Review of accelerometer development for use in Gravitational Wave detection interferometers.

Abstract

Accelerometers were, and are being, developed to instrument the seismic attenuation chains of Gravitational Wave (GW) Interferometric detectors. The main requirements of these instruments are strong directionality (>10^3 rejection of signal from orthogonal directions for feedback) and vacuum compatibility, as well as high low frequency sensitivity. Because of the directionality requirements, GW accelerometers tend to be more specialized for sensing of different degrees of freedom (horizontal, vertical, and tilt) than the classical geophysics seismometers, but share with these several characteristics. The initial design of GW-dedicated accelerometers was inspired by geophysics instruments. Techniques developed for the GW field are now starting to spill over back into the geophysics field.

Introduction

The interferometric Gravitational Wave (GW) detector community has a long history of developing Ultra High Vacuum (UHV) compatible accelerometers.

The development started in the Early "80s, when Virgo was considering a stage of active pre-attenuation of its superattenuators. UHV compatible instruments were developed, instead of using commercial instruments, in order to avoid the risk associated with the possible leaks from pressurized tanks containing commercial units. Operation under UHV also allows for better performance, as the air-induced friction in the test masse motion is eliminated. In addition UHV operation allows for lower thermal fluctuations, and no acoustic coupling. Custom accelerometer design was also desirable because of the requirement that each instrument be sensitive only and uniquely to a well-defined degree of freedom, to simplify the control matrix. A signal built with the vectorial sum of multiple sensors may have a frequency dependent directional sensitivity, and lead to complex controls. There were also concerns about the stability over time of the signal mixing matrix.

These considerations brought to the development of separate horizontal, vertical and tilt accelerometers. Yaw sensitivity was simply extracted from the pin-wheel configuration of horizontal accelerometers and no yaw sensor was ever developed.

The development of active attenuation in Virgo was abandoned in 1995, when it was realized that the "swing" effect fundamentally limits the effectiveness of active attenuation. The equivalence principle dictates that a horizontal accelerometer mounted on a swing cannot detect the motion of a swing because the swing's ropes only apply forces perpendicular to the swing's seat where the accelerometer would reside. The amplitude of the swing motion only appears (at the second order) on the signal of vertical accelerometers and on tilt-meters. In other words a horizontal accelerometer in Earth's gravitational field cannot distinguish between a tilt and a horizontal acceleration.

Initially, development of suitable tilt-meters was pursued, to complement the horizontal accelerometer signal and disentangle the horizontal from the tilt signals.

With the know-how acquired with the development of the accelerometers, in parallel with the superattenuator seismic attenuation system, came the realization that accelerometers are just passively isolated test masses of which the test mass position is readout. An active attenuation can only transfer the mechanical isolation of the accelerometer's test mass to the platform to be seismically isolated. As the development of the superattenuators and of its accelerometer matured, it was realized that, since a control loop cannot be any better than the sensors that provides its feedback signal, no actively attenuated platform can possibly have better performance than a passively isolated platform built with the same technology of the accelerometers that would be used for active attenuation. Additionally it is in general easier to isolate large masses than to do it in miniaturized form. Even if all the accelerometer sensitivity could be completely transferred to the isolated bench without degradation, most accelerometers would have hard time competing at low frequency with (for example) IPs that are routinely tuned at 30 mHz.

After that realization, the development of active pre-isolation in the Virgo superattenuators was halted.

The development of accelerometers was not halted though. It was realized that the chain of seismic filters hanging down from the pre-isolator had unwanted resonances, and that feedback from suitable accelerometers on the pre-attenuation stage would be the ideal way to damp those resonances without reintroducing noise from the seismically active ground (inertial damping). Even this reduced scope would not have been achievable with accelerometers, because of the swing effect, if it had not been for the specific design of the Virgo pre-attenuator.

The Virgo pre-attenuator is an Inverted Pendulum (IP) table followed by a low frequency vertical filter. The IP table is constrained to motions in the horizontal plane[1] and horizontal accelerometers mounted on that table are immune from the swing effect thus allowing the use of horizontal accelerometers without the aid of matching tiltmeters.

Vertical accelerometers were also used in the Virgo superattenuators, mounted on the pre-attenuation filter, for inertial damping of resonances.

The successful IP plus horizontal accelerometer configuration was later adopted by the TAMA GW interferometer and as a baseline design of the LCGT GW interferometer. After installation on the superattenuator in 2000 [1], Virgo stopped all accelerometer developments. The design of UHV-compatible horizontal and vertical accelerometers continued at LIGO, University of Pisa and TAMA for use in future GW detectors.

