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New class of sensors for high-sensitivity-low frequency monitoring of historical monuments

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***Abstract* – An effective evaluation of the static and dynamic structural status of historical monuments for health evaluation and long term preservation requires the analysis of their low frequency dynamic behavior (< 1 Hz). The UNISA folded pendulum class [1], based on the Watt`s linkage, developed at the University of Salerno and already successfully applied to low-frequency monitor of historical monuments, can provide this information with very high accuracy allowing effective tunings of numerical models describing their dynamical behavior. In this paper, after a description of the characteristics and performances of this class of sensors, the attention is focused on their possible application to the historical monuments monitoring for their preservation.**

I. INTRODUCTION

In the last years the interest has largely increased in high sensitivity large band sensors for compliance test and long term monitoring of large buildings and infrastructures (dams, bridges, sky-scrapes, oil platforms) aimed to the evaluation of their health status, also in connection with natural events.

The basic idea is very simple. In fact, each structure, of any material and size, has its own intrinsic dynamics, defined by a set of vibrations modes dependent on the geometry and on the materials: the vibration modes of a structure are its *fingerprint* directly connected with its geometrical and physical characteristics. For example, a structural compliance test is aimed to check the compliance of the design and measured vibration modes: deviations among the design and measured vibration modes of a structure indicate an implementation not coherent with its design. In a similar way, the evolution of the modal structure underlines a dynamical evolution that may lead to partial or total structural collapses (e.g. weakened or broken beams), as well as the appearance of additional vibration modes. In fact, a careful analysis, in synergy with FEM (Finite Elements Method) simulations may quantify these structural features highlighting structural failures at a very early stage (e.g. cracks), which need more detailed and local investigations to understand the causes (degradation of materials, structural misalignment, earthquakes effects, etc.) to drive very specific and successful actions to remove their causes. Furthermore, not less important, and probably often neglected due to the lack of the necessary instrumentation, is the long term monitoring both of the angular and torsional internal motions of the structures such as the subsidence of the site, due to natural events (earthquakes, etc.) and anthropic actions (gas and oil extraction, city car traffic, etc.) that may mine stability of the structure. It is very important, therefore, to asses in real-time the effective dynamic status of the structure and of the site, aimed to the identification of possible causes of damage and to the definition, well in advance, of all the actions for their prevention and safeguard, minimizing also the risks for the population.

But, although in principle the idea of an integrated real-time monitoring of a structure in connection with a structural and physical analysis is very simple, problems arise when the requirements on the sensors measurement band ($10^{-6} \div 1\,kHz$) and on sensitivity ($< \, 10^{-11}\,m/\sqrt{Hz}$) are analyzed. In fact, large infrastructures are characterized by very low resonance modes (often less than $1\,mHz$), so that the sensors must guarantee a large band, mainly in the low frequency region. Just as an example, the night and day insulation may cause a slow (angular) motion of the structure ($f_o \approx 0.01\,mHz$), while large concrete beams of large infrastructures may be characterized by a first mode resonance frequency of the order of mHz. Hence the need of large band sensors ($10^{-6} \div 1\,kHz$). A different reasoning can be done to justify the high sensitivity required ($< 10^{-11}\,m/\sqrt{Hz}$). This sensitivity is justified by the fact that, for evident technical reasons, as a general rule, it is preferable to build the structural dynamical spectrum has without any external forcing, but using only natural (seismic noise, wind, earthquakes, etc.) and/or anthropic (traffic, etc.) vibration sources, that, as it is well known, do not produce large excitations of the resonant modes of the structure, a consideration that alone justifies the use of very sensitive instrumentation. Furthermore, for a complete and effective measurement, the monitoring system should consist of an adequate number of sensors, suitably positioned and left there often for years in unattended mode, satisfying precise requirements in terms of space, dimensions and weight. Therefore, the size, weight and last but not least, cost of the sensors assumes a relevant role.

