Low Frequency - High Sensitivity Horizontal Inertial Sensor based on Folded Pendulum

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Abstract. This paper describes a new implementation of monolithic horizontal sensor, developed at the University of Salerno, based on the Folded Pendulum architecture, configurable both as seismometer and as accelerometer. The large low-frequency band ($10^{-6} \div 10 \text{ Hz}$), the high sensitivity ($10^{-12} \text{ m} \sqrt{\text{Hz}}$ in the band $0.1 \div 10 \text{ Hz}$) and the high quality factor in air ($Q > 1500$) are largely better than all the previous Folded Pendulum implementations. Moreover its monolithic implementation of the whole mechanics, coupled with a full tunability of its resonance frequency ($70 \text{ mHz} \div 1.2 \text{ Hz}$) obtained with a specially designed calibration procedure and with an integrated laser optical readout, guarantees both compactness, robustness and immunity to environmental noises. This makes this sensor suitable for a large number of scientific applications, also in high vacuum and cryogeny. Applications of this sensor are already started in the field of geophysics, including the study of seismic and newtonian noise for characterization of suitable sites for future underground interferometric detectors of gravitational waves.

1. Introduction

The present generation of interferometric detectors of gravitational waves, GEO600 \cite{1}, LIGO \cite{2}, TAMA \cite{3} and VIRGO \cite{4}, although very close to their design sensitivity, have not yet detected gravitational waves. For this reason a second generation of detectors, (\textit{Advanced LIGO} \cite{5} \cite{6} and \textit{Advanced Virgo} \cite{7}) have been designed to improve the global sensitivity of at least one order of magnitude, so that, according to the current models of GW sources, they should be sensitive enough for the first detection of gravitational waves. Different is the already outlined scientific approach to the third generation of interferometric detectors, whose design is more oriented to the observational aspects than to the detection capability \cite{8} \cite{9}. Within this context, the reduction of the fundamental and technical noises limiting the first and second generation of interferometric detectors assumes great relevance.

In the low frequency band ($0.1 \text{ Hz} \div 10 \text{ Hz}$), this goal can be achieved only if seismic and newtonian noises are largely reduced. Seismic noise reduction requires the installation of detectors in carefully chosen underground sites and the improvement, at the same time, of the mechanical suspensions performances. Newtonian noise reduction, still an open theoretical
and experimental problem [10], requires instead a suitable design of the detector geometry in connection with the structure of the hosting underground site.

Therefore, on the basis of what said above, the general scientific interest in the development of new seismometers and accelerometers, with architectures that guarantee very good sensitivities, especially in the low frequency band (1 mHz ÷ 10 Hz), coupled to large immunity to environmental noises, becomes clear. On the other hand, the development of low frequency large-band high-sensitivity seismic sensors has been quite slow in the past decades. Only few large bans instruments are available today (e.g. STS-2 [11], Trillium-240 [12]).

Many architectures exist to build seismic sensors (seismometers, velocimeters, accelerometers), but only few of them are suitable for the design and implementation of large-band (ideally 0 ÷ 100 Hz) high-sensitivity seismic sensors. Among all the possible architectures, available in literature and/or currently used in experiments of physics or in commercial instruments, we chose the Folded Pendulum (hereafter FP) one. The FP, called also Watts-linkage, is a classical suspension system developed in 1962 [13], but recently rediscovered for application in gravitational wave research as ultra-low frequency mechanical suspension for vibration isolation in interferometric detectors of gravitational waves [14]. More recently single-axis monolithic FP accelerometers have been developed as sensors for the control system of advanced seismic attenuators [18], demonstrating the feasibility of compact and scalable FP suitable for application as sensors in the control of the mechanical suspensions of interferometric detectors of gravitational waves.

Moving from these experimental results, some years ago we started a research line aimed to the development of low frequency large-band high-sensitivity sensors for geophysical applications (exploration of the low frequency band of the seismic spectrum), as a stand-alone sensors or as part of large and geographically distributed seismic networks, specializing some of them also for applications of interest in the field of gravitational waves detection [15] [16] [17].