In the last few years, the University of Salerno took over refining the design of the horizontal accelerometers developed for TAMA for use both in GW detectors and for seismology.

The use of similar accelerometers was foreseen in 2006, as an optional, as a supplement to the performance of the passive seismic attenuators developed for Advanced LIGO [2] in case future accelerometers, built with advanced materials and new technologies, would provide sensitivity below the IP attenuation level.

The design of tilt-meters, abandoned with the introduction of the IP, resumed in 2007 at Virgo with the realization that ground tilt generated by sea and wind activity

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[1] The IP table moves rigorously in the horizontal plane if its legs have the same length, are mounted parallel and its base platform is horizontal. These conditions can be mechanically achieved within one or few parts in 10^4. The residual deviations from the horizontal plane are univocally position dependent (for example if the IP legs are mounted in a convergent geometry, the IP table would move along a sphere, and knowledge of the transversal coordinate would give the local tilt) and can easily subtracted.

could generate part of the residual motion of the superattenuator chain. Almost coincidentally development of tiltmeters was resumed at LIGO to reduce the swing effect problem in the Advanced LIGO active seismic attenuation system.

The Virgo accelerometers, common design features.

All of the Virgo accelerometers are force feedback sensors, using voice coil actuation and LVDTs as position sensor. All of their readout electronics was located outside the vacuum enclosures for added reliability and to avoid producing waste heat inside vacuum, for thermal stability.

The voice coil is the most convenient actuation method because of its linearity and ease of construction and low power dissipation; for these reasons it is used in most commercial and scientific instruments. It is easily made UHV compatible as it only comprises a kapton insulated wire coil wound on a glass, ceramic or PEEK spool, a small permanent magnet and soft iron for the yoke.

The LVDT [3] is a particularly convenient position sensor for reliable UHV operation because it is made of three simple coils and because its inductive signal, transported via twisted pairs, tolerates long cable lengths without degradation. Therefore its preamplifier can be located outside the vacuum tank. The LVDT resolution is typically of the order of a nm for cm long strokes, but in the case of force feedback accelerometers its sensitivity is pushed well below the pm (example, figure 1) at the expenses of a reduced sensitivity range. The LVDT linearity within the sensitivity range is not affected.

Both LVDTs and actuators generate negligible heat.

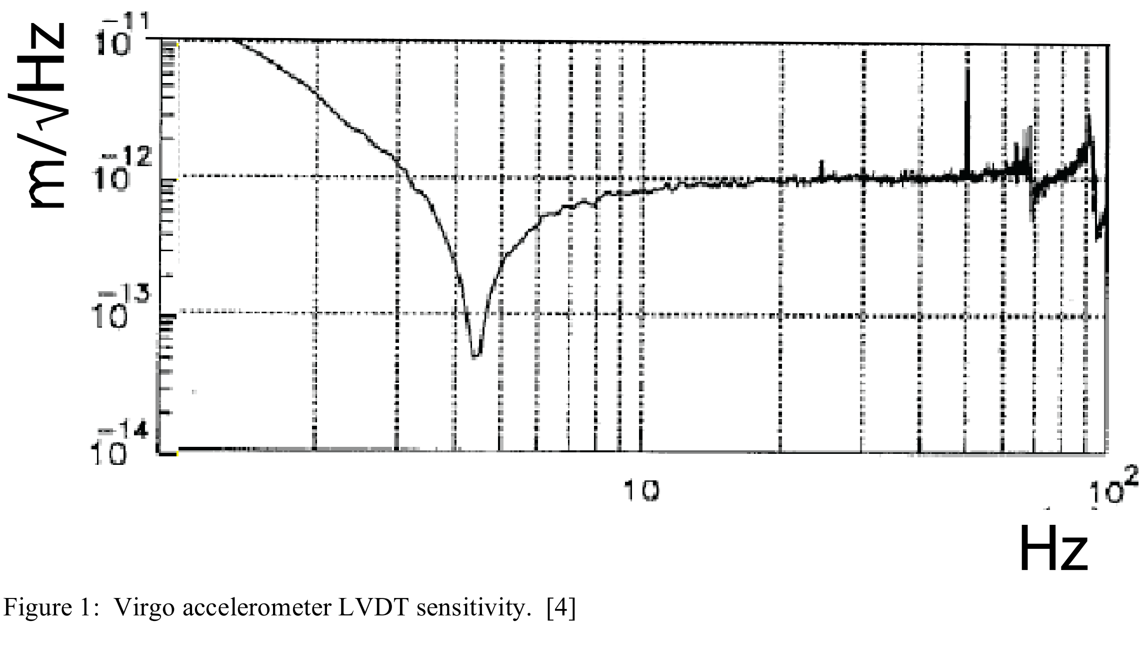

Figure 1: Virgo accelerometer LVDT sensitivity. [4]

The vertical accelerometers implemented in Virgo (developed in 1996 to 1998) are built on the Lacoste principle (figure 2).

