Dual Acoustic Gravitational Wave Detector

Michele Bignotto, on behalf of Dual collaboration

I.N.F.N. Istituto Nazionale di Fisica Nucleare – Sez. di Padova

Via Marzolo, 8 -35100 Padova - Italy

Email: Michele.Bignotto@lnl.infn.it

Web: www.lnl.infn.it

Summary

Dual detectors are new generation broadband gravitational wave (GW) detectors. FEM-designs heavily enters into optimization of sensor technology in order to machine the first non-resonant leverage amplifier for dual detectors.

Keywords

Leverage, Amplifier, Detector, gravitational wave, transducer

Introduction

Gravitational waves are perturbations of gravitational field propagating at light-speed [1]. They were predicted in 1916 by Einstein's Theory of General Relativity and their effect first had been indirectly observed by Hulse and Taylor [2] along 10 years of radio emission measurement of the binary pulsar PSR 1913+16 from 1974. They discovered a systematic shift in the observed time of periastron relative to that expected if the orbital separation remained constant in the aforementioned binary. Recently, a new binary pulsar was discovered in 2003, the PSR J0737-3039 [3] and the predictions for energy loss due to gravitational waves appear to match the theory. GWs are the weakest longrange physical signals of nature. Compared with the analog electromagnetic waves power emitted by an electron oscillator, there is a factor 10^{-53} that decreases the corresponding GW power [1]. That is the reason of the difficulties found to detect them and the 50 years delay for the detector development. A big effort was made in the last 40 years to build GW resonant acoustic detectors [4], and only in the last few years they were improved to reach a theoretical sensitivity able to detect intra-galactic GW burst sources like supernovae. New generation GW detectors are being designed to achieve deeper sensitivity for weaker GW sources emitting into a few kHz region. They are broadband non-resonant detectors.

To achieve a sufficient sensitivity for 100 kPc distant sources (embracing the Virgo Cluster), dual has to be equipped with a wide bandwidth leverage amplifier. Multi-objective optimization was used to design the highest gaining device vs. the highest resonance frequency of fundamental normal mode of the amplifier. Prototypes features are hereby described.

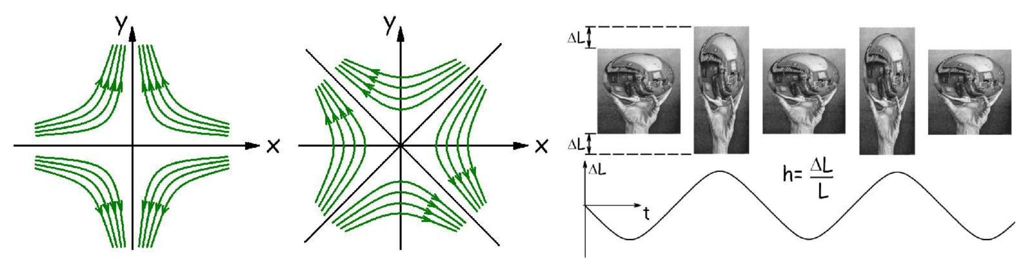

Figure 1: GW force line pattern for both polarization at a given instant. The plane is perpendicular to the direction of propagation of the wave. The second figure shows the stretching and squeezing effect of a crossing GW.

GW interacting with matter

Being transversal waves, GWs have two independent polarizations [1] and their force line patterns are show in fig.1. Because of their quadrupolar nature, when impinging a body of a given length "L", a GW induces a variation in amplitude "ΔL" into their vibrational quadrupolar modes of the body, measurable by its strain magnitude "h=ΔL/L". The GW signal emitted by supernova bursts of our galaxy are predicted to be centered at ~ 1.0 kHz and depending on their quadrupolar moment variation developed during the collapse, it is optimistically expected a strain intensity of about $h \sim 10^{-20}$. A GW generated by these sources squeezes and stretches by this factor any crossed body.