In the following sections we will describe the completely new architecture of the horizontal monolithic FP sensor developed at the University of Salerno, that removes all the configuration asymmetries limiting its performances both as seismometer and as accelerometer. We, then, compare the theoretical performances, as predicted by the theoretical/numerical models, and the experimental measurements and sensitivities in connection with different optical configurations of the integrated readout. Finally, we show the first experimental results obtained in its application at the INFN Gran Sasso National Laboratory, where some prototypes are operational since December 2010, discussing further developments and improvements, including the scheduled first tests as sensor on the top stage of a TAMA like mechanical suspension.

2. FP Theoretical Model
The simplified Lagrangian model developed by J.Liu et al. [14], is very useful to describe the basic FP dynamics, main characteristics and expected performances. On the other hand, the design and implementations of optimized FP sensors require a more detailed analysis of the FP dynamics, that can be obtained only with simulations based on very accurate numerical models, like the one we developed for this specific task [15].

The FP mechanical scheme, shown in Figure 1, consists of two vertical beams of equal length, \( l \), a pendulum of mass \( m_{p1} \) and an inverted pendulum of mass \( m_{p2} \), concentrated in their centers of mass in \( P_1 \) and \( P_2 \), respectively, at \( b_p = l/2 \). The central mass, \( m_c \), is modeled, instead, with two equivalent masses, \( m_{c1} \) and \( m_{c2} (m_c = m_{c1} + m_{c2}) \), concentrated in the pivot points \( C_1 \) and \( C_2 \), respectively at the same distance, \( l_p \), measured with respect to the pivot points of the pendulum and of the inverted pendulum arms. The distance between the pivot points \( C_1 \) and \( C_2 \) is fixed and equal to \( l_d \). All these hypotheses, are well satisfied in all our mechanical implementations of monolithic FP sensors. Then, for small deflections angles, \( \theta \), the
Figure 1. Folded Pendulum Mechanical Scheme

FP resonance frequency, $f_o$, is

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{K_{g_{eq}} + K_{e_{eq}}}{M_{eq}}} = \frac{1}{2\pi} \sqrt{\frac{K_{eq}}{M_{eq}}} \tag{1}$$

where $K_{g_{eq}}$, the equivalent gravitational linear stiffness constant, and $K_{e_{eq}}$, the equivalent elastic constant, are defined as

$$K_{g_{eq}} = (m_{p1} - m_{p2}) \frac{gl^2}{l_p^2} + (m_{c1} - m_{c2}) \frac{g}{l_p} \quad K_{e_{eq}} = \frac{k_\theta}{l_p^2} \tag{2}$$

and $M_{eq}$, the equivalent mass, as

$$M_{eq} = (m_{p1} + m_{p2}) \frac{l^2}{3l_p^2} + (m_{c1} + m_{c2}) \tag{3}$$

Equation 1 is the classic expression of the resonance frequency of a spring-mass oscillator with an equivalent elastic constant $K_{eq}$ and mass $M_{eq}$. This equation well describes $f_o$ also for the tuning procedure, performed with a tuning mass, $m_t$, as described in [15] [17]. It is here only worth underlining the importance of the FP tuning sensitivity for a comfortable and stable tuning, obtained deriving Equation 1 with respect to the position of the tuning mass, that is [15]

$$S_{f_o} = \frac{df_o}{dl_t} = \frac{g}{2\pi l_p l_d} \frac{m_t}{\sqrt{M_{eq}(m_t)K_{eq}}} \tag{4}$$

As expected, Equation 4 demonstrates that the FP sensitivity is function of the value of the tuning mass, $m_t$, and that to obtain the same $\Delta f_o$, the heavier is the tuning mass, the smaller is its necessary displacement.

Defining, then, the coordinate of the FP frame (fixed to the ground) as $x_g$ and the coordinate of the FP central mass ($m_c$) as $x_c$, then the mass displacement transfer function with respect to the ground displacement is [15]

$$\frac{x_c(\omega) - x_g(\omega)}{x_g(\omega)} = \frac{(1 - A_c)\omega^2}{\omega_o^2 - \omega^2} \tag{5}$$
where
\[ A_c = \left( \frac{1}{3} - \frac{1}{2} \right) \frac{(m_{p1} - m_{p2})}{M_{eq}} \]  
(6)
is the parameter related to the centre of percussion effects [14]. This transfer function describes the dynamics of a FP seismometer, that is the ground displacement, \( x_g(\omega) \), as function of the measured mass displacement, \( x_c(\omega) - x_g(\omega) \).

