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WATT'S LINKAGE BASED HIGH SENSITIVITY LARGE BAND MONOLITHIC SEISMOMETERS AND ACCELEROMETERS FOR GEOPHYSICS AND SEISMOLOGY

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Abstract

In the last two decades the need of mechanical seismometers (and accelerometers) for very different typologies of application is largely increased as well as their requirements: large measurement bands ($10^{-8} \div 10^{3}\ Hz$), very high sensitivities (down to $10^{-14} m/\sqrt{Hz}$), high directivities ($> 10^4$), compactness ($< 10\ cm\ (side)$), lightness ($< 2\ kg$), high thermal stability very often coupled with ultra-high vacuum ($< 10^{-5}\ Pa$) and/or cryogenic compatibility. For this task, strong efforts are being produced for the development of sensors able to globally satisfy the above quoted requirements.

Among the different mechanical architectures present in literature, the Watt's linkage is one of the most promising for the implementation of mechanical seismometers and accelerometers (horizontal, vertical and angular).

In this paper, we present a generalized model describing the dynamic behavior of monolithic seismometers and accelerometers based on the UNISA Folded Pendulum, an inertial sensor based on an innovative version of the Watt's linkage architecture, optimized for low frequency characterization of sites and structures. Typical applications of this class of monolithic sensors are in the field of earthquake engineering, seismology, geophysics, civil engineering (buildings, bridges, dams, etc.), and, in general, in scientific research and in all the applications requiring sensors characterized by large bands and low frequency performances coupled with high sensitivities.

Keywords: Seismometer; Accelerometer; Inertial Sensor; Mechanical Monolithic Sensor; Folded Pendulum.

1. Introduction

In the last decades, very strong efforts have been produced in the development of seismometers and accelerometers capable to satisfy the increasingly stringent application requirements in very different fields (geophysics, seismology, aerospace, civil engineering, monument and cultural heritage preservation, industry, etc.). The implementation of new ideas, made easier by the recent scientific and technologic advancements, has led to the design of different typologies of high quality sensors, although often focused to specific fields and/or applications and, therefore, capable to satisfy only subsets of the requirements. Hence, the relevance of a research aimed to develop sensors architectures able to satisfy the largest possible sets of requirements [1].

For this task, and focusing our research on mechanical sensors, we synthetized a reasonable set of global requirements that mechanical seismometers and/or accelerometers would have to satisfy to guarantee effective applications in the above quoted fields. In Table 1 a synthesis of the most relevant requirements is shown.

Table 1 – Global requirements set for mechanical seismometers and accelerometers.

Parameter	***Requirement***	***Parameter***	***Requirement***
Band	$10^{-7} Hz < B < 1\ kHz$	***Sensitivity (position)***	$10^{-14} \frac{m}{\sqrt{Hz}} < S_p < 10^{-7} \frac{m}{\sqrt{Hz}}$
Resonance Frequency	$50\ mHz < f_o < 1\ kHz$	***Sensitivty (acceleration)***	$10^{-9} \frac{m}{s^2\sqrt{Hz}} < S_a < 10^{-2} \frac{m}{s^2\sqrt{Hz}}$
Directivity	$D > 10^4$	***Weigth***	$< 2\ kg$
Dimensions	$< 20\ cm\ (side)$	***Environment***	*Ultra High Vacuum, Criogeny*

For this task, a modular approach is surely very effective for the development of high quality seismometers and accelerometers: the sensor is divided into three subsystems on the basis of the different functions performed: the mechanical system, the transducer and the force feed-back control module. The implementation of classical mechanical seismometers requires design and integration of the first two systems, while mechanical accelerometers (force feedback accelerometers) can be implemented by adding the force feedback control module. For this purpose, it is just worth underlining that force feedback accelerometers, introduced more than half a century ago to improve dynamic range and linearity of the mechanical transfer function of classical mechanical seismometers, are largely applied in modern mechanical sensors. They are based on the idea of keeping the reference mass at its rest position, compensating the inertial force with a force applied with suitable actuators: the control system error signal, proportional to the reference mass acceleration, is the mechanical output signal of the instrument [2].

The transducer module (readout) is relatively independent from the mechanical one, designed to convert the mechanical signal (relative motion of the *"inertial"* mass with respect to the reference mass) in an electric signal for data acquisition. In the *"ideal"* case, transducers do not introduce limitations to sensors, regardless their technical implementation (electromagnetic, optical, etc.). In the real case mechanical sensors are largely limited by their own transducers noises, especially in the low frequency region (LVDT, optical levers, interferometers, etc.) and by noises generated by their coupling with environmental noises [1].

The development of an inertial mechanical sensor, capable to satisfy the requirements shown in Table 1, requires, as first step, the definition of a mechanical architecture able to provide large mechanical dynamics and limitations due only to its intrinsic noises (e.g. thermal noise). This procedure guarantees also improvements of the quality of force feed-back accelerometers based on this mechanical architecture, due to the relaxation of the control electronics and the actuators requirements, although force feed-back actuators (e.g. magnet-coil actuators) always introduce limitations due to their intrinsic noise and coupling with environmental noises [1].