In the last decades, very strong efforts have been produced in the development of seismometers and accelerometers capable to satisfy the increasingly stringent requirements for very different fields (industry, aerospace, engineering, monument and cultural heritage preservation, geophysics, etc.). Such requirements can be globally synthesized in large measurement band ($10^{-6}\, Hz \div 1\, kHz$), high sensitivity (down to $10^{-14}\, m/\sqrt{Hz}$), high directivity ($> 10^4$), compactness ($10\, cm\, side$), lightness ($< 0.5\, kg$), high thermal stability, and, often, ultrahigh vacuum and/or cryogenics compatibility [1]. The difficulty of satisfying such requirements becomes clear analyzing the architecture of the modern accelerometers, generally based on a force feed-back design, a classic control technique aimed to improve their linearity and dynamic range, where the inertial force is compensated acting on the test mass with a feed-back force proportional to the ground acceleration, obtained with electromagnetic transducers. But, although this control technique is very effective and robust, accelerometers based on force feedback configurations, beyond their intrinsic limitations (e.g. thermal noise, etc.), have to face limitations in sensitivity and band due to their readout system noise (LVDT, optical lever, etc.) and due to the often unpredictable noises generated by the force feedback actuators (e.g. magnet-coil actuators) coupling with environmental noises. Therefore, the implementation of accelerometers with large dynamic range, large band, very high sensitivity and mechanical robustness is still an open problem.

To solve this problem, we introduced a new class of sensors based on the so called Folded Pendulum architecture. Based on the Watt`s Linkage (1774) [2], the horizontal folded pendulum architecture is a well known architecture, first hypothesized by Ferguson in 1962 [3], that can be modeled as a combination of a simple pendulum and of an inverted pendulum both connected to one end by means of joints to a bar (the inertial mass) and to the other ends by means of other joints to a supporting structure fixed to the ground (frame). The horizontal folded pendulum has been applied in force feedback configuration as a very effective horizontal vibration isolation system for gravitational wave detectors and low frequency accelerometers [4, 5]. But, although very effective, the dimensions and the complexity of this implementation probably prevented a large diffusion and application. Taking advantage of the technological progress in precision micro-machining and electric discharge machining, a specific research on new compact implementations of monolithic horizontal sensors with extremely soft flexures at the pendulum`s hinges was performed, that allowed large improvements in terms of sensitivity [6, 7, 8], including applications as tiltmeters [6, 9]. All these implementations of folded pendulum are based on the same architectural typology, characterized by joints working in tension, according to the classic engineering approach, so that all these configurations suffer of limitations in sensitivity and band, especially in the low frequency region, being it very difficult for this class of sensors to effectively operate with no force feedback configurations.

The innovative solution introduced with the horizontal and vertical UNISA Folded Pendulum [10, 11] is the implementation of folded pendulums with two of the four joint working in compression (the inverted pendulum ones), a solution that has pioneered the design of innovative configuration of horizontal folded pendulums, allowing large improvements of its performances. The seismometer configuration (no force feedback) of this inertial system is limited, in principle, only by the thermal noise of the mechanics and by the sensitivity of the readout system. Typical performances obtained with standard horizontal UNISA Folded Pendulums are the low sensor natural resonance frequency (down to values of $\approx 60\, mHz$) obtained with a 14 cm size sensor [1] and the large measurement band ($10^{-7} \div 10\, Hz$), sensitivity (typically of the order $10^{-12}\, m/\sqrt{Hz}$ with optimized LVDT and optical levers readout systems, but better with other readout systems) in the low frequency region of the seismic spectrum. It is worth underlining that a suitable choice of the readout system may provide the folded pendulum with large immunity to environmental noises, as occurs in the case of optical readouts [1, 12, 13, 14].

In the following sections after a description of the UNISA Uniaxial/Triaxial Folded Pendulum Seismometer/Accelerometer and a discussion on the mechanical performances and sensitivity of its components in connection with different mechanical and optical readout configurations [1, 12, 13], we present and discuss the results obtained and expected in a next future with monitoring system based on this class of sensors in the field of cultural heritage preservation [15, 16, 17].

II. FOLDED PENDULUM THEORETICAL MODEL

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. On the other hand, an analytic approach, although not enough accurate to be used for folded pendulum designs, guarantees a global and synthetic overview of its mechanical performances and dynamic behavior. The Lagrangian two-dimensional analytical model of Bertolini [18], based on the simplified Liu et al. [4] model, generalized by Barone et al. [1], developed to describe the dynamical behavior of a horizontal folded pendulum, whose basic mechanical scheme is shown in Figure 1, is sufficient for the latter purposes.

