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Wide bandwidth dual acoustic gravitational wave detectors

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Abstract
In a 'dual' detector a wideband sensitivity is obtained by measuring the differential displacement, driven by the gravitational wave, of the facing surfaces of two nested massive bodies mechanically resonating at different frequencies. By using the recently proposed 'selective readout' scheme, capable of specifically selecting the signal contributed by the vibrational modes sensitive to the gravitational waves, a flat spectral strain sensitivity can be obtained. In the case of a 1 m diameter molybdenum dual cylinder, the sensitivity expected at the standard quantum limit is about 10^{-23} $\mathrm{Hz}^{-1/2}$, in the wide frequency interval of 2–6 kHz. We discuss here the requirements imposed by the 'dual' design on the differential displacement readouts. A possible readout scheme is presented and its current limits analysed. The feasibility of a mechanical amplification stage (compliant mechanism) to increase the expected displacement at the readout input is also discussed.

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1. Introduction

Substantial progress has been made over the last 40 years in preparing instruments and methods to search for gravitational waves from the universe. Theoretical astrophysics and numerical relativity focus on candidate sources, whose signals will be efficiently extracted by the dominating noise with analysis methods developed *ad hoc*. Resonant mass 'bar' detectors, the first historically to come to continuous operation, have been improved by four orders of magnitude in energy sensitivity, so that they can detect energy changes in a 2300 kg bar of as little as a few thousand of quanta of vibration at about 1 kHz. The five bar detectors distributed worldwide have operated for a few years as a network, giving for the first time significant upper limits to the yearly rate of violent gravitational wave (GW) events in the galaxy [1, 2]. A first generation of long baseline interferometric detectors is now operating or coming into operation and, complemented by the upgraded bars, may well give a first detection in the next few years.

However, it is commonly accepted in the community that, to enter the 'observatory phase' and open up a new GW astronomy, a substantial improvement in detector sensitivities should be achieved. It is also becoming clear that interferometric detectors are most sensitive in the few Hz to few hundred Hz frequency range, while resonant mass detectors are potentially very sensitive in the kHz frequency range, where possibly fully relativistic features will show up. Traditional acoustic detectors are seriously limited in terms of bandwidth (typically to about 10% of the resonant frequency) due to the usage of the resonant transducer, which is needed to reduce the effect of the noise of the final amplifier. Moreover, the resonant transducer has proved so far to lower the mechanical quality factor of the main resonator, thus reducing its potential sensitivity. A different approach is needed to fully exploit the potential sensitivity of resonant detectors and make them complementary to the advanced versions of interferometric detectors. We are actively investigating a novel detection scheme, the 'dual' resonator system [3–5], which can provide both high sensitivity and wide bandwidth.

2. Dual detectors

The design of the conventional resonant detectors sets an intrinsic limit to the maximum achievable bandwidth, of the order of 10% of the operating frequency. This is due to the resonant operation of the transducer [6], which enhances the transfer function of the gravitational signal against the white noise introduced by the amplifier in a frequency range close to the resonance of the main resonator. As a drawback, the resonant transducer carries its own thermal noise, in such a way that the signal-to-noise ratio is deteriorated a little away from the central operating frequency. This causes the intrinsic limit on the width of the sensitivity band. However, these limitations can be overcome by the novel concept of acoustic detector, which gives up the method of resonant operation of the transducer: a 'dual' resonator GW detector is in fact formed of two nested mechanical massive resonators both sensitive to GW and whose relative vibrations are measured by non-resonant readouts.

We consider the nested configuration as two nested spheres, an inner solid one and a hollow outer one, or two nested cylinders. These massive bodies act as mechanical quadrupolar oscillators. Figure 1 shows the scheme of a dual detector of cylindrical symmetry. The useful sensitivity bandwidth for gravitational waves is then included between the fundamental quadrupolar mode of the outer body, at lower frequency, and the fundamental quadrupolar mode of the inner body, at higher frequency. In fact, in this frequency range the external resonator acts as an oscillator driven above its resonance while the inner one acts as an oscillator driven below its resonance. In response to the same GW excitation, the two induced vibrations are out of phase by 180° and the resulting differential vibration can thus be sensed by a displacement readout, in a way which adds up the responses of the two resonators. Therefore, by measuring the differential deformation as shown in the figure, the sensitivity to the signal is preserved within the resonances. In contrast, the response to the readout noise force, which back-acts out-of-phase on the two resonators, tends to be reduced (because it acts with opposite sign on the faced bodies). The overall result can be a very large bandwidth with quite uniform sensitivity (2–5 kHz). Of course the readout is required to be wide band and suitably adapted, i.e. to provide the optimal balance between the displacement noise and the