Following this strategy, we decided to use the folded pendulum as mechanical architecture for the implementation of horizontal seismometers and accelerometers. Based on the Watt's Linkage (1774) [3], the horizontal folded pendulum is a well-known architecture, first hypothesized by Ferguson in 1962 [4]. In the past, folded pendulums have been applied as low frequency force feedback horizontal accelerometers and as horizontal vibration isolation systems for gravitational wave detectors [5-9], but, recently, the technological progress in precision micro-machining and in electric-discharge machining has allowed the implementation of very sensitive and compact horizontal monolithic force feedback accelerometers [10], inertial seismometers [11], tilt meters [12,13,14] and control sensors [15, 16].

A new impulse in the direction of the improvement of the performances of inertial seismometers and force feedback accelerometers was given with the introduction of the horizontal UNISA Folded Pendulum [1, 17]. The UNISA Folded Pendulum configured as inertial seismometer is limited, in principle, only by its mechanical thermal noise and by the readout system sensitivity. In fact, standard horizontal UNISA Folded Pendulums allow to obtain low natural resonance frequency (e.g. down values of $60\,mHz$ with a $14\,cm$ size sensor), large measurement band (10^{-7} Hz $-$ $10\,Hz$), very high sensitivity in the low frequency region of the seismic spectrum, typically of the order $10^{-12} m/\sqrt{Hz}$ with optimized LVDT and optical levers readout systems, but much better with interferometric readout systems. The latter two readouts assume great relevance for folded pendulum immunity to environmental noises (e.g. optical and interferometric readouts) [1, 18-21].

Recently, for the first time, the range of application of the Watt's Linkage was extended also to the vertical direction, with the introduction of the vertical UNISA Folded Pendulum [1, 22], whose performances are similar to the ones obtained with the horizontal one, allowing the implementation of large band - high-sensitivity - large dynamics class of triaxial mechanical sensors (seismometers and/or accelerometers), based on the Watt's Linkage, capable to guarantee the simultaneous acquisition of all the three displacement (and/or acceleration) degrees of freedom [23-25].

In the following sections, we will present a simplified but enough accurate model of the UNISA Folded Pendulum, as basis for the analytical description of a triaxial folded pendulum Seismometer/Accelerometer, together with uniaxial and triaxial monolithic folded pendulum implementations, discussing their characteristics and performances (sensitivity, band, etc.) in connection with different readout configurations.

2. Folded Pendulum Generalised Model

A folded pendulum is basically a combination of a simple pendulum and of an inverted pendulum both connected to one end by means of joints to a bar (the central mass or inertial mass) and to the other end by means of other joints to a supporting structure fixed to the ground (frame) [1]. Despite the apparent simplicity of the folded pendulum mechanical architecture, analytical solutions of its motion equations based on a Lagrangian approach are actually very complex, so that, its dynamical behavior can be described with enough accuracy only with a numerical approach based on finite element method (FEM). On the other hand, an analytic approach based on a folded pendulum simplified scheme guarantees anyway a global and synthetic overview of its mechanical performances and dynamic behavior.

The Lagrangian two-dimensional analytical model of Bertolini [26], based on the simplified Liu et al. model [7] and extended by Barone et al. [1, 16,19-21], developed to describe the dynamical behavior of horizontal folded pendulum (basic mechanical scheme in Figure 1), is sufficient for the latter purposes. A more general Lagrangian two-dimensional model has been developed by Barone et al. [21] in order to take into account also folded pendulums oriented differently from the horizontal one, a model necessary for the description of the innovative vertical folded pendulum. In the scheme of Fig. 1 the different orientation from the horizontal one (a generic system $X'Y'Z'$) is defined through the rotation angle, ϕ, obtained by rotating plane XZ around the Y axis as shown in the square on the right side of Fig. 1.

The folded pendulum reference frame, XYZ, of Fig. 1 is oriented in such a way that the motion of the central mass occurs, for small displacements, along a direction parallel to the X-axis and the Z-axis is parallel (but opposite) to the direction of the local gravitational acceleration, $\vec{g}$. Finally, all the mechanical components are constrained to move in the plane XZ, being the rotation axes of all the pivot points parallel to the Y-axis of this reference system, the latter constraint, in particular, guaranteeing high directivity to the folded pendulum.