Actually, this transfer function only qualitatively predicts the dynamical behavior of FP sensors, because in the Liu et al. model [14] the dissipation effects have been neglected, that are real limitations to the FP performances and are measurable. To globally solve this problem, we introduced a global dissipation term in the lagrangian model, that led us to rewrite Equation 5 in the Laplace domain as
\[ \frac{x_c(s) - x_g(s)}{x_g(s)} = \frac{-(1 - A_c)s^2}{s^2 + \frac{\omega_o}{Q(\omega_o)}s + \omega_o^2} \]  
(7)
where \( Q(\omega_o) \) is the global Quality Factor. The dependence of \( Q \) on the FP resonance angular frequency, \( \omega_o \), that we introduced in Equation 7, has been experimentally demonstrated and will be discussed in the following section. This Equation can then be rewritten in the Fourier domain as
\[ \frac{x_c(\omega) - x_g(\omega)}{x_g(\omega)} = \frac{(1 - A_c)\omega^2}{-\omega^2 + i \frac{\omega}{Q(\omega_o)} \omega + \omega_o^2} \]  
(8)

3. The UNISA Horizontal Seismometer
The UNISA horizontal seismic sensor is a new FP implementation, developed starting from the FP original architecture [13] and from the monolithic design by Bertolini et al. [18], that allows very compact and robust FP implementations. The main limitation of the Bertolini implementation is the very small dynamics of the arms (few hundreds of microns), consequence of the use of circular hinges, that allow only small rotational angles of the joints. Therefore, the force feed-back configuration (accelerometer) was an obliged choice, with the consequent limitations in band and sensitivity due to the control electronic noise. We solved this problem enlarging the gaps among the arms, the central mass and the frame, increasing the sensor dynamics to few mm, but, as drawback, we are obliged to use elliptically shaped flexures, as suggested in [18] and experimentally tested in [15] [19], that have the advantage both of a stiffness scaling down as \( 1/e \) (\( e \) is the ratio of the major to minor axes) [20], of a reduced stress and of a strain distributed over a larger length [21].

It is important to underline that, although the instantaneous rotation centre is better defined with circular hinges (compared to the elliptical ones), a suitable choice of the hinge ellipticity factor in connection with the mechanical dynamics minimizes all the coupling effects. As result, we designed and implemented very compact broadband single-axis monolithic FP horizontal sensors of reasonable size with very low natural resonance frequencies (down to \( \approx 70\, mHz \)) to be used both as seismometers and accelerometers (with or without external force feed-back control systems). Furthermore the innovative application of laser optics techniques for the implementation of the FP monolithic readout (laser optical levers and laser interferometers), has improved its sensitivity, especially in the low frequency band, increasing, at the same time, its immunity to environmental noises [15] [19]. It is important to underline here that the sensitivity of the interferometric optical readout depends on many parameters, like the optical configuration, the quality of the laser, the open loop error signal extraction techniques used, etc.. Many configurations and techniques exist in literature suitable for this purpose (e.g. [22] [23] [24]), and applied to seismic sensors since long time (e.g. [25] [26] [27]), so that any improvement of the optical readout may be simply a matter of suitable choice, and does not require special dedicated studies.
Actually, the main problem that prevented the use of monolithic FP as open loop sensors, is geometric. In fact, all the previous versions of FP were designed with the constraint that the four joints, necessary for the mechanical implementation, work in tension. This technical choice led to the implementation of FP with asymmetric arms. In particular, the moment of inertia of the inverted pendulum arm cannot be minimized, becoming a real problem for the quality of the FP dynamics. These asymmetries become very relevant in the open loop configuration FP sensor. In fact, being the rotation center of the elliptic hinges time and position dependent, the coupling of the inverted pendulum arm motion with the central mass motion largely increases the couplings of different degrees of freedom, reducing the quality factor and increasing the noise on the horizontal axis.