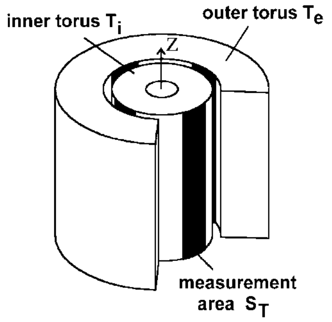

Figure 1. The detector is made of two concentric cylinders, T_e, T_i. The inner cylinder may also have null internal radius. The optimally oriented gravitational wave travels along the z-axis and induces relative displacements among the two cylinders. The output signal is obtained by measuring the relative distance in four regions (in black), each of area S_T, for the whole cylinder height.

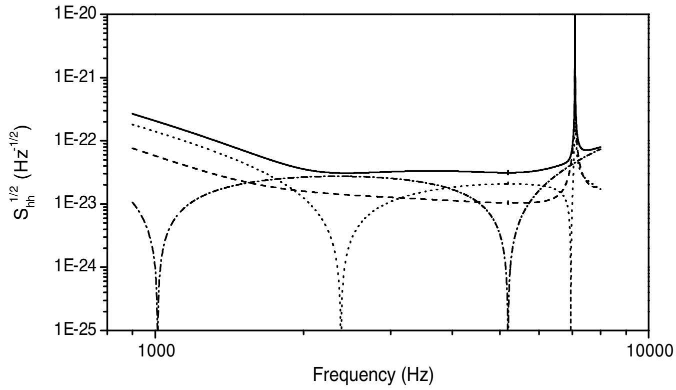

Figure 2. The contribution to the detector noise at the SQL is evaluated for a Mo detector. Continuous line: total noise. Dashed line: thermal noise evaluated at $Q/T \sim 2 \times 10^{-7}$ K^{-1}. Dashed-dotted line: amplifier displacement noise. Dotted line: amplifier back-action noise.

back-action force noise. The detector reaches its standard quantum limit (SQL) of sensitivity when the thermal noise is negligible and the readout works at the quantum limit: this is reached when the product of the noise power spectral densities in displacement and in back-action force is $\sim(\hbar^2)/4$. Figure 2 shows the contributions to $\sqrt{S_{\rm hh}}$ at SQL for a cylindrical configuration of dual detector made of molybdenum, whose external diameter is 0.94 m, $Q/T \sim 2 \times 10^{-7}$ K^{-1} (Q is the mechanical quality factor and T the temperature) and the readout displacement noise $\sim 2 \times 10^{-23}$ m Hz$^{-1/2}$.

3. Possible readouts

The non-resonant readouts for a 'dual' detector are evolutions both conceptually and in technology of the resonant readouts used in the bar detectors. In order to achieve the wide frequency interval of high sensitivity, of the order of many kHz, the differential deformation between the facing surfaces of the nested bodies needs to be measured by readouts that are not in mechanical resonance. Another relevant requirement for the transducer system is to sense the deformation of the resonant masses on a wide surface, in order to be less sensitive to the resonant modes of higher frequency, which do not carry any gravitational signal. In this way the thermal noise of the detector is minimized, while preserving the sensitivity to the signal. A further progress in this noise reduction can be achieved by a readout scheme which is geometrically selective to the fundamental quadrupolar modes, as shown in figure 1. This selectivity also allows us to clean the bandwidth of the spurious modes not sensitive to gravitational waves [5].