The test mass is constrained to move in the vertical direction by a pair of leaf flexures. A spring at roughly 45 degrees provides preloading force. The vertical component of this force counters the force of gravity and allows the mass to flat at the

LVDT zero voltage working point. The horizontal component compresses the two flexures and brings them close to collapse, thus reducing the vertical resonant frequency.

The accelerometer is mechanically tuned by vertical and horizontal micropositioning of the grounded end of the spring.

The flexures, etched from a thin foil of Copper Beryllium, can have a double hourglass profile for optimally softness, uniform stress distribution, and rigidity in the orthogonal degrees of freedom.

The bobbin of the voice coil actuator is part of the test mass and coaxial with it.

Its performance is illustrated in figure 3.

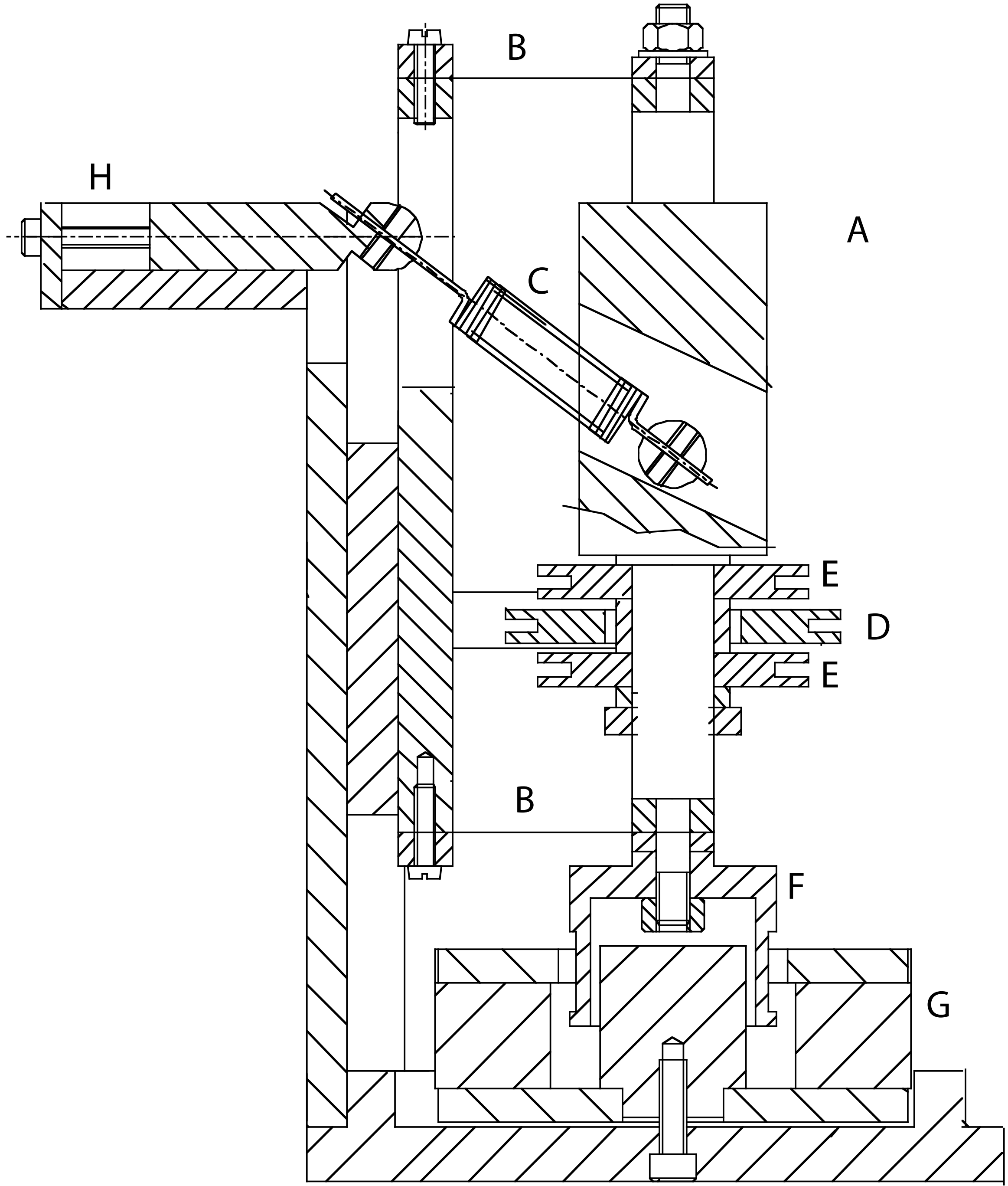

Figure 2, Virgo vertical accelerometer.