The simplified folded pendulum model schematically consists of two vertical arms of equal length, l_p, connected

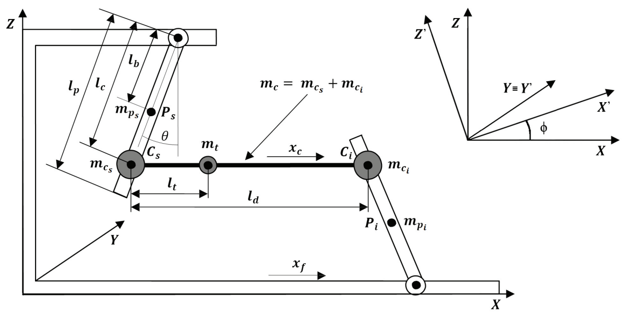

Fig. 1. Folded Pendulum Mechanical Scheme [1].

to one side to a single support (frame) by means of two hinges, forming a simple pendulum of mass m_{p_s} and an inverted pendulum of mass m_{p_i}. The two pendulums masses 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, while the mass of the central bar is modeled 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, $\dot{x}_p$ and the two equivalent masses (m_{c_s}, m_{c_i}) have the same velocity of the center of mass of central bar, $\dot{x}_c$. Therefore, the folded pendulum simplified Lagrangian model of Bertolini [18], extended by Barone et al. [11, 14] can be conveniently described by the classic Lagrangian:

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

T the approximate analytic expression of the kinetic energy

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

with J_s and J_i moments of inertia of the two arms, while U is the approximate analytic expression of the potential energy, that for an ideally horizontally positioned folded pendulum can be expressed as

$$U = \left[\frac{(m_{p_s} - m_{p_i})}{2} g_{eq} l_p + (m_{c_s} - m_{c_i})\, g_{eq} l_c + k_\theta\right] \frac{\theta^2}{2} \tag{6}$$

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

$$g_{eq} = g \cdot \cos\phi + a_{ext} \tag{7}$$

where ϕ is the inclination angle of the folded pendulum with respect to the local horizontal plane. $\phi = 0°$ 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 reduce the effects of the acceleration of gravity changing its natural resonance frequency [11]; $\phi = 90°$ describes a vertical folded pendulum, whose resonance frequency does not depend on the acceleration of gravity: only the application of an external acceleration, α_{ext}, to the central mass, perpendicular to its direction of motion can change the natural resonance frequency due global elastic constant of th joints, k_θ, introduced to take into account that the pivot points may be elliptic flexure joints, whose behavior is well described by the generalized Tseytlin formula [19].

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

$$\begin{aligned} f_o &= \frac{1}{2\pi}\sqrt{\frac{\left[\left(m_{p_s} - m_{p_i}\right)\frac{l_p}{l_c} + \left(m_{c_s} - m_{c_i}\right)\right]\frac{g_{eq}}{l_c} + \frac{k_\theta}{l_c^2}}{\left(m_{p_s} + m_{p_i}\right)\frac{l_p^2}{3l_c^2} + \left(m_{c_s} + m_{c_i}\right)}} \\ &= \frac{1}{2\pi}\sqrt{\frac{K_{g_{eq}} + K_{e_{eq}}}{M_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{K_{eq}}{M_{eq}}} \end{aligned} \tag{8}$$

where $K_{g_{eq}}$ 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

$$K_{g_{eq}} = (m_{p_s} - m_{p_i})\frac{g_{eq} l_p}{l_c^2} + (m_{c_s} - m_{c_i})\frac{g_{eq}}{l_c} \tag{9}$$

$$K_{e_{eq}} = \frac{k_\theta}{l_c^2} \tag{10}$$

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

$$M_{eq} = (m_{p_s} + m_{p_i})\frac{l_p^2}{3l_c^2} + (m_{c_s} + m_{c_i}) \tag{11}$$

Equation 8 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, $K_{e_{eq}}$, consequently reducing the natural resonance frequency, f_o, increasing the measurement band of the sensor. Equation 8 (and the related equations 9, 10 and 11) are very useful in the design phase to define the folded pendulum resonance frequencies on the basis of suitable combinations of their physical and geometrical parameters. Nevertheless, the resonance frequency of a folded pendulum is a parameter that can be largely modified also after manufacturing, using suitable calibration techniques, operation often necessary to optimize its performances according to the requirements of different applications. It is possible, in fact, to always change the resonance frequency, for example, using a calibration mass, m_t, to change the value of the equivalent gravitational elastic constant, $K_{g_{eq}}$ [8], or using an external force to change the value of the potential energy, U[10, 11].