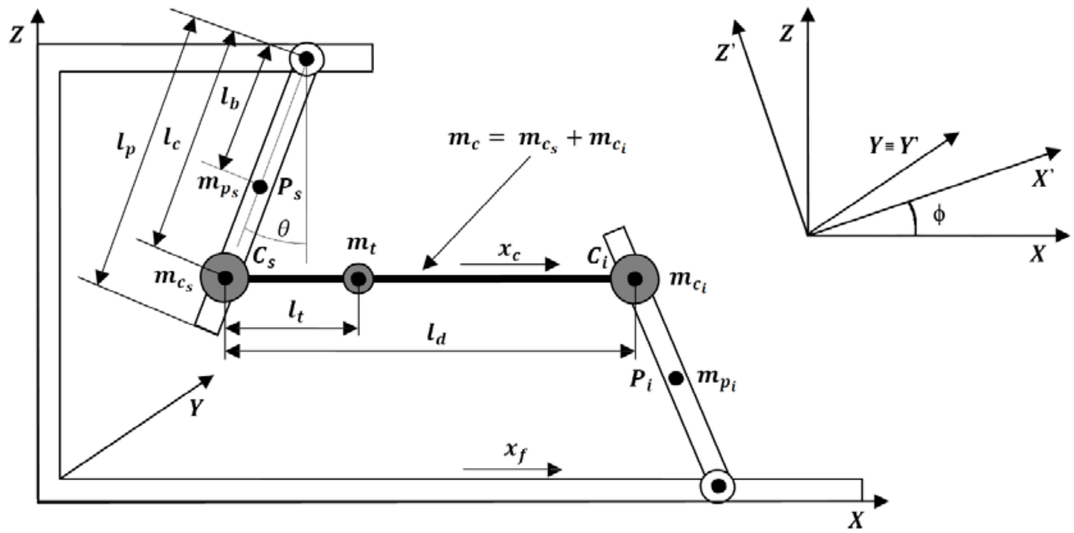

Fig. 1 – Folded Pendulum Mechanical Scheme.

The simplified folded pendulum model consists of two vertical arms of equal length, l_p, connected to one side to a single support (frame) by means of two hinges, which form a simple pendulum of mass m_{p_s} and an inverted pendulum of mass m_{p_i}. The masses of the two pendulums are concentrated in their centers of mass, P_s and P_i, respectively, positioned in $l_b = l/2$. The other sides of the arms are connected (in C_s and C_i, respectively) to a bar of mass, m_c, and length, l_d, by means of two other hinges. An external movable mass, m_t (tuning mass), positioned on the central mass at a distance l_t from C_s, is added to tune the folded pendulum resonance frequency. The mass of the central bar is modelled with two equivalent masses m_{c_s} and m_{c_i}, being

$$m_c = m_{c_s} + m_{c_i}, \tag{1}$$

whose value is defined by the position of the center of mass on the central bar, l_m (being $l_m < l_d$), measured with respect to the pivot point, C_s, according to the relations

$$m_{c_s} = m_c \left(1 - \frac{l_m}{l_d}\right) \tag{2}$$

$$m_{c_i} = m_c \left(\frac{l_m}{l_d}\right) \tag{3}$$

The positions of the couples of equivalent masses (m_{p_s}, m_{p_i}) and (m_{c_s}, m_{c_i}) differ by a constant, so that for small deflection angles, θ, the centers of mass of the two arms have the same velocity, $\dot{x}_p$, the two equivalent masses (m_{c_s}, m_{c_i}) have the same velocity of the centre of mass of central bar, $\dot{x}_c$, then the folded pendulum can be described by the classic Lagrangian:

$$\Lambda = T - U \tag{4}$$

where T is the approximate analytic expression of the kinetic energy

$$T = \frac{1}{2}(J_s + J_i)\dot{\theta}^2 + \frac{1}{2}\left(m_{p_s} + m_{p_i}\right)\dot{x}_p^2 + \frac{1}{2}\left(m_{c_s} + m_{c_i}\right)\dot{x}_c^2 \tag{5}$$

with J_s and J_i moments of inertia of the two arm, that below their resonant frequency can be approximated by a rigid bar with

$$J = \frac{ml^2}{12}, \tag{6}$$

and where U is the approximate analytic expression of the potential energy, that for an ideally horizontally positioned folded pendulum is

$$U = \frac{1}{2}\left[\frac{1}{2}\left(m_{p_s} - m_{p_i}\right)g_{eq}l_p + \left(m_{c_s} - m_{c_i}\right)g_{eq}l_c + k_\theta\right]\theta^2 \quad (7)$$

where g_{eq} is the equivalent gravitational acceleration, that is the component of the folded pendulum central mass acceleration perpendicular to its direction of motion, that can be conveniently written as

$$g_{eq} = g \cdot \cos\phi + a_{ext} \quad (8)$$

where ϕ is the folded pendulum inclination angle with respect to the local horizontal plane. $\phi = 0^o$ describes a classical horizontal folded pendulum characterized by $g_{eq} = g + a_{ext}$, being a_{ext} any other external acceleration different from the acceleration of gravity applied to virtually increase or to reduce the effects of the acceleration of gravity changing its natural resonance frequency [21]; $\phi = 90^o$ describes a vertical folded pendulum, whose resonance frequency does not depend on the acceleration of gravity: only the applications of an external acceleration, a_{ext}, to the central mass, perpendicular to its direction of motion can change the natural resonance frequency due to global elastic constant of the joints, k_θ, introduced to take into account that of the pivot points (hinges or flexures). Each of the joints can be modeled with the introduction of elastic constants, k_{θ_j}, so that

$$k_\theta = \sum_{j=1}^{n} k_{\theta_j} \quad (9)$$

being n the total number of flexure joints.

