Considerations on collected data with the Low Frequency Facility experiment

A.Di Virgilio¹, G. Cella¹, V. Dattilo ², F. Frasconi¹, A. Gennai¹, P. La Penna², G. Losurdo ³, A. Pasqualetti², D. Passuello¹, F. Piergiovanni⁴, A. Porzio⁵, F. Raffaelli¹, P. Rapagnani⁶, F. Ricci⁶, S. Solimeno⁵, Z. Zhang ²

¹Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Polo Fibonacci Ed. C, via F. Buonarroti 2, Pisa, Italy
²EGO, European, Gravitational Observatory, Cascina (Pisa)
³INFN Sezione di Firenze, Sesto Fiorentino, Italy
⁴Universitá di Urbino, Urbino, Italy
⁵Coherentia, CNR-INFM Napoli
⁶Università di Roma, Roma1, Roma Italy
⁷Istituto Nazionale di Fisica Nucleare, Sez. Napoli, and Dipartimento di Scienze Fisiche, Università di Napoli “Federico II”

E-mail: angela.divirgilio@pi.infn.it

Abstract. The Low Frequency Facility consists of a 1 cm Fabry-Perot cavity suspended to a single SuperAttenuator, which is the mechanical system adopted to isolate the test masses of the Virgo interferometer. In this paper we present the preliminary results of measurements performed with a cavity of finesse 4000 and lasting 1-2 hours in different working conditions. The analysis presented here is focused mainly on the region below 100 Hz, and uses data collected with longitudinal control bandwidth below 150 Hz. A calibration test confirmed that the collected data are in good agreement with the model of the longitudinal control loop based on the open loop measurements. In addition to this, above 2 Hz the power spectrum of the two mirrors relative displacement shows a stationary noise floor and few peaks with high mechanical quality factor. Studying these peaks in the time domain, it has been observed that the energy associated with a single peak is Boltzman distributed, whether the oscillations are not excited. The measured upper limit of the seismic noise contamination at 10 Hz is around $2 \times 10^{-14} m/\sqrt{Hz}$.

1. Introduction

The noise investigation in the region around 10 Hz is one of the most important task to improve the sensitivity of gravitational wave detectors extending their bandwidth in the low frequency region [1, 2, 3, 4, 5]. This region is of great interest for the detection of gravitational waves, since there most of the signals coming from pulsars and coalescing binary stars are expected. Below 500 Hz the antennas are limited by thermal noise coming from the suspension and mirrors. The Low Frequency Facility (LFF) has been built to measure the relative displacement of two mirrors hung to a suspension system identical to the Virgo SuperAttenuators (SA) [6, 7, 8, 9]. The first installation of the experimental apparatus at the INFN Pisa laboratory has been concluded in 2001; changes have been done in order to improve its sensitivity around 10 Hz: the cavity
finesse from 1000 up to 4000 and the modulation frequency of the laser beam from 13 to 17 MHz, in this way the optical gain of the cavity is well calibrated by using the signal produced when the cavity is unlocked (a typical value is higher than \(10^{10} \text{ V/m}\)). All control loops are based on a DSP electronic card, and in the present measurements the DSP bandwidth has been pushed up to 20 kHz, while the acquisition system has been changed to have longer runs. Particular care has been devoted to improve the response of the Inertial Damping (ID) control loops. In the next section the experimental apparatus is presented, giving some details on the longitudinal control loop and data taking. In section number three the calibration check and the displacement power spectrum are described with the results of a special run focusing on the seismic noise contamination. This is an important parameter to characterize the suspension system adopted in isolating the optical cavity from environmental vibrations [10].

2. The Experiment set-up and Data Taking

The experimental apparatus is here shortly described. A more detailed description can be found in reference [8]. The suspension system used for the LFF is basically equal to the standard Virgo, as represented in fig. 1, where the sketch of the setting-up and few photos are shown.

![Fig. 1, up left: sketch of the LFF apparatus, EOB is the table containing the laser, the frequency stabilization circuit and all the optical circuit with the exception of the suspended 1 cm cavity, up right: the large vacuum chamber containing the suspension, vacuum \(10^{-4} \text{ mbar}\), down left: photo of the optical table EOB, down right: the suspended cavity, the flat mirror 10 cm diameter is clearly visible (AM), behind the 1 inch curved mirror supported by the large 25 kg cylinder (VM), the reference mass (RM) is the external cylinder.](image)

The curved mirror is 1 inch diameter mirror attached to a large steel cylinder, which plays the role of the Virgo test mass (VM). The flat mirror of the cavity (called AM and sometime...
AX, auxiliary mirror) is suspended by an independent three stages suspension attached to filter7, which represents the last vertical spring of the SA (see fig. 1 up left and fig.2). Since the AM mirror is lighter than the other (0.3 kg compared with 25 kg), it is assumed that the thermal noise of the AM suspension is higher than the VM one. The control of the longitudinal motion is done acting on the VM mirror only using the 4 magnets attached to the back of the support and applying currents to the 4 coils of the reference mass RM, in a Virgo like scheme[12]. Figure 2 shows the cavity, the input beam, the longitudinal control loop and the acquired signals.

