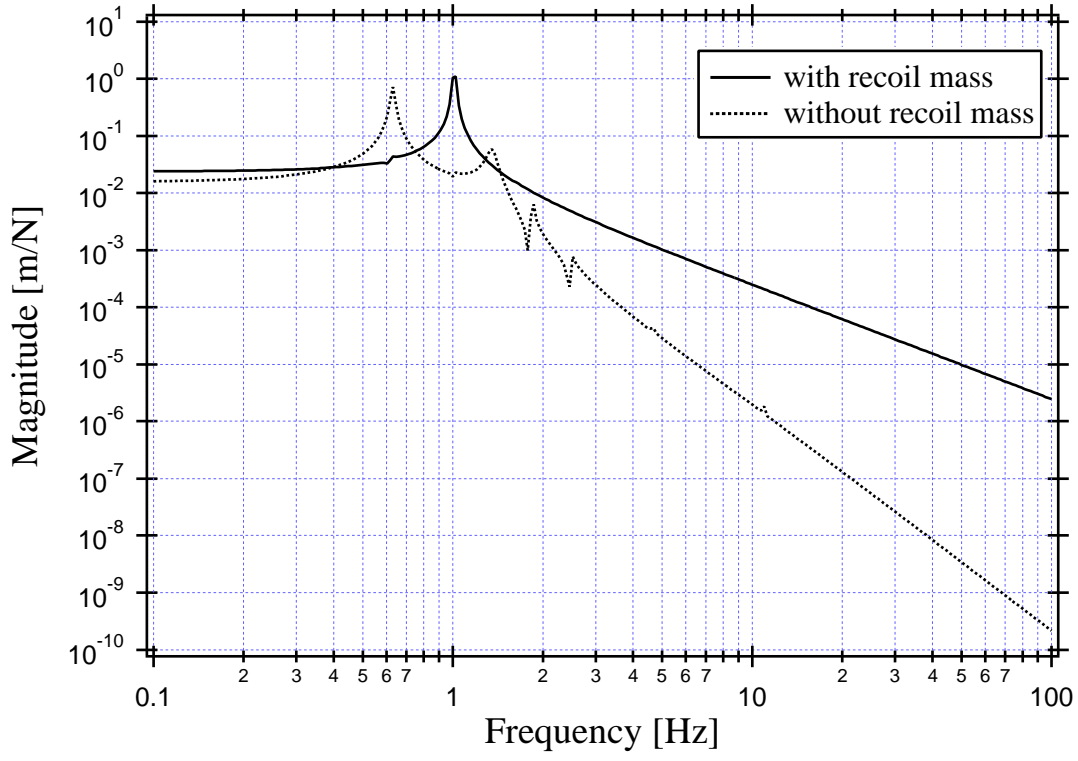
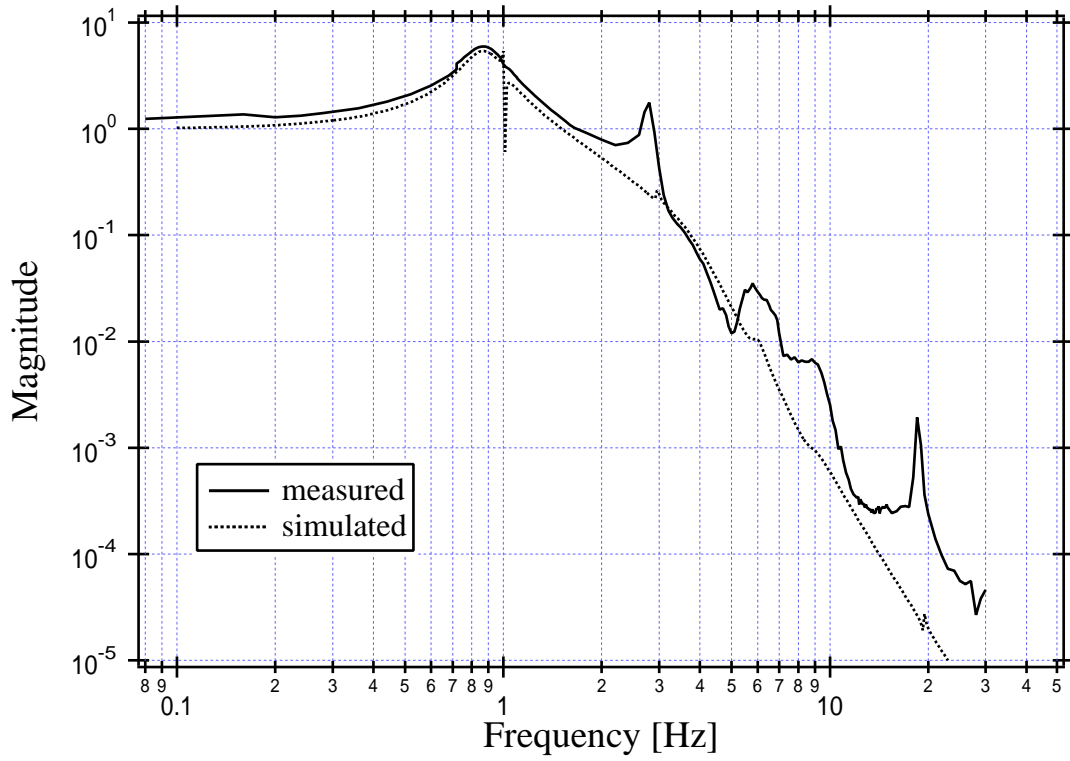
