Wideband mechanical amplifiers for ”dual” gw detectors.

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Abstract.
We report on the status of the R & D towards a dual detector. We discuss the experimental advances for a broadband mechanical amplifier equipped with a Fabry-Perot cavity and for an increase of the breakdown voltage in capacitive transducers.

1. Introduction
Dual detectors are a new concept acoustic detectors [1]. Their main distinguishing features from the traditional acoustic resonant detectors are the wide bandwidth they can perform (up to 5.0 kHz ) with an enhanced sensitivity produced by a mode selection strategy [2].

We can picture a dual system as two independent nested masses: a hollow one containing a massive one. If the two bodies have a cylindrical shape, (see fig.1, a) we speak of a dual cylinder [3]. The dual detector’s working principle is very simple: an impinging monochromatic gravitational wave (gw) propagating along a parallel direction to the dual cylinders’ axis, excites all the quadrupolar vibrational modes of both masses. Because the inner one has a fundamental quadrupolar resonance at higher frequency than the outer one, in the range limited by the two fundamental quadrupolar resonances the phase lag of the differential motion of the facing surfaces is nearest π and then we have an enhancing effect on the signal and a back-action reduction effect also, that results in an increased gw transfer function. The detection is accomplished by measuring the differential displacement of the facing surfaces during the vibrational motion through an optical readout (Fabry-Perot or Folded Fabry-Perot [4]) or a capacitive readout. The predicted dual sensitivity at Standard Quantum Limit is shown in fig. 1, b.

2. Dual detectors and leverage-amplifier.
The selection strategy using capacity transducers can be implemented as shown in fig. 2: this circuit enables to use a DC SQUID amplifier in order to read the signal coming out from the quadrupolar filter built by four gradiometrically connected capacitors. In order to achieve the optimum Standard Quantum Limit (SQL) sensitivity of $10^{-23}m/\sqrt{Hz}$ it is necessary to develop a non-resonant amplifier that senses the differential deformation of the two cylinders over all the dual bandwidth with a mechanical gain ~ 10. We need a capacitive readout system able to accomplish out of resonance measurements, i.e. able to amplify displacements of main elastic body without affecting the overall dynamic (neither the phase, nor the amplitude). A wide bandwidth readout cannot profit from the resonant amplification of conventional resonant
Figure 1. a) Dual torus: the detector is made of two concentric cylinders, $T_e, T_i$. The output signal is obtained by measuring the relative distance in 4 regions (in blue), each of area $S_T$, for the whole cylinder height.

b) This is the predicted spectral strain SQL sensitivity of two different dual configurations. The predicted SQL sensitivity of LIGO advanced is also shown. For the outer SiC cylinder, height is 3.0 m, the internal-external radius is 0.83-1.44 m, inner cylinder diameter is 0.82 m, amplifier noise $S_{xx} = 6 \times 10^{-46} \text{m}^2/\text{Hz}$ and $Q/T = 2 \times 10^8$ its total weight is $20.5 + 41.7$ ton [2]. For a Mo outer cylinder: 2.35 m high, the internal-external radius 0.83-1.44 m, the inner cylinder radius is 0.25 m. Its total weight is $4.8 + 11.6$ ton (we considered an amplifier noise $S_{xx} = 10 \times 10^{-46} \text{m}^2/\text{Hz}$ and $Q/T = 2 \times 10^8$).

