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Thermal and excess noise in suspension fibres

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Abstract
We present a progress report on the measurement of mechanical noise in mirror suspension prototypes. Excess noise in the metal wires has been detected. An advanced technique for the fused silica fibres test has been developed.

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1. Introduction

The sensitivity of large-scale gravitational wave detectors [1] is limited by the stochastic forces applied to the interferometer mirrors. The random motion of the suspension structure is a source of the force acting directly on the mirrors. In the interferometric detectors LIGO-I and TAMA steel wires are currently used as the final stage of the test mass suspension. It is expected that fused silica fibres will be a good alternative in the advanced detectors (VIRGO, LIGO-II and GEO-600). The main advantage of fused silica is a low acoustic loss, which makes it possible to increase the quality factor of all modes of mechanical vibration in the test mass suspension system. Recent investigations have shown that this value can reach $Q_{\mathrm{silica}} \sim 10^8$ for fused silica fibres [2, 3] and it is believed that it is limited by the surface loss. The rms variation of the amplitude for an oscillator with a resonant frequency ω, quality factor Q, effective mass m^* measured over the time t is

$$\Delta A_{rms} \sim \sqrt{\frac{kTt}{m^*\omega Q}}.$$

This means that the spectrum density of the equilibrium thermal noise induced by the fused silica suspension can be reduced by a factor of ~30 compared with the steel wires design ($Q_{\mathrm{steel}} \sim 10^5$). On the other hand, the existence of an extra (excess) noise of nonthermal origin is possible. Its source could be the development of microcracks, the migration of dislocations and other defects in the suspension material. There is a big difference between the structure of steel (metal) wires and fused silica (glassy) fibres. In our previous experiments [4, 5], it was observed that the mechanical noise in the steel and tungsten wires depends on the applied stress. It is well known that the mechanical properties of metals change abruptly when the

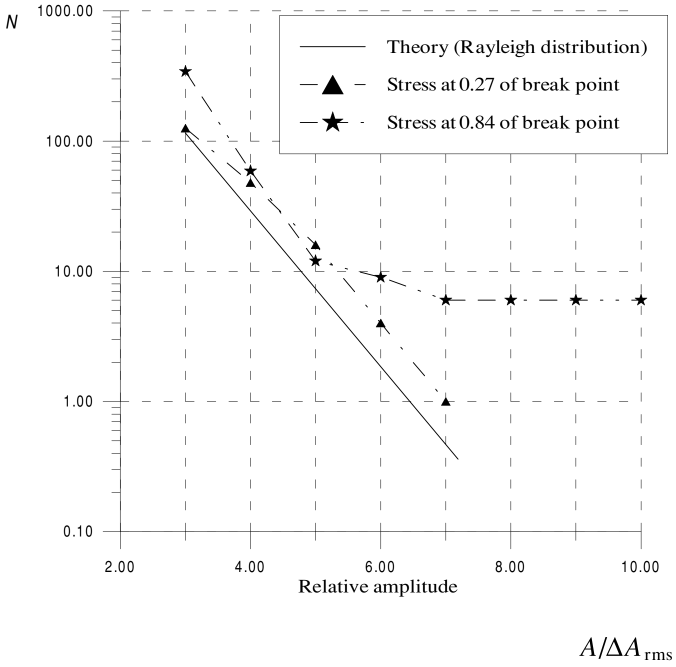

Figure 1. Amplitude variation intensity cumulative histogram for the steel wire oscillation on the fundamental violin mode. *N* is the relative number of variations per hour with amplitude exceeding the threshold *A*.

applied stress overcomes the yield point. It is not clear if a threshold stress value exists for fused silica. Thus, the experimental investigation of this type of suspension is important for the design of the next generation of gravitational wave detectors.