The test mass (A) is constrained to motion in the vertical degree of freedom by two flexures (B). The weight of the test mass is supported by the vertical component of the tensioning force of the spring (C). The LVDT position sensor is made of an excitation coil (D) sandwitched between two, oppositely wound, receivers coils (E). The coil (F) of the actuator and the LVDT excitation coil are coaxially mounted on the test mass. The actuator's permanent magnet, the LVDT secondary coils are solidly mounted on the instrument's case. The tuning screw (H) changes the vertical resonant frequency of the instrument by changing the horizontal compressional force applied on the flexures.

The Virgo vertical accelerometers are mounted on the pre-isolator vertical filter of the superattenuators, downstream of the IP seismic pre-attenuation.

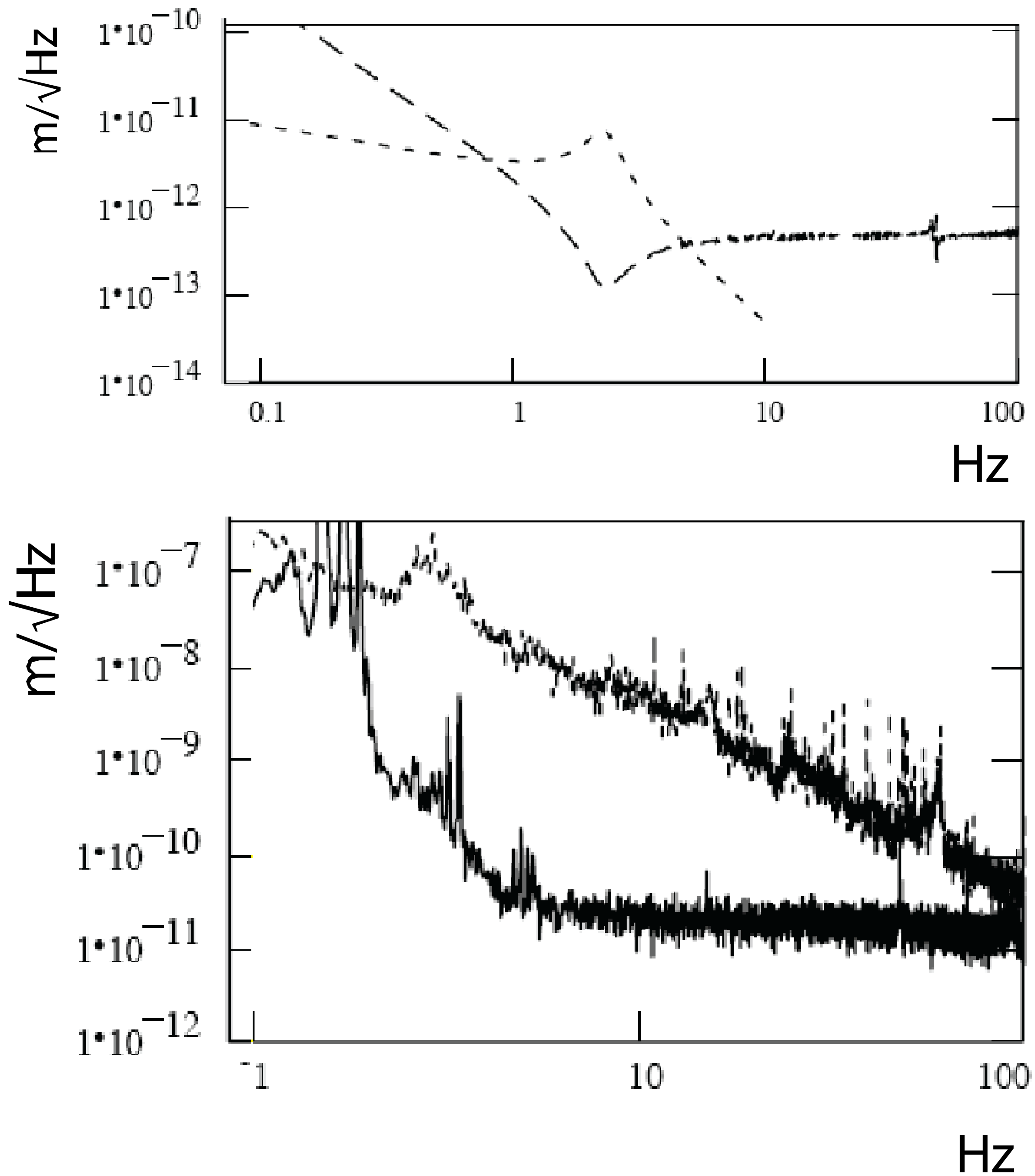

Figure 3. Performance of Virgo Vertical Accelerometer. Top graph: long dashes, thermal noise (calculated from quality factor and resonant frequency), short dashes position sensor resolution. Bottom graph: performance verification on lab floor (dashed) and on a suspended platform (slid line). The measurement is dominated by seismic noise below 2 Hz and may still contain seismic noise above. [5].