The dual cylinder sensitivity curves are optimized with a quantum limited readout with displacement sensitivity of the order of 3×10^{-23} m Hz$^{-1/2}$. This figure is impressive and indeed has not been achieved so far, and we stress that a wide-band readout cannot profit from the displacement amplification at resonance of conventional transducers. Up to now, the lowest displacement noise we have achieved experimentally is about 5×10^{-20} m Hz$^{-1/2}$ [8, 9] in the kHz range. This has been demonstrated by two different kinds of readout which we are developing: an optomechanical one [7, 9], based on Fabry–Perot cavities, and a capacitive one [8], based on SQUID amplifiers. The properties of these transducer systems are very different and both of them show peculiar advantages and could be profitably implemented in different configurations of dual detectors. We discuss now the advances over the present technology which must be achieved to allow their use as readouts in a dual detector.

3.1. Transduction efficiency

The efficiency of the signal conversion by the transducer is proportional to the bias field and the square root of the capacitance in the case of the capacitive transducer, and correspondingly to the product of the light power injected in the cavity and the finesse of the cavity in the case of the optical transducer. As for the capacitive transducer we aim at increasing by at least an order of magnitude (to achieve at least 100 MV m^{-1} [10]) the static bias electric field between the plates. As for the optical transducer, increasing the light power by a factor of 1000, up to a few W, requires to improve the active frequency stabilization (to better than 10^{-9} Hz^2 Hz^{-1}) and a different transducer configuration, where one measures the difference in the length of two close cavities, one of which is tunable. The finesse should be increased up to 10^6 [11].

3.2. The geometry—extension and symmetry—of the readout surface

The capability of implementing a quantum limited readout requires extending the area where the displacement is averaged over. In fact, transducers with a small surface 'see' many acoustic modes of the detector, up to high frequencies. Each mode has its own thermal noise and is excited by the back-action noise. It is thus useful to extend the sensitive region, averaging out high-order modes. In this way, we can approach a configuration with only two effective modes, i.e. the two lowest-order modes, sensitive to the gravitational wave and necessary for wide-band selective detection [4, 5]. Moreover, the reduction of thermal noise makes it easier to meet the requirements on the operating temperature and on the mechanical losses of the detector. A second major step is the development of a specific readout geometric design that is sensitive to the deformations that have quadrupolar symmetry, thus reducing the response of those with different symmetries that are not sensitive to the gravitational radiation. For the capacitive transducer a conceptual configuration that realizes this readout selectivity has already been proposed [5]. In this case the selectivity allows us to clean the bandwidth of spurious modes and makes possible an effective back-action reduction. As for the optical readout, a new cavity configuration, the folded Fabry–Perot [12], was proposed which allows us to extend the effective waist size.

3.3. The quantum limit to the noise

Standard quantum limited performances of the detector can be reached only if the readout system is itself at the quantum limit. As for the capacitive transducer, the crucial improvement with respect to the state-of-the-art technology is with regard to the energy resolution of the SQUID amplifier. Up to now the best performance achieved in a setup that can be implemented in a bar detector is about 200 hbar [13], but energy resolution of about 10 quanta was recently obtained [14] and the single quantum of sensitivity seems to be not so far away. As for the optical transducer, on the other hand, the quantum limited sensitivity seems more easily achievable. Major progress in this case is with regard to the cryogenic operation.

4. The need for a mechanical amplifier

The improvements described in the previous section could allow us to reach, in the near future, sensitivities of a few 10^{-22} m $\mathrm{Hz}^{-1/2}$ for both capacitive and optical readouts. Then to achieve the needed 10^{-23} m $\mathrm{Hz}^{-1/2}$ displacement sensitivity range, it may be necessary to develop an alternative and non-resonant device to amplify the differential deformation of the massive bodies [15]. Mechanical amplifiers based on the elastic deformation of monolithic devices—compliant mechanisms—are well known for their applications in mechanical engineering [16]. Their application to GW detectors seems promising but the contributed noise needs to be investigated thoroughly. We note that this stage will also work as a mechanical impedance matching stage, since it affects the balance force–displacement and in particular the back-action forces due to the readout. This feature could also be helpful to fit the detector mechanical impedance to the noise impedance of the amplifier, in order to obtain the so-called ‘noise matching’ condition and to optimize the signal to noise of the system.

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