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

$$H_a(s) = \frac{X_c(s) - X_g(s)}{A_g(s)} = \frac{X_{output}(s)}{A_g(s)} = \frac{(1 - A_c)}{s^2 + \frac{\omega_o}{Q(\omega_o)} s + \omega_o^2} \quad (12)$$

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

$$A_c = \frac{\left(\frac{l_p}{3l_c} - \frac{1}{2}\right)(m_{p_s} - m_{p_i})}{(m_{p_s} + m_{p_i})\frac{l_p^2}{3l_c^2} + (m_{c_s} + m_{c_i})} \quad (13)$$

is the parameter related to the center of percussion effects [1].

III. THE UNISA FOLDED PENDULUM

Although the problem of uncoupling horizontal forces with tilts still remains an open problem, the new vertical folded pendulum configuration [11] has offered new possibilities in the design of more complex geometric configurations. In fact, it is now possible the implementation of folded pendulums, singularly on in subsets, able to operate tilted with respect to the local horizontal [1, 11], that is, as discussed in the previous section, the key for the implementation of high performance uniaxial/triaxial folded pendulum seismometers and accelerometers. In fact, all the intermediate configurations between the folded pendulum configuration in horizontal mode (its classical configuration for the measurement of the horizontal displacement and/or acceleration) and the folded pendulum configuration in vertical mode (for the measurement of the vertical displacement and/or acceleration) are now fully feasible with a suitable design of the mechanical components, coupled with an improved calibration technique [1].

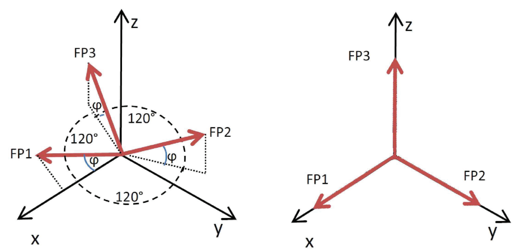

Fig. 2. Triaxial Folded Pendulum Accelerometer: 120° *Configuration (left) - xyz Configuration (right).*

On the basis of what said above, the output signal of a folded pendulum positioned, for example, tilted of an angle, ϕ, with respect to the ground, is a linear combination of the horizontal and vertical components of the ground displacement (or acceleration), whose weights are classically functions of the sensor tilt angle, ϕ, easily evaluable using standard trigonometric formulas. A direct consequence is that it is now possible the implementation of triaxial sensors consisting of folded pendulums positioned according to suitably designed geometric configurations. The first obvious configuration for the implementation of a triaxial sensor is that of positioning three folded pendulums 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 (Figure 2 (left)). Another different configuration, but still equally valid (the choice depend on the specific application) is again reported in Figure 2 (right), but with the folded pendulums, this time aligned along the three main axis of a cartesian reference system, xyz, allowing a direct measurement of the three different degrees of freedom.

In Figure 3 a typical implementation of standard very light ($250\,g$) UNISA Horizontal Folded Pendulum is shown. The sensor is made of Aluminum Alloy 6082-T6, has dimensions ($77.5\,mm \times 85\,mm \times 40\,mm$) and hinges characterized by ellipticity (16/5) and thickness ($100\,\mu m$). UNISA inertial sensors can be designed using different readouts (shadow meters, fiber bundle, LVDT, capacitive,

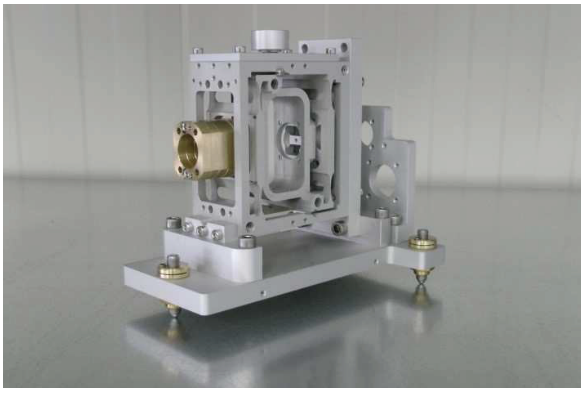

Fig. 3. Uniaxial Horizontal Folded Pendulum - model GE15 - equipped with a commercial LVDT readout module to obtain the sensitivity of $10^{-9} m/\sqrt{Hz}$, as required for the Trajan Arch preliminary monitoring tests.