The co-developed Virgo horizontal accelerometers (figure 4) are of inverted pendulum design, otherwise they are very similar to the vertical design and use the same readout electronics.

Three of these accelerometers are mounted at 120^o on the IP table in a pinwheel configuration and also provide readout of the yaw angular acceleration. As they sit on a non-vertically attenuated platform, one of their important requirements of this accelerometer is insensitivity to vertical seismic noise, obtained from the transversal rigidity of the flexures. Micrometric screw leveling effectively nulls the force of gravity and the vertical sensitivity.

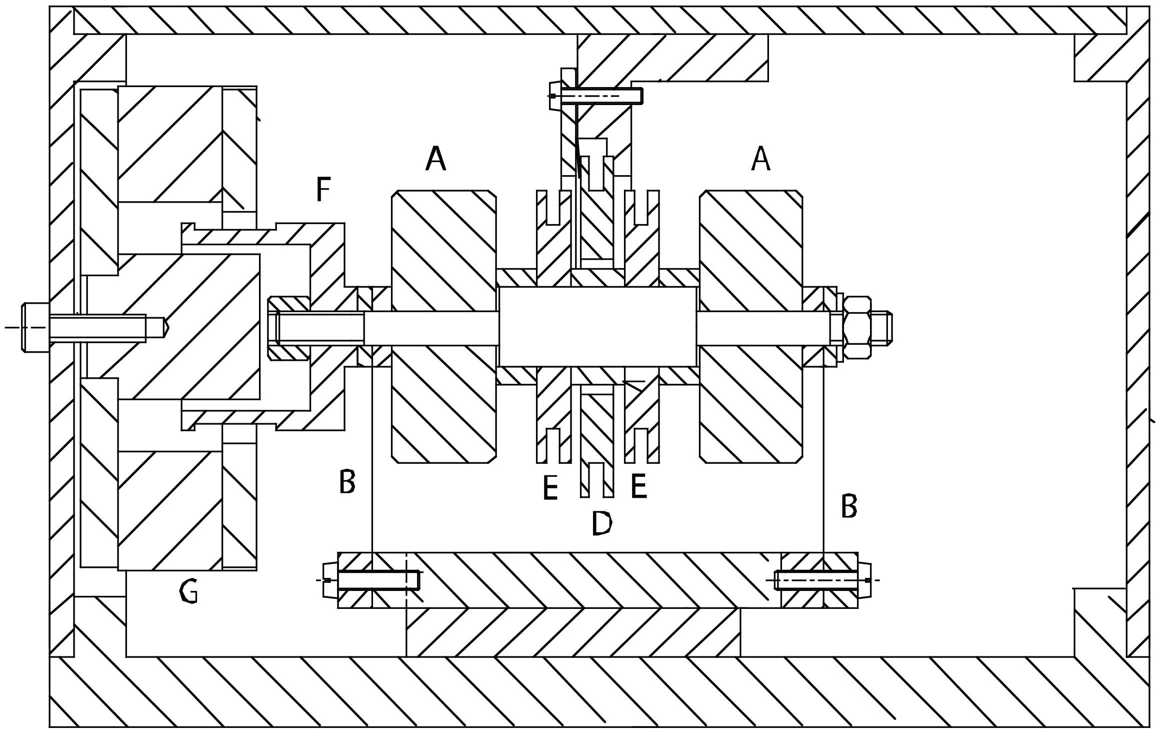

Figure 4. Virgo horizontal accelerometer.
It is an inverted pendulum design, the flexures constrain the test mass motion in the horizontal degree of freedom only, the resonant frequency is tuned by changing the weight of the test mass. The same label descriptions of figure 2 apply, where relevant.