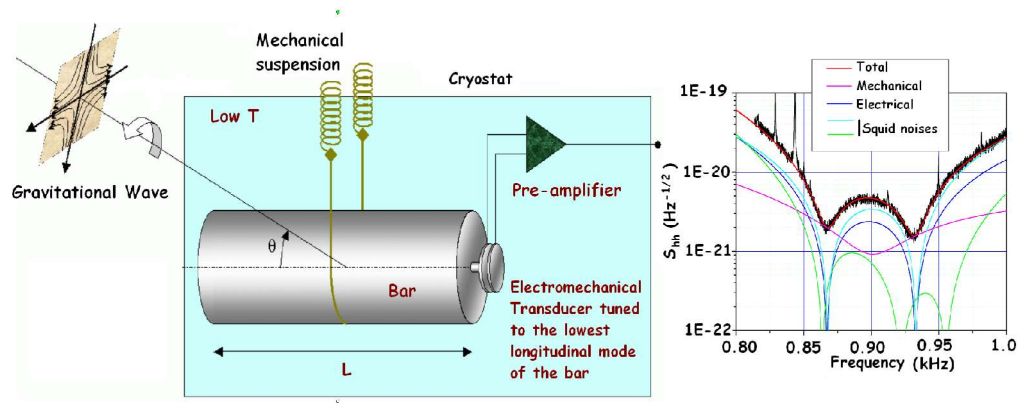

Figure 2: GW Detector's scheme and the theoretical spectral strain sensitivity compared with the experimental one.

A resonant acoustic detector: AURIGA

The simplest device able to detect GWs is the harmonic oscillator [1]. By symmetry, it is the simplest GW source as well. Existent GW detectors can detect a GW signal up to $h=10^{-20}$ at 1.0 kHz. Traditional acoustic detectors are mechanical resonators (see fig. 2) i.e. the best sensitivity is peaked on a detector mechanical resonance [5]. The purpose of the AURIGA experiment is a direct detection of GW of astrophysical origin. AURIGA is a resonant device that exploits the fundamental vibrational mode at 900 Hz of a cylinder made by al 5056 cooled down at 4.0 K. The sensitivity of a resonant detector is determined by the value of the thermal noise of the amplifier matched to the resonator [6]. The antenna is coupled to a resonant transduction chain that uses a capacitive sensor to transform the mechanical displacement into electrical signal. The signal out of the transducer is enhanced by a two stage SQUID pre-amplifier and then acquired by a sampler. The cylinder is suspended by a mechanical isolator system that can filter high and low frequency seismic noise generated by the environment.

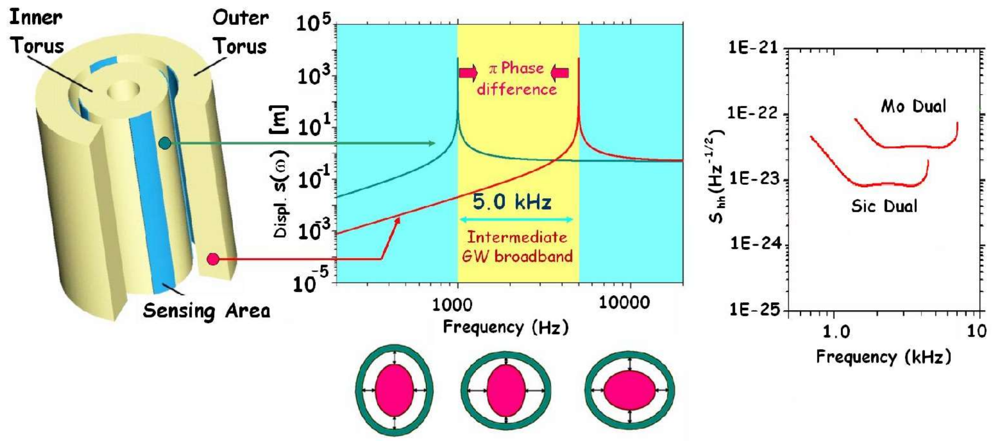

Figure 3: Working principle of dual detector. The measurement is performed by sensing the differential vibrational motion driven by a GW crossing the two antennae. The spectral strain sensitivity of Mo or SiC dual detectors are also show: the SiC one corresponds to two nested cylinders (~60 ton!), the outer radius is 1.44 m, while the Mo one has a diameter of 2.0 m. Both are 3.0 m high (~15 ton).