This problem was solved in the UNISA Horizontal Seismometer [28], characterized by a symmetric FP configuration, that allows the optimization of the moments of inertia of both the arms according to the specific application. In this new design, the two joints of the inverted pendulum work in compression. In order to compare the results obtained with the UNISA Horizontal Seismometer and the previous monolithic FP versions we implemented this new Seismometer using the same material (Aluminium Alloy 7075-T6), the same dimensions (134 mm × 134 mm × 40 mm) and the same ellipticity (16/5) and thickness (100 µm) of the hinges of the previous versions. In Figure 2 the UNISA Horizontal Seismometer is shown together with some particulars of the hinges, the box used for thermo-insulation and the tuning mass, necessary for changing its resonance frequency. It is clear from what said above that the application of the sensor as seismometer (no force feed-back control) has the great advantage that no limitations to the band and sensitivity are introduced by the control electronics, so that the quality of the instrument depends mainly on a careful and optimized mechanical design. The real limitations to the performances of a mechanical monolithic sensor become then the thermal noise, the sensitivity to the external temperature and acoustic noise (in air) and the readout sensitivity. Being the latter actually a laser optical readout (optical lever and laser interferometer) [15] [16] [17], its quality is a problem of cost and portability of the sensor. In particular the monolithic horizontal FP sensor can be used both as stand alone seismometer/accelerometer for seismic noise monitoring for geophysics environment and as seismometer/accelerometer for the automatic control of suspensions of the present and future generations of interferometric detectors of gravitational waves.

**Figure 2.** UNISA Horizontal Seismometer
Of course, although the new FP configuration presented here solves many technical and sensitivity problems, the problem that the FP configuration couples horizontal forces and frame tilts is still an open problem, only partly solved, for example, if they are separate in band or if the FP is coupled with a tiltmeter of comparable sensitivity [29] [30] [31] [32].

4. Tests of the UNISA Horizontal Seismometer

In order to understand performances of the UNISA Horizontal Seismometer we performed a series of tests aimed both to demonstrate that the prototype follows the predictions of the theoretical/numerical models developed for simulation and design. Their reliability was proved by comparing the experimental monolithic FP transfer function at its natural design resonance frequency [15], made using a standard measurement procedure used in control theory to obtain the transfer function of a linear system injecting white noise. The results of this first test are shown in Figure 3 where the theoretical and experimental transfer functions are shown. Another important feature of the UNISA sensor is the very effective tuning procedure developed: a resonance frequency of 66 $mHz$ has been obtained. This result is still more relevant if the small dimensions of the monolithic FP are taken into account. It is anyway important to underline that tuning the FP at its lowest possible natural resonance frequency improves the sensor measurement band at low frequencies, but at the same time reduces the restoring force of the pendulum to external perturbations, increasing the probability for the test mass to touch the frame, saturating the sensor output. Although this may be again only a problem of dynamics for the UNISA Horizontal Seismometer (that can be partially solved enlarging the gaps among the central mass-arms and arms-frame), it is not at all a problem if it is configured as accelerometer, being the central mass always forced in its rest position by the force feedback control.

The real problem is that the FP quality factor, $Q$, decreases together with its natural frequency, so that the FP performances decrease moving its resonance frequency towards the low frequencies region. This effect is fully taken into account in Equation 8, where the theoretical prediction and/or the experimental measurements of the function $Q = Q(\omega_o)$ of the mechanical system becomes relevant. We remind that the function $Q = Q(\omega_o)$ depends also on the value of the tuning mass, $m_t$. This dependence is function of the ratio $m_t/m_c$: the larger is this ratio, the larger is the increase of $Q$. In order to validate the performances of the UNISA sensor we performed a series of tests to experimentally evaluate the function $Q = Q(\omega_o)$. The tests were
performed positioning the sensor in a vacuum chamber and measuring the function $Q = Q(\omega)$ for different values of the pressure in the chamber, with a tuning mass, $m_t = 240 \, g$. The measures were repeated for different values of the resonance frequency obtained through the calibration procedure, both increasing and decreasing the frequency. The results are reported in Figure 4 and 5. As expected, the Quality Factor increases at the increase of the resonance frequency and shows the expected parabolic dependence, $Q(\omega) = a \cdot \omega^2$.