Virgo also developed angular accelerometers of dumbbell design, otherwise they are very similar to the vertical and horizontal design and use the same readout electronics [6]. The angular flexure was a commercial Bendix unit. The tiltmeter presented an excess of low frequency 1/f noise. Similar excess noise was found in similar instruments previously and subsequently developed, all using the Bendix flexure, in different geometries and readout systems [7, 8, 9, 10]. Although in some of these instruments there may have been more than one cause contributing to the observed noise, there is evidence that the Bendix flexure was the main source of the excess 1/f noise. Because of the excess noise, this angular accelerometer was never implemented in the Virgo superattenuators while the vertical and horizontal brethrens are very successful instruments, and are still in continuous and uneventful operation.

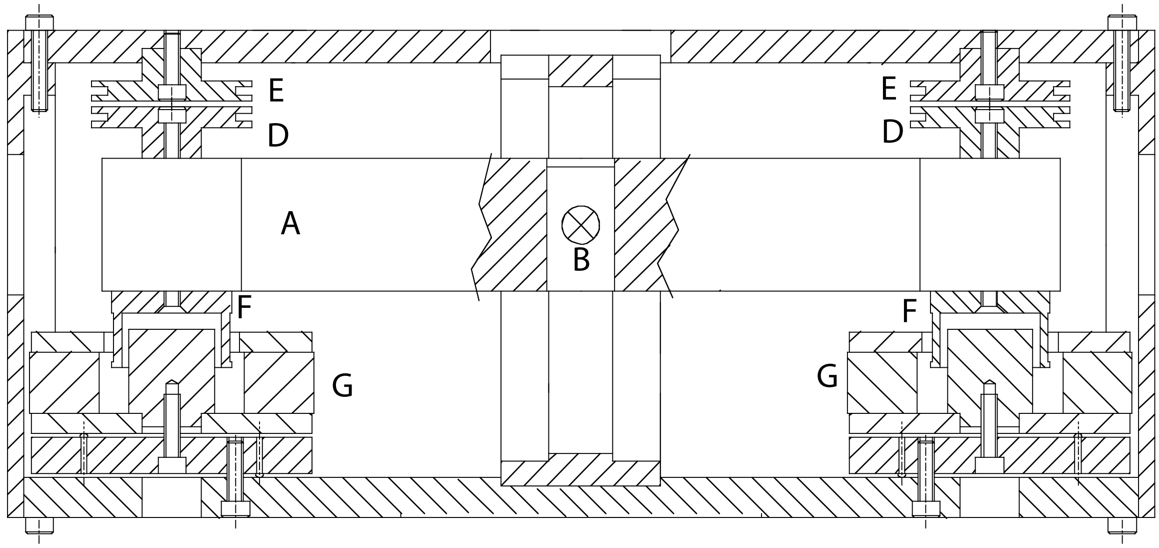

Figure 5:Virgo angular (tilt) accelerometer.
The virgo tilt accelerometer is a dumbbell design, the dumbbell test mass (A) balances on a Bendix flexure. Two identical actuators coiled with opposite polarity and mounted below the end masses of the dumbbell provide the control forces. The LVDT design has been modified. The excitation coil have been de-double into two identical ones (D), wired with the same polarity. They face two identical received coils, this time wired with opposed polarity. This LVDT is then sensitive to torque and insensitive to all other degrees of freedom.
All other label descriptions of figure 2 apply, where relevant.

It is worth noting that the University of Western Australian group also developed tiltmeter based on a wire suspended disk, readout with a multiple reflection optical lever system [11].

The LIGO-TAMA accelerometers.

New horizontal accelerometers were designed at LIGO for the TAMA IP pre-attenuators to eliminate the shortcomings of the initial Virgo design.
They were based on the Folded Pendulum (FP) geometry (figure 6), introduced, and used to build a seismometer, by the UWA group [12,13], to eliminate, as much as possible, all elastic restoring forces and thus minimize material losses and (presciently) hysteresis effects.

A FP test mass is supported by two (pairs of) legs, the leg at one end of the test mass is a normal pendulum, with a positive restoring force. The other half of the test mass is supported by an equal length inverted leg, contributing a negative restoring force. In this configuration, if it were not for the flexure stiffness, the FP would be in indifferent equilibrium, with zero resonant frequency. The inverted leg geometry is such that (contrary to other IP design) even its flexures are tensional and contribute very little restoring force. Because of this design the FP present very low resonant frequency. The resonant frequency can be tuned by loading a little more mass on the inverted leg side.