Dual detectors

“Dual” detectors are new generation broadband GW detectors [7] and constitute the natural evolution of traditional acoustic detectors. Their working principle is to have two concentric elastic and massive free-falling bodies (two nested cylinders) with its own quadrupolar mechanical resonances at different frequency. When eventually excited by the passing GW, we detect the signal by reading the differential deformation of the facing surfaces of the two antennae which are considered at rest frame of the center of mass of the system. Between the two main quadrupolar resonances the GW force drives one oscillator above and the other below resonance. The displacements are out of phase and thus they sum up in a differential measurement, resulting in a signal enhancement with respect to the single oscillator response (see fig. 3). Now we are studying the GW cross section of dual to get a good optimization by acting over a given set of free parameters.

Leverage Amplifiers

To keep a broadband bandwidth, the transducer has not to be resonant. So we need a readout system able to accomplish out of resonance measurements. We designed a kind of “speed amplifier” which is a compliant mechanism and does not affect the dynamic of dual bodies. This device is called “leverage” because it works like a lever (its gain depends on the geometrical features of its shape) and is machined starting from a monolithic piece. We used the ANSYS environment and optimized two different amplifiers: a three and four-joints leverage. The main feature of these devices is their geometrical constant gain factor, which does not dependent on the working frequencies. Because of its fundamental vibrational mode must be much higher than the highest frequency of dual bandwidth, our amplifier can be studied as if it were a low frequency device (static gain gives the right value of amplification for the full working bandwidth). We used ModeFRONTIER® [8] software to improve the four-joint leverage amplifier (see fig. 4). Now we are studying how to incorporate the amplifier inside the facing areas of dual. The first prototype was machined in Alumold 600 and tested: we measured its mechanical transfer function and now we are building the apparatus to perform a first thermal noise measurement in order to establish its experimental behavior.

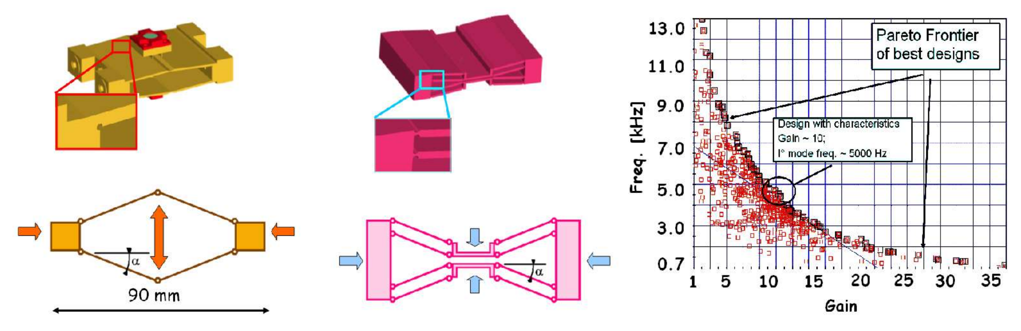

Figure 4: Three and four-joints leverage: the first optimized by an intuitive algorithm (gain=10, first resonance at 2.10 kHz); the second optimized by using ModFRONTIER® algorithm (gain=10, first resonance at 5.0 kHz) as shown by the Pareto curve in the second figure. The two different kinds of joints are also shown.

References

[1] Ohanian, H. C. and Ruffini, R. Gravitation and Spacetime, 2nd ed. New York: W.W. Norton, 1994.

[2] see nobel lecture at http://nobelprize.org/physics/laureates/1993/presentation-speech.html

[3] http://www.physicsweb.org/articles/world/18/3/6/1

[4] J. Weber, Phys. Rev. **117**, page 306 (1960)

[5] M. Cerdonio *et al.*, The Ultracryogenic Gravitational Wave Detector AURIGA, Class. Quantum Grav. **14** (1997) 1491

[6] M. Bonaldi *et al.*, Thermal noise in a high Q cryogenic resonator, Rev. Sci. Inst. **70** (1999) 1851-1856

[7] M. Cerdonio *et al.*, Wideband dual sphere detector of gravitational waves, Phys. Rev. Lett. **87** (2001) 031101, also in gr-qc/0011002.

[8] Dr E. Serra and Dr M. Saraceni, Private communication