2. Excess noise in the steel wires

The existence of additional mechanical fluctuations was demonstrated in our experiments with tungsten and steel wires [4, 5]. Short bursts (compared to the relaxation time) and spontaneous increase of the effective temperature were observed. A Michelson interferometer pumped by an He–Ne laser was used. The displacement resolution $\Delta x_{\mathrm{min}} \cong 2 \times 10^{-11}$ cm Hz$^{-1/2}$ was sufficient for the observation of the thermal oscillation on the fundamental violin mode averaged over the time $t = 0.2$ s, *short* compared to the relaxation time $\tau^* \sim 5$–12 s. (For a more detailed description see [5].) As a result, excess noise bursts were observed. In figure 1, the amplitude variation intensity cumulative histogram for various stress values is shown. We plotted the relative number of events when the amplitude overcame the threshold chosen *a priori* as a function of the threshold value. While the theory predicts a Rayleigh distribution for such events, a significant deviation from it was observed for the threshold $A > 5\Delta A_{\mathrm{rms}}$. One possible explanation for the noise burst origin is an avalanche-like grain displacement process within a small part of the sample that originally contained some type of inhomogeneity.

3. Towards the measurement of mechanical noise in the fused silica fibres

The main goal of this part of our project is to check if any mechanical excess noise exists in high-*Q* fused silica suspension fibre violin modes and investigate the dependence of this

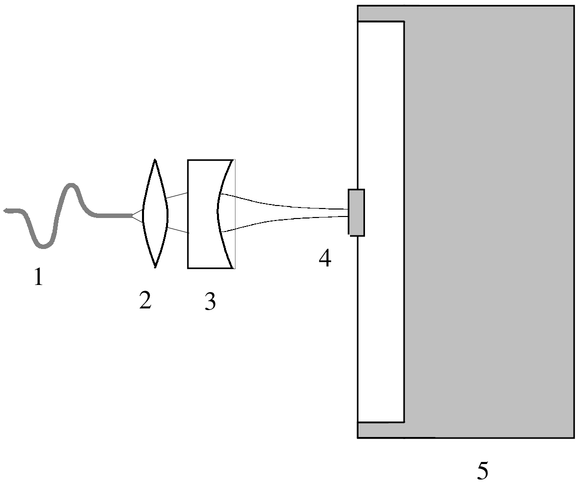

Figure 2. Design concept for the Fabry–Perot cavity-based sensor. 1, optical waveguide; 2, matching lens; 3, fixed mirror; 4, tested fibre with a small mirror in the middle; 5, fused silica support.

noise on the applied stress. As one might expect, much better resolution for the excess noise measurement is necessary to obtain ~30 times less thermal noise using the high quality factor fused silica suspension. The single-pass optical sensors did not satisfy this requirement, so another method had to be developed. Our efforts were focused on two main problems:

1. how to reach sufficient sensitivity of the readout system while keeping the fibre untapped (preserving the high quality factor of the violin modes);
2. how to keep the high quality factor and provide constant strain.

After several different approaches were tested [6], we decided to use a conventional Fabry–Perot resonator (optical meter) with a small flat mirror (4 × 2 × 1 mm) made of pure fused silica welded in the middle of the tested fibre (see figure 2). The surface of this mirror was coated with a highly reflective multilayer which provides high finesse. Two short fused silica sticks were welded to the opposite 'corners' of the mirror before coating. The 'free' ends of these sticks were used for welding the fused silica fibres in which noise will be measured. This design had already been tested and a finesse greater than $F \sim 50$ was obtained. It is important to note that the coating was not damaged by the welding of fibres. For the $W = 1$ mW, $\lambda = 0.6\ \mu$m He–Ne laser, the sensitivity of this method is

$$\Delta x^{f}_{\min} \sim \frac{\lambda}{4F}\sqrt{\frac{\hbar\omega}{W}} = 5 \times 10^{-14}\,\mathrm{cm\,Hz^{-1/2}}.$$

This value is good enough to resolve thermal noise over the averaging time $t < 10^{-2}$ s, while the relaxation time is expected to be $\tau^* > 2 \times 10^3$ s in the standard fibres (10 cm long, 100 μm in diameter). The technique of phase shift measurement in the beam reflected from this Fabry–Perot resonator is similar to [7].

We also managed to design a method to attach the fibre to the support structure which allows us to keep the quality factor of violin modes as high as 1.5×10^7 and to measure effective temperature related to the fundamental violin mode using the simple 'knife and slot' technique [8]. The preliminary measurements show that the effective temperature is close to room temperature, which means that the violin-mode oscillations averaged over longer time compared to the relaxation time, can be described as pure Brownian motion.

4. Conclusions

The progress report on the measurement of mechanical noise on the mirror suspension prototype is presented. To date, excess noise in the metal wires has been observed and an advanced technique for the fused silica suspension test is prepared.

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