Actually, the flexure joints are the most critical components of the folded pendulum mechanical architecture, being not only performances but also robustness and long-term durability of the mechanics strongly dependent on the correct choice of geometry, size and materials. Although, in general, the geometry of the flexure joints depends on a specific implementation, the most common and effective ones are characterized by elliptic geometry (circular geometry is a particular case of the elliptic one), probably the most effective and robust geometry for monolithic folded pendulums, whose relevant geometric design parameters are the ellipticity ratio, the major semi-axis length and the thickness at its minimum points, parameters necessary at the design level for the definition of the folded pendulum resonance frequency [10]. It is worth underlining that elliptic flexures allow the design of joints with low thickness values ($< 100\ \mu m$) and a quite well definite rotation point, still remaining very far from the material elastic limit [11]. Furthermore, a not negligible advantage of elliptic joints is that the eigen-frequency decreases at the increasing of the joint ellipticity. This behavior is described by the generalized Tseytlin formula [27], that is

$$k_\theta = \frac{C_{S_1} \cdot Eat^2}{16\left[1 + \sqrt{1 + C_{S_2} \cdot \left(\frac{2a_x^2}{a_y t}\right)}\right]} \quad (10)$$

where a is the sum of the width of all the joints, t is the joint thickness at its center, a_x and a_y are respectively the major axis (vertical) and minor axis (horizontal) of the ellipse, E is the Young's modulus of the material. C_{S_1} and C_{S_2} are coefficients, whose values depend on the shape and on the maximum deflection angle of the joint: for elliptic joints and small deflection angles, $C_{S_1} = 1$ and $C_{S_2} = 0.1986$. Finally, it is worth noticing that the joint ellipticity is a relevant parameter for the design of the folded pendulum resonance frequency [8].

The above described Lagrangian model, albeit simplified, can be conveniently used to demonstrate the possibility of designing small size very low frequency mechanical accelerometers. This impressive property becomes evident from the analysis of the expression of its natural resonance frequency, f_o, that is [1]

$$f_o = \frac{\omega_o}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{\left[\left(m_{p_s} - m_{p_i}\right)\frac{l_p}{l_c} + \left(m_{c_s} - m_{c_i}\right)\right]\frac{g_{eq}}{l_c} + \frac{k_\theta}{l_c^2}}{\left(m_{p_s} + m_{p_i}\right)\frac{l_p^2}{3l_c^2} + \left(m_{c_s} + m_{c_i}\right)}} = \frac{1}{2\pi}\sqrt{\frac{K_{g_{eq}} + K_{e_{eq}}}{M_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{K_{eq}}{M_{eq}}} \quad (11)$$

where is the equivalent gravitational elastic constant, function of the geometric and inertial characteristics of the folded pendulum in presence of gravitational acceleration, and $K_{e_{eq}}$ is the equivalent elastic constant of the flexure joints, defined, respectively, as

$$K_{g_{eq}} = (m_{p_s} - m_{p_i}) \frac{g_{eq} l_p}{l_c^2} + (m_{c_s} - m_{c_i}) \frac{g_{eq}}{l_c} \quad (12)$$

$$K_{e_{eq}} = \frac{k_\theta}{l_c^2} \quad (13)$$

and where M_{eq} is the equivalent mass, defined as

$$M_{eq} = (m_{p_s} + m_{p_i}) \frac{l_p^2}{3 l_c^2} + (m_{c_s} + m_{c_i}) \quad (14)$$

Equation (11) is the classical expression of the resonance frequency of a spring-mass oscillator with an elastic constant, K_{eq}, and mass, M_{eq}. The equivalent gravitational elastic constant, $K_{g_{eq}}$, can assume both positive and negative values: negative values compensate partially or, in principle, also totally the equivalent elastic constant, K_{eq}, reducing the natural resonance frequency, f_o, and, consequently, increasing the measurement band. Equation (11) (the related equations (12), (13) and (14)) are useful in the design phase to define the folded pendulum resonance frequency on the basis of suitable combinations of physical and geometrical parameters. For example, assuming m_{p_s} and m_{p_i} negligible compared to m_{c_s} and m_{c_i} to simplify computation, a resonant frequency equal to zero can be obtained setting $(m_{c_s} - m_{c_i}) g_{eq}$ equal to k_θ / l_c.

