GRAVITATIONAL WAVES DETECTORS [†)]

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Abstract: The work's first part deals with the gravitational radiation problem and the nature of the signal, which we expect to detect.

The essential part of the present work tackles the problem of future improvement of gravitational wave detectors, based on single mechanical oscillators, by increasing their band range along with keeping of increasing their sensitivity. The paper discusses the idea for eliminating the radical defect of the resonant-bar single-oscillator gravitational-wave detectors, that is, the detector extremely narrow frequency band, by performing a compensation of the differential elasticity of the gravitational sensor through a negative differential elasticity.

1. Introduction.

The detection of the gravitational waves (GWs) produced by extraterrestrial relativistic objects is one of the greatest challenge of modern physics which did not get yet a resolution after the thirty years racing for.

The importance of these studies consist in the attempt to confirm, first of all, one of the most essential corollaries of the General relativity theory and, secondly, to provide new channels for gaining information on the Universe.

Now an optimistic expectation is associated with a new generation of gravity wave detectors: supercryogenic bars and large scale free mass interferometers which have to allow the registration on the level of 10^{-21} in term of metric perturbations of the first version of set ups (for a comparison the sensitivity of the Weber's bar was only 10^{-16} [1]). An international network of gravitational-wave detectors consists of cross-correlated, several-kilometer-band laser interferometers at different sites of the USA, Italy, Germany, Japan, Australia [2].

The gravitational detector is a device for a measurement of the gravity gradient carried by the GWs. Its physical realization is a mass quadruple, i.e. a couple of test masses separated by the distance L. Generally speaking, there are two types of such devices: (i) so called a "resonance bar detector" where the test masses have an elastic coupling; this principal scheme is realized experimentally in the longitudinal oscillation mode of the aluminum bar measured by a special read out; (ii) a "free mass interferometrical detector" where the test pendulums separated by a long distance (the maximum admitted scale is $\lambda \sim \frac{\lambda_g}{2}$) carry mirrors attached to the pendulum masses; it allows a measurement of distance variations using an external

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source of light. For the both types, a principle of GWs detection is clear: the field of relative accelerations in the plane gravitational wave exites mutual displacement of test masses; its measurement presents the detection procedure. The sensitivity in general is limited by the intrinsic instrumental and environmental noises.

A modern generation of the resonance bar detectors is presented by the cryogenic ($T=(4-2)K$) and supercryogenic ($T=(0.1-0.01)K$) families: in each case the cooled bar (suspended in a wire loop around the central circle) has typical parameters: the mass $m \cong 2.10^3$kg, length $L \cong 3.10^2$ cm, quality factor of the mechanical mode $Q>10^7$ and central frequency $f \sim (890-930)Hz$. To facilitate the measurement of such negligible perturbation some additional oscillator of small mass μ (transducer) is attached to the end of the bar. Its amplitude in the process of energy transformation is in the factor of $\left(\frac{\mu}{m}\right)^{1/2}$ larger the bar's amplitude. The last link of the antenna is an electromagnetic read out. All this technique results in the following characteristics of the modern bar antennae.

The sensitivity (or a total noise level) for a continuous quasi monochromatic signal with a spectrum bandwidth $10^{-5}Hz$ is at the level $h \sim 10^{-21}$ for cryogenic set ups: "EXPLORER" in Geneva, CERN, "ALLEGRO" in Baton Rouge, LSU, "NIOBE" in Perth, AWU [3]. For example, the resonance bar detectors can register the continuous radiation emitted by a neutron star if the frequency falls in their sensitivity band. The "burst-sensitivity" as an ability of registration of a short pulse signal with duration $10^{-2}-10^{-3}$ sec is $h_{bst} \sim 10^{-18}$. Asymmetric supernovae in our Galaxy are the best candidate sources of that type.

The supercryogenic set ups ("NAUTILUS" in Frascati, INFN, "AURIGA" in Legniaro, INFN) [3]) have sensitivity, for a quasi monochromatic signals, at the level $h \sim 10^{-22}$, and "burst-sensitivity" at the level $h_{bst} \sim 10^{-19}$.