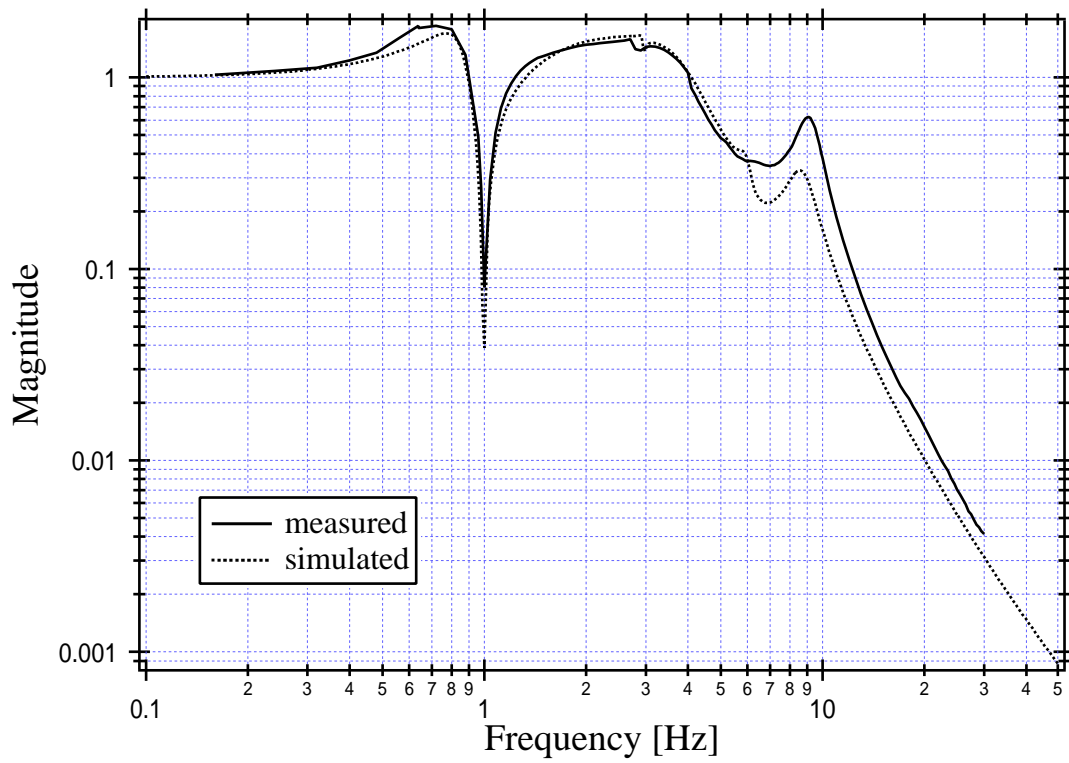