etc.). Just for sake of comparison in Fig. 4 we show the theoretical sensitivity curves of the UNISA Folded Pendulum sensor (at $T = 300\,K$) with this commercial LVDT readout (tuned at $3Hz$), compared with the typical theoretical sensitivities and bands of UNISA Folded Pendulum sensors equipped with an optical lever and interferometric readouts (tuned at $250\,mHz$). In the same figure, the sensitivity curves of the STS-2 by Streckeisen[20] and of the Trillium-240 by Nanometrics [21], representing the state-of-the-art of ground-based low frequency seismic sensors, are reported for comparison, together with the Peterson New Low Noise Model (NLNM) [22] and the McNamara and Bouland Noise Model [23], that represents 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 âĂŞ observed. A synthetic view of the global performances obtainable with the UNISA Folded Pendulum class of sensors is presented in Table 1. Figure 5 shows, instead, a triaxial mechanical accelerometer, consisting of three uniaxial monolithic UNISA Folded Pendulums (model GE15), positioned according to the cartesian xyz configuration.

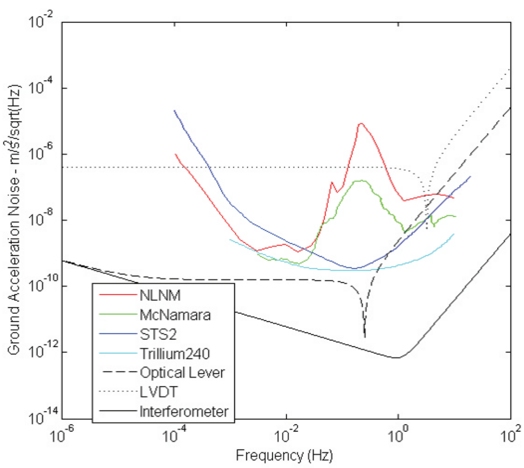

Fig. 4. Sensitivity curves of the UNISA Horizontal Folded Pendulum.

Band	$0.0001\,mHz < B < 1\,kHz$
Sensitivity	$10^{-15}\,m/\sqrt{Hz} < S < 10^{-6}\,m/\sqrt{Hz}$
Directivity	$D > 10^4$
Res. Frequency	$50\,mHz < f_o < 1\,kHz$

Table 1. UNISA Folded Pendulum Parameters Ranges [13].

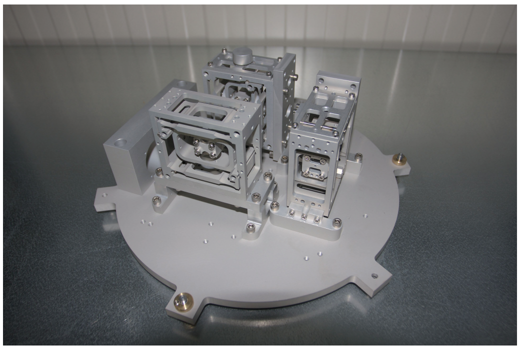

Fig. 5. Triaxial Folded Pendulum sensor - xyz configuration.

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

The present versions of the UNISA monolithic seismometers/accelerometers (uniaxial and triaxial) are already very good instruments for many applications, even if they have not yet reached their ultimate sensitivity. In fact, the limitations in terms of sensitivity and band of the UNISA Uniaxial/Triaxial Folded Pendulums [10, 11] configured as inertial sensors, are due only to the readout system electronic noise, to the thermal noise of the mechanical joints and to the air damping, when not operated in vacuum. The application to the low frequency large band monitoring of the Trajan Arch in Benevento (Italy), performed as field test in 2015 has already demonstrated the feasibility of implementation of a monitoring system based on the UNISA Folded pendulums, showing the possibility of exploring a band, yet unexplored, necessary to understand the dynamics of the monument and to evaluate its health status [15, 16, 17]. Long term tests have been since then planned and/or are in course on selected historical monuments and sites to demonstrate the effectiveness of the approach described in the paper: the first results are expected by the mid of the next year.

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