As rejection of sensitivity to other degrees of freedom require the use of pairs of flexures on either sides of the test mass, monolithic geometry was introduced to eliminate all assembly-related misalignments. The machining was made with Electric Discharge Machining (EDM) and the flexure surface was electro-polished to eliminate all EDM residual and reducing mechanical losses. A quality factor of 300 at 0.5 Hz was achieved.

This instrument had a rejection of vertical acceleration better than 80 dB.

Differential capacitive readout was introduced for further sensitivity improvements.

As capacitive sensing normally rely on local preamplifiers to avoid the stray capacitance of cables, a balanced ferrite differential transformer was developed and mounted next to the sensing capacitors. The transformer transfers the differential signal from the two capacitances on a single twisted pair and makes the readout immune to the cable length and fluctuating capacitance effects. External electronics readout of this sensor was thus allowed without loss of sensitivity (figure 7) [14].

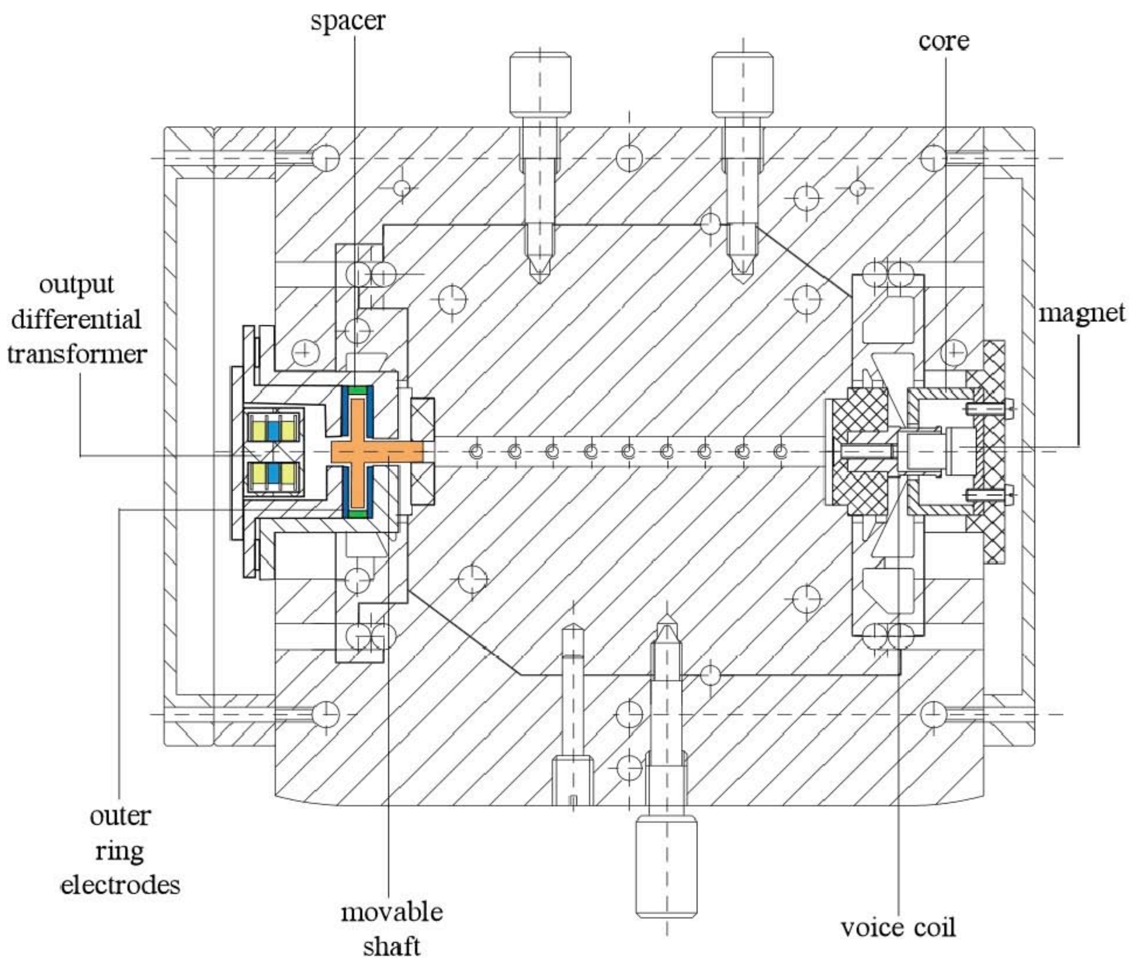

Figure 6. TAMA folded pendulum accelerometer.