Figure 4. Quality Factor vs. Resonance Frequency

Figure 5. Quality Factor vs. Air Pressure

Figure 4 shows that already at the atmospheric pressure and at the prototype design natural resonance frequency ($f_o \approx 0.721 \, Hz$) the value of the quality factor is $Q > 1800$, thus demonstrating that the UNISA sensor perfectly fits for applications in air. Moreover, a quality Factor, $Q \approx 6000$ was measured for the prototype at the design natural resonance frequency with a moderate vacuum ($p = 10^{-5} \, mbar$), reaching values up to $\approx 14000$ for a natural resonance
frequency of $f_0 = 0.94 \text{ Hz}$. These results demonstrate, instead, that this sensor works very well both in vacuum, as expected, and in air (that is the main goal of the FP monolithic new design). It is again relevant to underline that for this monolithic Aluminium (7075-T6) prototype values of $Q > 100$ are measured also for resonance frequencies below $100 \text{ mHz}$.

Finally, we report the readout noise that is the best UNISA Horizontal Seismometer sensitivity, assuming that the thermal noise is much lower. The measurements were made with the FP central mass clamped to the frame, in air and with no thermal stabilization both for the optical lever (with PSD photodiodes) and for the interferometric readouts. In Figure 6 the best theoretical and experimental sensitivities curves are shown at ($T = 300 \text{ K}$), assuming the FP tuned at a resonance frequency ($f_0 = 100 \text{ mHz}$).

![Figure 6. UNISA Horizontal Seismometer Readout Noise](image)

5. Applications of the UNISA Horizontal Seismometer

Experimental applications of the FP UNISA monolithic seismometer have started since 2009. Preliminary tests of FP monolithic sensors have been performed in 2009 at DUSEL, in the Homestake Mine, where all the necessary upgrades were defined to improve sensitivity and band [33].

Then, for long term tests on the field we had to choose a very quiet site (from environmental and seismic noise point of view), but equipped as well as a facility (in terms of power supply, network, etc) and very easily reachable for all the necessary adjustments and tuning procedures. The obvious choice was the Gran Sasso INFN National Laboratory. A test facility in a quiet location at the INFN Gran Sasso National Laboratory was built for this task. It consists in a thermally insulated box, whose dimensions are 2 m (length) $\times$ 1 m (width) $\times$ 1.80 m (height), equipped with power supply and network for remote monitoring. It hosts thermally insulated boxes at the bottom, containing the UNISA horizontal seismometers, and placed on granite slabs fixed to the ground (Figure 7). The whole station guarantees the thermal stability of the sensors. In fact, although the environmental temperature outside the whole station changes at most of $2^\circ \text{C}$ along the year, no correlation effects between temperature changes and FP output have been highlighted. In Figure 8 the first noise spectrum measured by the UNISA
Horizontal Seismometer. This spectrum, based on a temporal acquisition of about 1130 hours data, shows that the FP UNISA horizontal monolithic sensors, although not yet optimized in terms of resonance frequency, $f_o = 150 \text{ mHz}$, acquisition dynamics and optical lever as readout have useful measurement bands for the site that already spans from $50 \text{ mHz} \div 500 \text{ mHz}$.

The quality of the data as sensor and its sensitivity let us think that is can useful also as sensor in the control system of mechanical suspensions. For this task preliminary tests are in progress on a TAMA like suspension operational in the INFN Napoli Virgo Laboratory.

6. Conclusions

in this paper a new implementation of monolithic horizontal sensor, developed at the University of Salerno, based on the Folded Pendulum architecture, configurable both as seismometer and as accelerometer has been described. The UNISA Horizontal Seismometer shows a large low-frequency band ($10^{-6} \div 10 \text{ Hz}$), high sensitivity ($10^{-12} m/\sqrt{Hz}$ in the band $0.1 \div 10 \text{ Hz}$) and high quality factor in air ($Q > 1500$), largely better than all the previous Folded Pendulum implementations. Moreover its monolithic implementation, coupled with a full tunability of
its resonance frequency (70 mHz $\div 1.2$ Hz) together with an integrated laser optical readout, guarantees both compactness, robustness and immunity to environmental noises, making this sensor suitable for a large number of scientific applications, also in high vacuum and cryogeny. Applications of this sensor are already started in the field of geophysics, including the study of seismic and newtonian noise for characterization of suitable sites for future underground interferometric detectors of gravitational waves.

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