A wider band instrument is presented by the second general type of GWs detectors, that are the free mass interferometers. Their principle construction was stimulated by the fact of a growth of the equivalent "GWs force" with an increasing of test masses separation. It is valid up to the distance $\frac{\lambda_g}{2} \sim 150km$ for frequencies of the *kHz* region. In principle it is possible to use an interferometer of the moderate scale (3-4 *km*) but with multi reflection arm, 50 – 100 bounces (a total photon traveling time must not exceed a half GWs period). Modern GWs interferometers have the Michelson configuration with Fabri-Perot cavities in each arm.

A laser interferometer gravitational wave detector consists of four masses that hang from vibration-isolated supports as shown in Fig.1, and the indicated optical system for monitoring the separation between the masses. The arm lengths are nearly equal, $L_1 \cong L_2 = L$. When a gravitational wave, with frequencies high compared to the masses' ~ 1 *Hz* pendulum frequency, passes through the detector, it pushes the masses back and forth relative to each other as though they were free from their suspension wires, thereby changing the arm-length difference, $\Delta L \equiv L_1 - L_2$.

Interferometric detectors currently under construction are supposed to increase our ability to directly observe GWs. A 300m detector TAMA has already been built in Tokyo, Japan. Several other projects are now completing: a British-German collaboration is constructing a 600m interferometer (GEO600) in Hannover, Germany, a French-Italian collaboration is building a 3km detector (VIRGO) near Pisa, Italy and Americans are building two 4km antennas (LIGO), one in Livingston and the other in Hanford, USA (we do not consider here their small scale prototypes). The largest of these detectors, LIGO and VIRGO, are likely to be upgraded in sensitivity by an order of magnitude with a better low-frequency performance in 2005. In addition to these ground-based antennas, it is planned to place an interferometer in space by the end of this decade. The Laser Interferometer Space Antenna (LISA) consists of three drag-free satellites, forming an equilateral triangle of side 5 million km, in a heliocentric orbit, lagging behind the Earth by 20^o. LISA is expected to be sensitive to waves in the low-frequency band of $10^{-4} - 10^{-1} Hz$.

This general picture of the GWs detector net permits us to hope that in the nearest three - five years we certainly have to wait an accumulation observational data by both bar and interferometric detectors at least at the level 10^{-21}.

Significant contributions to interferometer technology are made by groups at the California Institute of Technology (Caltech), Massachusetts Institute of Technology (MIT), Stanford University, JILA (the University of Colorado), Syracuse University, "M.V. Lomonosov" Moscow State University.

2. Some Background on Gravity Wave Detection

A gravitational wave is the wave of acceleration gradients perpendicular to the direction of the wave vector alternating in time and space, which propagates with the speed of light. For example, if a sine-like gravitational wave propagates along the z-axis, in one half period the acceleration gradient is positive along the x-axis, and is negative along the y-axis. Over the next half a period, the direction of the gradients reverses. According to a convenient expression by K.S. Thorne [2], the gravitational wave is a ripple over the static curvature. Thus, it is impossible to discover a gravitational wave at one point. However, this becomes possible using two point masses, separated by a finite distance or an extended body, measuring variable tensions inside it, caused by gravitational-wave force.

Gravitational waves are similar to electromagnetic waves in some aspects. They propagate with the velocity of light c, have two independent transverse polarization states, and exhibit some analogs with the action of electric and magnetic components on masses. The gravitation-wave field is dimensionless, and its strength is characterized by a single quantity – the GWs amplitude h. The amplitude falls off in the course of propagation from a localized source, in inverse propotion to the distance traveled: $h \sim \frac{1}{r}$. The difficulty of direct detection of GWs can be seen from the fact that the amplitude *h* of the signal from realistic astronomical sources is expected to be exceedingly small on the Earth, of the order of or smaller than 10^{-21}. However, in cosmos, GWs are an important factor of cosmic evolution. Gravitational waves are routinely taken into account in the study of the orbital evolution of close pairs of compact stars.

In many other aspects, there are great differences between the electromagnetic waves, on which our present knowledge of the Universe is based, and the gravitational waves: Astronomical electromagnetic waves are almost always incoherent superpositions of emission from individual electrons, atoms or molecules. By contrast, cosmic gravitational waves are produced by coherent, bulk motions of huge amounts of mass-energy – either material mass, or the energy of vibrating, nonlinear space-time curvature. Electromagnetic waves are easily absorbed, scattered, and dispersed by matter. Gravitational waves, by contrast, travel nearly unscathed through all forms and amounts of intervening matter [2].