Nevertheless, the folded pendulum resonance frequency is a tunable parameter, a very important property useful to optimize its performances on the basis of the application requirements. For this task, different calibration techniques have been developed, based, for example, on a tuning mass, m_t, to change the value of the equivalent gravitational elastic constant, $K_{g_{eq}}$ [1] or on an external force to change the value of the potential energy, U, by means of an external acceleration, a_{ext} [1, 17, 22]. The effect of a positioning an tuning mass, m_t, on the central mass at a distance l_t from C_s (see Fig. 1) is that of changing the relative distribution $m_{c_s}$and m_{c_i}, that are increased of a fraction of the tuning mass determined by its position, at a distance l_t , according to the relations

$$\Delta m_{c_s} = m_t \left(1 - \frac{l_t}{l_d}\right) \qquad \Delta m_{c_i} = m_t \left(\frac{l_t}{l_d}\right). \quad (15)$$

The equivalent gravitational elastic constant, $K_{g_{eq}}$, and the equivalent mass, M_{eq}, change accordingly in the following way

$$\Delta K_{g_{eq}} = (\Delta m_{c_s} - \Delta m_{c_i}) \frac{g_{eq}}{l_c} = m_t \left(1 - \frac{2 l_t}{l_d}\right) \qquad \Delta M_{eq} = m_t \quad (16)$$

modifying the value of the folded pendulum natural resonance frequency. It is easy to verify that, while the equivalent mass variation, ΔM_{eq}, is always positive, the equivalent gravitational elastic constant variation, $\Delta K_{g_{eq}}$, may assume positive or negative values according to the position and value of the tuning mass. This property guarantees the possibility of changing the folded pendulum natural resonance frequency, f_o, by simply changing the position, l_t, of the tuning mass. On the other hand, the folded pendulum resonance change due to the introduction of an external force is direct: the application of an external force changes the value of the equivalent gravitational acceleration, g_{eq}, and consequently the value of the equivalent gravitational elastic constant, $K_{g_{eq}}$.

The precision, stability and limitations of the resonance frequency calibration is a relevant parameter, that can be described by the resonance frequency sensitivity to position changes of the calibration mass, m_t. This sensitivity is obtained deriving equation (11) with respect to the position of the calibration mass, obtaining [1]

$$S_{f_o} = \frac{df_o}{dl_t} = \frac{g_{eq}}{2\pi l_d l_c}\frac{m_t}{\sqrt{M_{eq}(m_t)K_{eq}}} \tag{17}$$

Equation (17) shows that, being S_{f_o} practically proportional to the calibration mass, m_t, for equal resonance frequency changes, Δf_o, the higher is the value of the calibration mass, the lower is the required calibration mass displacement, Δl_t. In the same way it is possible to define the resonance frequency sensitivity to changes of the equivalent gravitational acceleration, g_{eq},

$$S_{f_0} = \frac{df_o}{dg_{eq}} = \frac{1}{8\pi^2}\frac{K_{g_{eq}}}{g_{eq}f_o M_t} \tag{18}$$

Although, the simplified Lagrangian model is sufficient to globally understand the peculiar features of a folded pendulum, nevertheless, an effective description of its dynamics requires the introduction of global energy losses in the model, synthesizing in a simplified but effective way both internal (e.g. internal frictions in the joints) and external (e.g. air damping) losses [1]. The transfer function of a folded pendulum accelerometer is then expressed as

$$H_a(s) = \frac{X_c(s)-X_g(s)}{A_g\,(s)} = \frac{X_{output}(s)}{A_g(s)} = \frac{(1-A_c)}{s^2+\frac{\omega_O}{Q(\omega_O)}s+\omega_o^2} \tag{19}$$

where $Q(\omega_o)$ is the global mechanical quality factor, whose dependence on the resonance frequency has been theoretically predicted and experimentally demonstrated on folded pendulum prototypes [1], and where

$$A_c = \frac{\left(\frac{l_p}{3l_c}-\frac{1}{2}\right)\left(m_{p_s}+m_{p_i}\right)}{\left(m_{p_s}+m_{p_i}\right)\frac{l_p^2}{3l_c^2}+\left(m_{c_s}+m_{c_i}\right)} \tag{20}$$

This generalized folded pendulum model is sufficient to describe the behavior of the main classical mechanical oscillators like the simple pendulum, the inverted pendulum, but also the double simple pendulum and the double inverted pendulum, particular cases of the Watt's linkage. In fact, the Lagrangian of the simple pendulum can be obtained cancelling the values of the masses corresponding to the inverted pendulum section of the folded pendulum, m_{p_i} and m_{c_i}, while the Lagrangian of the inverted pendulum can be obtained cancelling the masses m_{p_s} and m_{c_s} that refer to the simple pendulum, still using all the analytic results presented in this section. The specialization of the folded pendulum model to the double simple pendulum and double inverted pendulum is again direct: the double pendulum model is obtained by changing the two negative signs with two positive ones in the expression of the potential U of equation (8), because of the opposite effect of the action of the acceleration of gravity, while double inverted pendulum model requires the opposite action for the same physical reasons.

Finally, for completeness, it is important to underline that the folded pendulum configuration always couples horizontal and angular displacements (or accelerations), an intrinsic characteristic of the folded pendulum mechanical architecture as demonstrated in literature [1]. Actually this problem has been recently solved by Barone and Giordano [28], so that it is now possible to use folded pendulums both as linear and/or angular displacement (or acceleration) sensors.