Figure 2. Selective readout principle. A possible readout configuration: the four capacitors are charged with a constant charge and connected so as to give an output current $I_p$ proportional to the variations of $X = X_1 - X_2 + X_3 - X_4$. The resulting current $I_p$ is then amplified by a SQUID device $A$ through a flux transformer made by the coils $L_p$ and $L_s$. The amplifiers should be mounted between the charged plates of each capacitor.

transducers, it is then of fundamental importance to design a device that can perform a constant amplification factor over a large bandwidth. Amplifiers incorporated in dual detectors have to keep working the filtering technique, so it will be inserted between the facing surfaces of cylinders with regard to the angular symmetry represented by the four capacitors. One possible amplifier that accomplish these requests is a lever type, i.e. a mechanical amplifier that work as a pure lever when incorporated in dual detectors. The main features that a lever-amplifier has to accomplish for dual purposes are briefly described:

- Lever-amplifiers have to cover an overall range up to 5.0 kHz.
- Lever-amplifiers have to perform a displacement gain factor $1/\alpha$ as larger as possible to reach...
Figure 3. The 3-joints leverage and the 4-joints one. The geometrical gain is inversely proportional to the angle $\alpha$ of the wing with the horizontal axis of symmetry. The mirror supports of the Fabry-Perot cavity are also indicated. The bias electric field for the capacitive leverage is also indicated. Both leverages perform a geometrical gain $1/\alpha = 10$.

SQL. For a given mechanical gain $1/\alpha = 10$ and using a bias electric field $E_0 \sim 10^8 V/m$ applied to the moving plates of an eventually capacitive leverage, SQL is assured if we couple a $1\hbar$ DC SQUID readout chain not so distant to be achieved with today’s technology [5].

- The first internal resonance has to be out of the working band (above 5.0 kHz)
- The intrinsic leverage thermal noise must be lower than the dual one amplified by the leverage itself.

To preserve the material characteristics (like the mechanical quality factor) we have to design a lever-amplifier from a monolithic sample: this kind of amplifier is usually called leverage [6].

3. Leverage-amplifiers

The first ever designed leverage was conceived by H.J.Paik [9] and it had been simulated by using Finite Element Method (FEM) to predict its mechanical behavior. We developed two leverages with different readout: the first type is a three joints-leverage, equipped with an optic readout (Fabry-Perot cavity hosted by the two moving masses as shown on fig.4, b) the second is a four joints-leverage, shaped so as to work like a capacitor sensor. The former type is the simplest geometric conceivable leverage, the latter is a wide area capacitance transducer so it needs a four joints mechanism to allow a normal displacement of the facing plates of the capacitor. The electric bias field is applied between the two plates and we started studying a metal surfaces polishing technique [7],[8] to increase the transduction efficiency (see fig. 3).

For the first prototype we performed a geometric optimization by changing a set of geometrical parameters. The set of parameters was chosen out from a larger selection after identifying the best improvement they produces by changing their value of a few percents. This prototype was machined using an aluminum alloy (Alumold 1-600). To understand which is the thermal noise contribution injected by the amplifier to the dual detector, it was designed a test oscillator that emulates the dynamical boundary conditions of the main elastic body, a sort of simplified dual device. The lumped model of the full system is very simple and it is described here in fig 4, a.
a) Simplified lumped mechanical model of the leverage+test-oscillator; the first mass $M$ stays for the oscillators effective mass. The second mass $m$ stays for the mirror+support effective mass. $K$ is the stiffness of the oscillator and $h$, $\zeta$ are two stiffness parameters that take into account the dynamical and statical stiffness of the leverage. Each beam $R$ is considered ideally rigid and without any inertial role over the motion. Both piezo forces $F_a, F_b$ applied along $x$ direction and used for the direct gain transfer function are indicated. The two piezo’s masses $p$ give account for the inertial effect introduced by the actuators.

b) The test-oscillator with leverage incorporated: both were machined using Alumold 1-600, an aluminum alloy. The mirror supports are the two symmetric masses in the center of the leverage.

Using the FEM analysis we calculated the thermal noise displacement for both the Fabry-Perot cavities by using Fluctuation Dissipation Theorem (FDT). It can be observed that the so called ”ideal lever-behavior” is performed up to 750 Hz as shown in fig. 5, a. In this range, the lever amplifier multiplies by $1/\alpha = 10$ thermal noise of the test-oscillator (fig. 5, b).