These differences make it likely that most (but not all) gravitational-wave sources will not be seen electromagnetically, and conversely, most objects observed electromagnetically will never be seen gravitationally. For example, typical electromagnetic sources are stellar atmospheres, accretion disks, and clouds of interstellar gas – none of which emit significant gravitational waves; while typical gravitational-wave sources are the cores of supernovae (which are hidden from electromagnetic view by dense layers of surrounding stellar gas), and colliding black holes (which emit no electromagnetic waves at all).

There are several key consequences of this: (i) It is important to be able to extract detailed information about the source of a gravitational wave from the gravitational wave alone, without any electromagnetic assistance; (ii) Our present, electromagnetically based information about the Universe does not prepare us well to predict the sources and strengths of the gravitational waves that are expected to be seen; (iii) Correspondingly, it is reasonable to expect great surprises – perhaps even a revolution in our understanding of the Universe comparable to that which radio-astronomy has produced. The detection of relic GWs is the only way to learn about the evolution of the very early Universe, back to the limits of the Planck era and the Big Bang.

It is necessary to be able to extract the full information carried by gravitational waves. From the waveforms, much can be deduced about the waves' sources. The most reliably understood sources at present are the coalescences of neutron-star / neutron-star, neutron-star / black-hole, and black-hole / black-hole binaries in distant galaxies. The study of such coalescences are likely to give us much knowledge about the distribution of black hole and neutron stars in the Universe and their masses and spins, the gravitational waves from the early Universe, the nature and nonlinear dynamics of gravity, the astrophysical catastrophes, information about the space density of binary neutron stars in galaxies and the contribution they give to the so-called dark matter and perhaps the equation of state of nuclear matter.

The present work deals with the problem of obtaining wide-band single-resonator gravitational-wave detectors along with keeping of increasing their sensitivity. The study proposes to widen the receiver extremely narrow band by performing a compensation of the differential elasticity of the gravitational sensor through a negative differential elasticity. The latter is to be created by a 4-frequency electro-mechanical parametric system.

3. Diagram of the gravitational waves receiver

The diagram of the gravitational wave receiver is shown in Fig.2, consisting of: HQMO (GS) – high quality mechanical oscillator (gravitational sensor); 4-FEMPS – 4-frequency electro-mechanical parametric system; 4-FPA – 4-frequency parametric amplifier; PG – high frequency pumping generator; DPA – degenerate parametric amplifier; FC (x2) – frequency converter (doubler); SOR – system for oscillations registration.

4-FEMPS is to compensate the elasticity of the gravitational sensor HQMO (GS), which provides practically a frequency independence of the impedance and of the transmission coefficient in the input circuit of the gravitational wave receiver within its working frequency band range, for example $f \leq 10^4 Hz$. 4-FPA provides a low noise amplification of the received signal in a regime, optimal with respect to noise. DPA is a second parametric amplifier, which, together with performing a low-noise amplification, damps down the noise from the lateral frequency bands of 4-FPA. PG provides a direct high frequency supply of 4-FEMPS and 4-FPA. It supplies DPA, too, through FC (x2). The frequency of the PG voltage is much higher (e.g. 1,5 order higher) than the frequency range of the expected gravitational wave. The concluding unit SOR of the gravitational wave receiver performs an adaptive damping of the HQMO (GS) eigen free oscillations, and the signal sought is to be identified on such a background. Parallel to the basic problem, SOR is a system for damping down seismic, electromagnetic and other noise effects, disturbing the receiver functioning.

To state things more clear, the idea of the design of a gravitational wave receiver is given in Fig.3. A mechanical oscillator with mass *m* and differential coefficient of elasticity *K* stands for HQMO (GS). The transformation of the mechanical oscillations into electrical ones is performed by a capacitive sensor *C*, directly switched to HQMO (GS). The capacitive sensor *C* is an element of the oscillating system CLR which, together with the pumping generator PG and on line with HQMO (GS) realizes negative elasticity and low-noise parametric amplification, combining the functions of 4-FEMPS and 4-FPA. For a definite set-up of 4-FEMPS, its reaction to the mechanical modulation of C is expressed by an introduction of an equivalent negative elasticity and equivalent friction in the mechanical oscillator HQMO (GS). In this case 4-FPA lacks a definite parametric element, whose parameter should vary with the high pumping frequency, as is assumed in the theory of parametric systems. However, the modulating effect of HQMO (GS) through the capacitive sensor *C* causes the generation of sum and difference combination frequencies, which determine the CLR system character as a 4-frequency parametric amplifier (4-FPA). DPA can be designed by employing a bridge-balance circuit with high positive input impedance and low eigen fluctuation noises. One of the SOR possible configurations is given in [4].