3. The UNISA Folded Pendulum

The generalized folded pendulum model demonstrates that the output signal of a folded pendulum tilted of an angle ϕ is a linear combination of horizontal and vertical components of the ground displacement (or acceleration), whose weights are trigonometric functions of the tilt angle, ϕ. This characteristic is the key for the implementation of high performance triaxial folded pendulum seismometers and accelerometers [1,17, 22,23,25]. Different are the possible configurations for the implementation of triaxial folded pendulums, whose choice depends on the specific application. The first obvious and direct design suggests to place three folded pendulum (configured as seismometers or accelerometers) along three radii of a circumference, with the direction of the central mass motion aligned respectively to 0°, 120°, 240° with respect to x-axis, and tilted of an angle ϕ with respect to the plane (Fig. 2 (left)), so that the performances of triaxial folded pendulums are strongly related to the performances of each folded pendulum component.

This typology of geometric configuration is used, for example, in many seismometers and accelerometers of the present generation, like, for example, the STS-2 [29]. This geometric configuration allows to obtain the two horizontal and the vertical components of the ground displacement (or acceleration) from the three folded pendulum sensors output signals using a classical procedure based on a suitable rotation matrix, function of the relative geometrical positions of the three folded pendulum sensors and of the global position of the triaxial sensor [1]. Another different configuration, still equally valid is again reported in Fig. 2 (right), but with the folded pendulums, this time aligned along the three main axis of a Cartesian reference system, xyz.

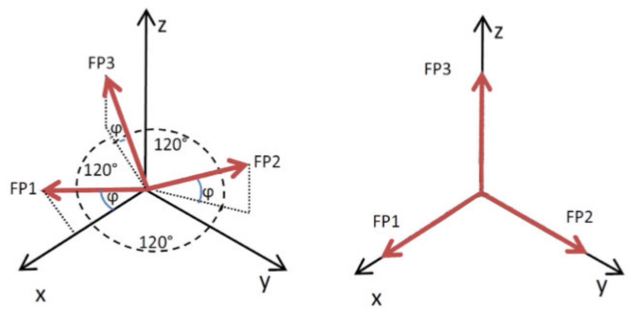

Fig. 2 - Triaxial Folded Pendulum Seismometer/Accelerometer configurations: 120° (left) - xyz (right).

The basic element of the triaxial sensors is the single-axis monolithic UNISA Folded Pendulums (vertical and horizontal), designed and implemented in different models of different sizes and weights, some of them with very low natural resonance frequencies (down to $\sim 60\ mHz$), configurable both as seismometers (no force feed-back configuration) and accelerometers (force feed-back configuration), with sensitivities strongly dependent on the readout system, being their mechanical modules limited by their intrinsic mechanical thermal noise. In particular, the application of laser optics techniques for the readout implementation (laser optical levers and laser interferometers) has largely reduced the limitations introduced by the readout in the low frequency band and increased their immunity to environmental noises [1, 17, 22, 23, 25].

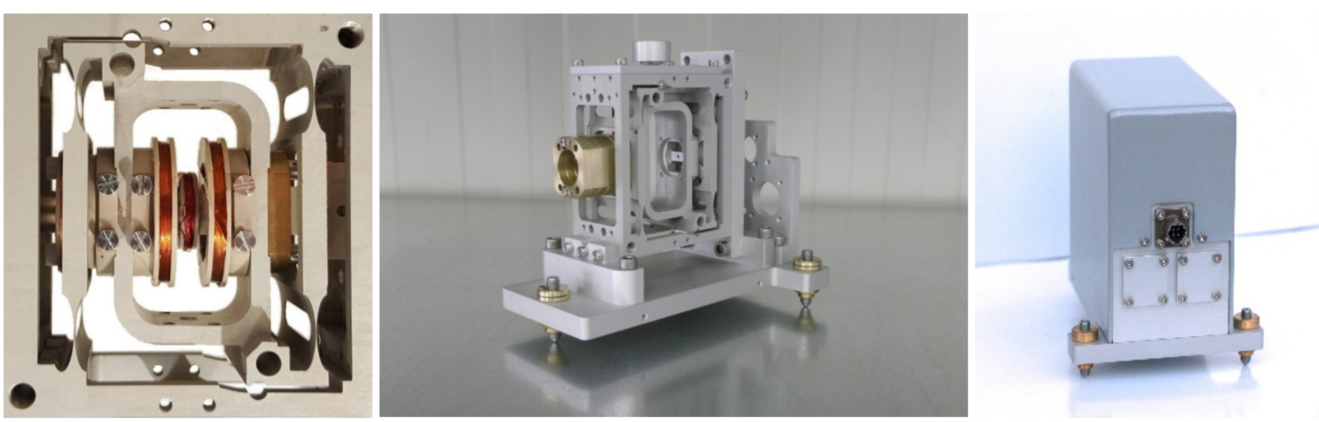

Fig. 3 – Uniaxial Horizontal Folded Pendulum – Model GE15: equipped with high sensitivity LVDT readout (left); mechanical mounting (center); standard enclosure (right).