Fig.3 Computer simulated motion transfer function needed for mirror actuation in the longitudinal direction (dotted line). One needs to deal with a complicated response without the recoil mass. The response is simplified like that of a single pendulum (solid line) with the recoil mass.



(a)



(b)

Fig.4 Measured motion transfer function in the horizontal direction between the suspension platform to the mirror (a), and to the intermediate mass (b). Apart from slight difference in appearance of a few peaks, the measured curves (solid line) agree well with the simulated ones (dotted).

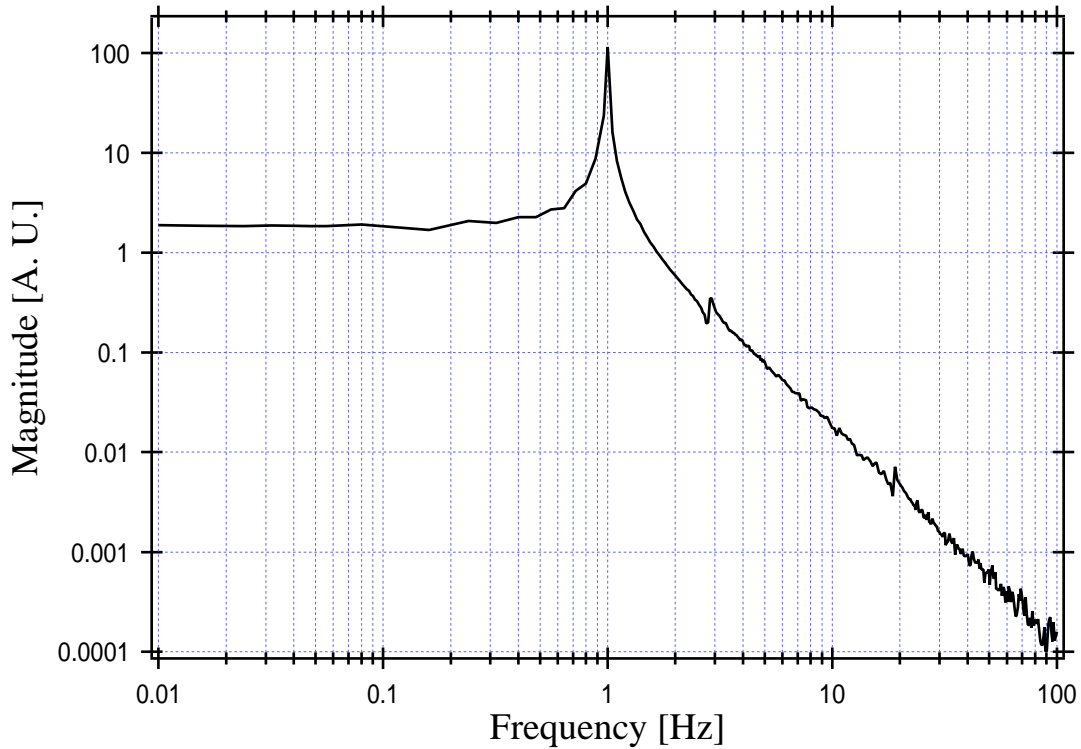


Fig.5 Measured motion transfer function of the mirror actuation in the longitudinal direction. Due to cancellation of the recoil effect on the intermediate mass, the mirror can be controlled as a simple single pendulum.