Direct gain function was measured by using a pair of piezo ceramic actuators applied at ends of the test-oscillator. The measurement was performed by acquiring the signal of four accelerometers: two fixed at the leverage and two fixed at the test-oscillator (see fig. 5, a). The ideal lever behavior is performed up to 750 Hz. Above this value a dynamical contribution (relied on the elasticity of the material it is made the leverage), affects the geometrical gain and dynamics overwhelms the pure lever behavior. A frequency shift from the FEM prediction can be explained as the inertial effect of the electrical cable that read the signal of the accelerometers.

Multi-objective Optimization was performed using the $modeFRONTIER^{\text{®}}$ software which explored hundred of geometrical configurations and produced a set of compromised solutions determined by a set of nine parameters. The Pareto curve is the set of all vectors that describe the possible optimized configurations [10]. Among them, we extracted our best model: gain=10 and first mode frequency $f=5000\text{Hz}$. In principle, we could choose the one with biggest gain ($\sim 37$), but its own fundamental mode vibration frequency is too low ($\sim 800\text{Hz}$).

4. Next future work
We designed two different leverages and measured the mechanical transfer function of the one equipped with optic readout. We studied a method to perform the thermal noise measurement predicted by FEM and shown in fig. 5, b, for the 3-joints leverage at room temperature. It will be implemented by using a classic Pound-Drever loop applied to the Fabry-Perot cavity hosted inside the leverage supports [11]. To avoid macroscopic length variation of the two cavities converted through the thermal expansion coefficient of the Alumold 1-600, we built a system of nested boxes that should be able to stabilize the maximum temperature fluctuation up to
Figure 5. a) FEM predictions and experimental measurement of the direct gain function for the 3-joints leverage shaken by the piezo actuators as schematized in fig. 4. a. The drift in frequency of the peak below the FEM prediction is probably due to the electric cables inertial mass contribution of the accelerometers fixed on the leverage supports. We are studying the apparent lack of the second resonance peak at 2.0 kHz.

b) We predicted thermal noises read on both the F-P cavities of the 3-joints leverage (higher curve) and the one of the test-oscillator (lower curve) by using FDT. The ideal lever behavior can be observed performed up to 750 Hz. In this range, the lever amplifier “multiplies” by the geometrical gain $1/\alpha = 10$ the thermal noise of the test-oscillator. At higher frequencies, higher vibrational mode contributions change the geometrical regime to the dynamical one. We used a Gaussian force profile with a waist value $w_0=365 \mu m$. The material data used for simulation correspond to the Alumold 1 – 600, or $(Y = 7 \times 10^{10} \text{ N/m}^2, \sigma = 0.31, \rho = 2.7 \times 10^3 \text{ kg/m}^3)$ for the leverage and Fused Silica for the optical mirrors $(Y = 7 \times 10^{10} \text{ N/m}^2, \sigma = 0.17, \rho = 2.2 \times 10^3 \text{ kg/m}^3)$; the loss angle used for both materials is $\phi = 10^{-4}$.

50 $\mu K$ at room temperature, using NTC technology. Folded Fabry-Perot is going to be tested also to give a first experimental confirmation of the predicted noise reduction [4]. Because of its importance on dual applications, we are studying the best method to improve the capacitive readout performances. In order to increase its transduction efficiency, we designed and built a vacuum apparatus to study the voltage breakdown limit for cylindrical aluminum samples faced with a gap of 50 $\mu m$. The main goal is to reach a stable bias field of about $10^8 V/m$ for wide area surfaces of the capacitor’s plate. This goal is implemented by studying the surface polishing technique (applying voltage at radio frequency or static voltage increased step by step) and refining the superficial roughness by a process based on diamond machining [12]. By exploiting these improved readout coupled to the leverage amplifiers, dual detectors will be able to work with a the SQL sensitivity as shown in fig. 1,b.

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