Fig. 3 shows a standard very light ($< 250\ g$) implementation of a horizontal UNISA Folded Pendulum seismometer (model GE15) capable to resonate at low natural frequencies (down to $0.5\ Hz$), The sensor, made of Aluminum Alloy 6082-T6 and anodized for operation in standard environments, has dimensions ($77{,}5\ mm\ \times 85\ mm\ \times 40\ mm$) and hinges of ellipticity $16/5$ and thickness $100\ \mu m$. The version shown in the left picture of Fig. 3 is equipped with a force feedback actuator, so that the sensor can operate directly as an accelerometers, and a high sensitivity LVDT readout ($10^{-12}\ m/\sqrt{Hz}$) that guarantees a mechanical dynamics of ± 6.0 mm. Another possible (and cheaper) readout is the standard commercial LVDT readout (MHR010 from Measurement Specialties) that guarantees a mechanical dynamics of $\pm 5\ mm$ and a sensitivity of $10^{-9} m/\sqrt{Hz}$. It is just worth reminding that the best performances of a folded pendulum, configured as an inertial seismometer, can be obtained with interferometric readouts. The central picture of Fig. 3 shows, instead, the folded pendulum GE15 mechanics with a tuning mass mounted and configured to obtain a resonance frequency of ~ *1 Hz.*

Fig. 4 shows instead a monolithic implementation of the UNISA Folded Pendulum as horizontal inertial seismometer, developed for geophysical measurements. The sensor (dimensions $140\ mm \times 134\ mm \times 40\ mm$) is made of Aluminum Alloy 7075-T6 and hinges characterized by ellipticity $16/5$ and thickness $100\ \mu m$.

Fig. 4 – Uniaxial Horizontal Folded Pendulum – Model GF15.

This sensor is capable to resonate at very low natural frequency (down to $60\ mHz$) with external tuning masses (not shown in figure) [1], a very relevant characteristics if the small dimensions of the monolithic folded pendulum are taken into account. It is anyway important to underline that tuning the folded pendulum 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 seismometers (a possible solution is that of implementing a version with larger gaps among the central mass-arms and arms-frame), it is not at all a problem if the monolithic sensor is configured as accelerometer (like the majority of present instruments), being, in this configuration, the central mass always forced in its rest position by the force feed-back control.

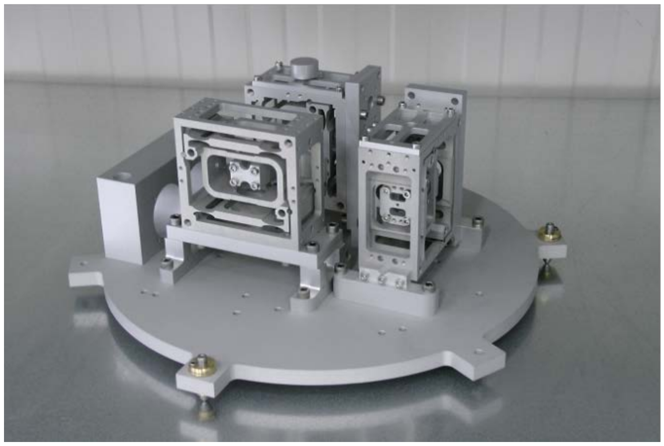

Fig. 5 – Triaxial Folded Pendulum Seismometer/Accelerometer - xyz configuration.

Fig. 5 shows a triaxial mechanical seismometer/accelerometer, consisting of three uniaxial monolithic UNISA Folded Pendulums (model GE15), two horizontal and one vertical, positioned according to the Cartesian xyz configuration.

Finally, Figure 6 shows, as example, typical acceleration sensitivities (at $T = 300\ K$) relative to the horizontal monolithic UNISA Folded Pendulums model GF15 tuned at a resonance frequency of $250\ mHz$ equipped with different readouts: high sensitivity LVDT readout, optical lever readouts with Position Sensing Devices (PSD) and quadrant photodiode and Michelson Interferometer readout. The sensitivity of the STS-2 by Streckeisen [28] and the Trillium-240 by Nanometrics [29], representing the state-of-art of the low frequency seismic sensors are reported for comparison in this figure, together with the Peterson New Low Noise Model (NLNM) [30] and the McNamara and Bouland Noise Model [31], representing the minimum measured Earth noise evaluated from a collection of seismic data from several sites located around the world: noise levels below this are never - or extremely rarely - observed.