4. Analysis of the noise characteristics

An equivalent circuit of the gravitational wave receiver, together with the noise sources, is given in Fig.4. The equivalent gravitational impact (IA) on the oscillator mass is expressed by the equivalent conductance of the irradiation resistance G_G. The gravitational sensor HQMO (GS) is presented by the reactive parameters L_s, C_s and by the conductance of friction losses G_s. 4-FEMPS is represented by the equivalent conductance G_g, and by the equivalent negative capacitance C_{g-} introduced in the input circuit of the gravitational wave receiver. The presence of 4-FPA is outlined by the general complex admittance Y_p and by the complex admittance Y_{add}, added due to the reversibility of the modulation – parametric interactions in 4-FPA. Since a large coefficient of amplification of 4-FPA, as well as of DPA, is expected to be attained, DPA is presented, together with SOR, as an amplifying two-port unit (load) ATP (L), with an input general complex admittance Y_L.

The noise-generated properties of IA, HQMO (GS), 4-FPA and ATP (L) are characterized by equivalent effective values of noise electric current generators $\sqrt{\overline{i_{NGS}^2}}$, $\sqrt{\overline{i_{Np}^2}}$, $\sqrt{\overline{i_{NL}^2}}$, by a noise voltage $\sqrt{\overline{U_{NL}^2}}$ and by a noise correlation admittance $\dot{Y}_{cor}$.

5. Estimations and conclusions

Parallel to the negative differential elasticity, positive effective friction is introduced in the mechanical oscillator of the gravitational sensor (that is shown in [4]): $H_o = \dfrac{SU_o^2 Q_p^4}{16\pi d^3 \omega_p}$, which determines the occurrence of an equivalent 'cooling' in the mechanical sensor.

Applying the approach developed above it is possible to design laser interferometer "point" masses with a natural frequency much less than unity. The latter is very important especially when searching for relict gravitational waves in the frequency interval of $10^{-3} - 10^{-2}$ Hz.

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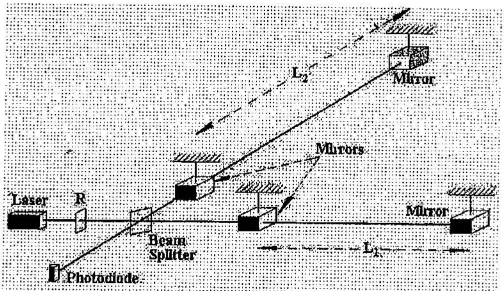

Fig.1 Schematic diagram of a laser interferometer gravitational wave detector.

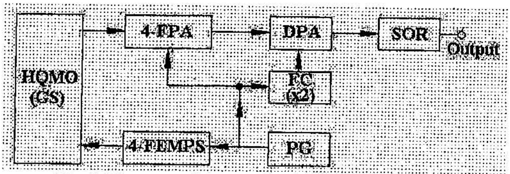

Fig.2 Diagram of the gravitational wave receiver.

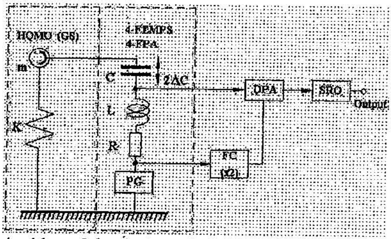

Fig.3 An idea of the design of a gravitational wave receiver.

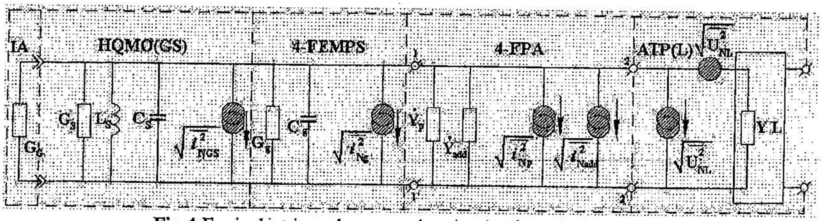

Fig.4 Equivalent impedance – noise circuit of gravitational wave receiver