The laser beam, modulated at 17 MHz, and independently frequency stabilized by a reference cavity (not shown in the figure 2) is injected in the cavity. The reflected power, deviated by the polarizer, is detected by a photodiode and demodulated by the mixer (Pound-Drever-Hall scheme)[13]. The cavity signal is amplified and digitised by means of a 16 bit ADC, while the DSP filters the signal to make stable the longitudinal electromechanical control loop. Above few Hz, the DSP filter is a pure derivative, with the zero at 30−50 Hz. In order to keep stable the digital filter poles at 13 kHz are used. The filtered signal is sent to 4 DAC channels, then to the 4 coils drivers (voltage generators with gain 2), very flat up to 50 kHz. As soon as the control loop is closed they are set in a low noise condition, where a 100 Ohm resistance is put in series with the coils, reducing the DAC noise contribution by approximately a factor 10 [6]. The coils plus cables have a resistance of about 10 Ohm (the coil resistance being 5 Ohm) and inductance of 0.7 mH. Each driver has a monitor to measure the current flowing in the coil.
The error signal (Error), which is the mixer output, the DAC output (Coil2, correction signal expressed in volts), and the current monitor (Probe) are acquired with Labview program using a 16 bits ADC.

The SA has a control loop, which reduces the large low frequency motion, called Inertial Damping[11]. This feedback loops has been designed by using the accelerometer signals, obtaining a residual motion of the cavity of $2 - 3$ µm R.M.S. It has been activated during all the data collecting period. In order to lock the cavity, the relative motion of the two mirrors has to be less than about 20 free spectral ranges with periods of 1 Hz (10µm/s); in fact when the residual motion is larger it is not possible to start the locking procedure because the DSP response is too slow and the cavity itself is outside the linear region. The linear zone of the read-out signal is about $10^{-10}$ m. The DC gain of the loop has to be larger than $10^6$ in order to keep the relative motion of the two mirrors inside the linear region. The relative velocity is a random variable, and it is easier to start the lock procedure when the velocity is low, i.e. when the direction of the motion changes and the mirrors are far from the equilibrium point of the pendulum. So, the cavity locks detuned with respect to the zero of the error signal, and the typical detuning is of the order of $10^{-12}$ m.

3. Calibration, Displacement Power Spectrum and Seismic Noise Contamination

The region we study is around 10 Hz, where the loop gain is very high. Figure 3 left shows the time distribution of the residual motion of the two mirrors around the lock point, for a typical data taking run lasting 1 hour.

![Distribution of the error signal (run 7)](image)

![Compared with 10 Hz cavity occupied flat mirror and flat mirror flat mirror](image)

Fig. 3 left: distribution of the residual motion of the two mirrors around the lock point; and right: reconstructed relative displacement power spectrum, two different parts of the run, please note that in the red curve the noise floor remain the same while the peaks are higher.

The open loop motion of the two mirrors can be reconstructed by the signals acquired and by the knowledge of the open loop response of each part of the chain: the DSP filters, the coil drivers and the reference mass transfer functions [7, 8]. The calibration procedure has been tested injecting known sinusoidal signals in the loop. For the runs described in this paper it has been checked that the closed loop transfer functions were in agreement with the model based on the open loop measurements.

Fig. 3 right shows the typical spectrum: above few Hz peaks with high mechanical factor are visible (for instance the 3.6, 6 and probably 12.36 Hz peaks are ascribing to the suspension of the flat mirror AM). Those peaks are rather stable, in the quiter runs the distribution of energy associated with such displacements exhibit a Boltzmann distribution, other runs looks exited, and focusing on the resonances, with a less than 1 Hz bandwidth band-pass filter, it is possible
to see sometimes the presence of sudden release of energy, see figures 3 right (red curve) and figure 4, where it is shown the time evolution of data band-passed around resonances, with bandwidth less than 1 Hz. In figure 4 the distribution are fitted; in the case in which the oscillator is thermal noise exited, the result of the fit gives the mass associated with the oscillator; this part of the analysis is still in progress.

Fig. 4 a: time evolution of the data band passed around 12.35 Hz and corresponding distribution of energy, temperature associated is 300 K, the mass of the oscillator estimated fitting the data is 16.5 gr. b and c: as in previous picture, for the resonance at 3.4 Hz, in b the resonance is clearly excited. The region off resonance shows a $1/\nu^2$ behaviour, where $\nu$ is the frequency, and it is stationary. It has been checked that its level is higher than the expected electronic noise. The noise floor at 10 Hz is about 10 times higher than the expected thermal noise of the AM suspension. As shown in fig. 4 it is the same for non-excited and excited runs, indicating that the noise floor and the peaks are independent. The electronic noise, evaluated with independent measurements, can be subtracted from the spectrum in quadrature. The result is shown in figure 5, where the black curve gives the estimation of the thermal noise of the AM suspension, with two different sets of parameters and assuming constant $\phi$ for the structural damping[5]. In the same figure the red curve is related to an old measurement of ours[6].
A dedicated run has been done to study the seismic noise contamination, about 1 hour long. Several accelerometers have been installed around the experiment: three ground connected, along the three main direction, and three mounted on top of the suspension, used for the inertial damping purpose. These six signals have been acquired for one hour with the interferometer locked, studying their coherence. The measured limit of the seismic noise contamination is $2 \times 10^{-14} \text{ m/} \sqrt{\text{Hz}}$ at 10 Hz, decreasing approximately as $1/\nu^2$, where $\nu$ is the frequency. On top of some resonance above 20 Hz, the contamination seems to be a bit higher. The obtained seismic noise contamination is higher than the expected one, but it has been measured by using the vertical spring of the SA suspension not properly tuned. This problem can be avoided re-tuning the vertical spring of the suspension chain and collecting an additional set of data.

4. Final Considerations
Several sets of data have been collected with LFF Fabry-Perot cavity of finesse 4000. The runs with control bandwidth below 150 Hz are reported here. In these working conditions, the noise floor measured at 10 Hz has been higher than the expected electronic noise. An upper limit of the seismic noise contamination has been evaluated at $2 \times 10^{-14} \text{ m/} \sqrt{\text{Hz}}$, at 10 Hz, with a not perfect vertical attenuation performance of the SA. For this reason we plan to take one more set of data with the LFF apparatus, after an improvement of the SA vertical tuning.

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