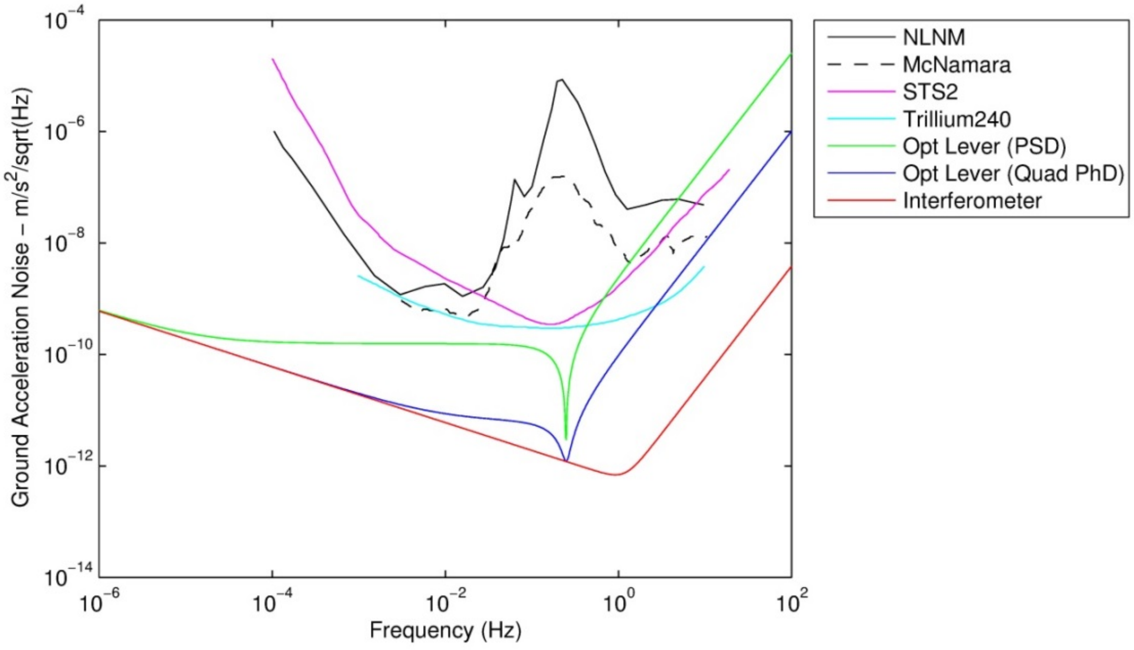

Fig. 6 – Sensitivities of typical monolithic folded pendulum (Model GF15) with resonance frequency, $f_o = 250\,mHz$, for three different optical readout systems: optical lever with PSD, optical lever with quadrant photodiode and Michelson Interferometer. The sensitivities are compared to the New Peterson Low Noise Model, with the McNamara Noise Model and with two standard instruments like the Streckeisen STS-2 and the Nanometrics Trillium-240.

Figure 6 shows also that, being the sensitivity limits of folded pendulum sensors (configured as seismometers, i.e. with no force feedback) defined by its thermal noise [1], actually very low for this class of sensors, then the instrumentation sensitivity and the measurement band are determined by the folded pendulums resonance frequencies and by the quality of the readouts. Note that in figure the effect of the air damping has not been taken into account (it has been assumed a folded pendulum working in moderate vacuum), although the generalized UNISA Folded pendulum model is able to correctly predict the air damping effect on the quality factor, Q, that at a resonance frequency of $f_o = 250\,mHz$ is $Q > 500$. Of course, many other configurations and techniques, different from the ones proposed in the figure, exist in literature and are perfectly suitable for the implementation of folded pendulum readouts: the choice depends on the requirements of the specific single application, often based also on parameters like robustness, compactness and, last but not least, cost.

The UNISA folded pendulum sensors (both in their configurations uniaxial/triaxial and seismometer/accelerometer), also commercially available, have been already used and developed for different scientific applications, in particular as inertial seismic sensors for scientific applications [1, 25], including the control of multistage seismic attenuators [16], seismic noise monitoring [11, 18, 19, 20, 21, 23, 33] and as sensors for the monitoring aimed to the preservation of the health status of the Trajan Arch in Benevento (Italy), one of the most important monuments of the Roman Empire [34, 35, 36]. New models for applications in different scientific fields (e.g. geophysics and seismology), civil, industrial and aerospace [26] applications are being designed or under test, and will be available and applied in short times.

4. Conclusions

The characteristic of the present versions of the UNISA monolithic seismometers/accelerometers (uniaxial and triaxial) appears to satisfy the requirements of applications in many different fields, although their ultimate sensitivities and band have not yet reached. In fact, the limitations in terms of sensitivity and band of the UNISA Triaxial Folded Pendulum Sensor configured as inertial seismometer, are due only to the readout system electronic noise, to the thermal noise of the mechanical joints and to the air damping, when the operation is not in vacuum. Very good performances have been already reached with optical levers with PSD and quadrant photodiodes ($< 10^{-10}\ m/\sqrt{Hz}$), high sensitivity LVDTs ($< 10^{-12}\ m/\sqrt{Hz}$), simple Michelson Interferometric readouts ($< 10^{-13} m/\sqrt{Hz}$) in the band ($10^{-1} \div 10\ Hz$), that demonstrate the validity of the UNISA Folded Pendulum class of sensors, especially in consideration of their very light weight ($< 250\ g$) and size ($< 10\ cm\ (side)$). Further improvements of sensitivity and band are under study and/or test.

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