The test mass (poligon at the center), the pendulum legs and the case are carved from a single block of aluminum or metal. The test mass is suspended by a pendulum leg on the right and supported by an equal length IP leg on the left. A voice coil actuator is mounted on the pendulum leg side and electrostatic position sensing is mounted on the IP leg end of the test mass. A local differential RF transformer allow remote pre-amplifier operation.

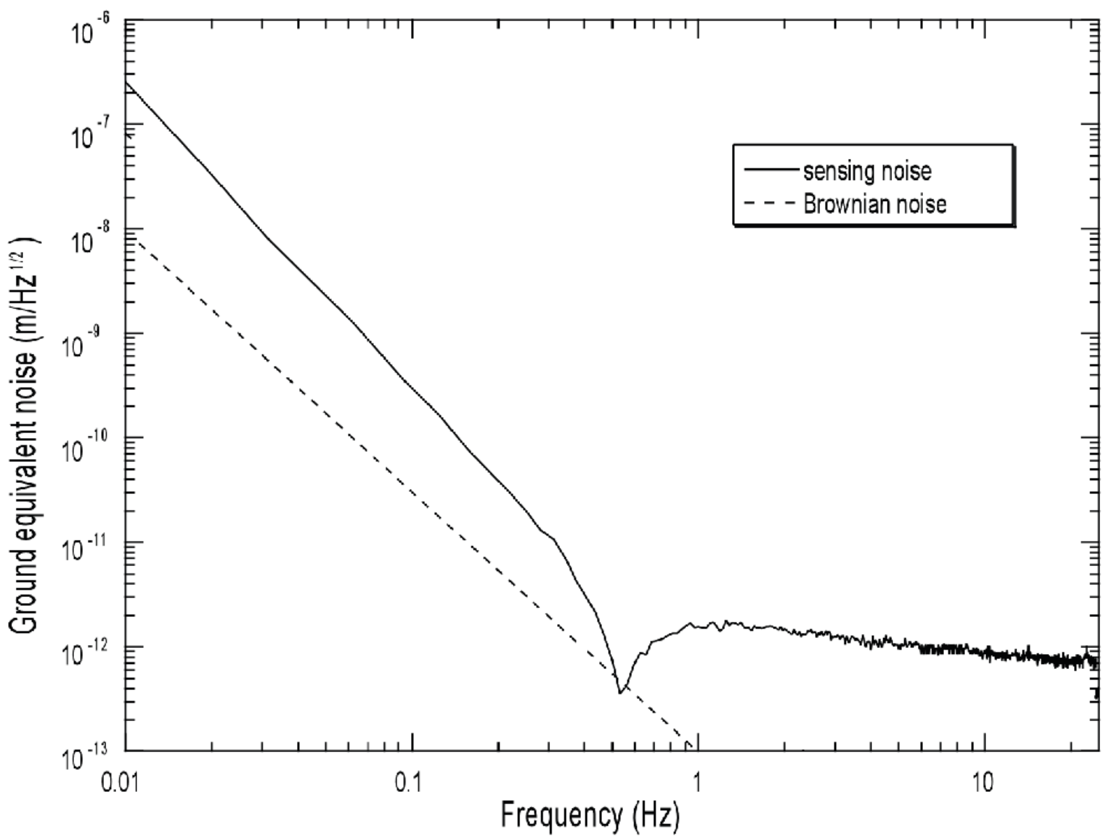

Figure7: Folded Pendulum accelerometer estimated sensitivity curve.

Taking advantage of the sensitivity to tilt of the horizontal accelerometers, the design of the folded pendulum accelerometer was later used by Akiteru et al. to develop a small (4 cm length) borehole tiltmeter with optical fiber bundle readout [15]
The design of the FP accelerometer was then refined by Acernese et al. [16], both for geophysics and GW applications, introducing an elliptical flex joint in place of the more fragile circular cross section used at LIGO/TAMA and testing an optical lever readout. The softer joint resulted in a resonance quality factor improvement of 2.4 with respect to the Bertolini design (normalized at the same frequency) and a correspondingly better expected thermal noise. Equally importantly, the original flex joints were too rigid in the other degrees of freedom and broke easily. The elliptical flexure resulted in a vastly less fragile instrument, suitable for field implementation. Field tests are at the moment limited by the resolution of the optical levers (10^{-10} m/√Hz down to 0.1 Hz). An interferometric readout (in development) will allow testing of the instrument mechanical quality.

Bertolini also designed a robust, UHV-compatible, vertical accelerometer based Geometric Anti Spring vertical flexures and on the same differential capacitive readout and control technique of the folded pendulum horizontal accelerometer (figure 8) [17]. This sensor was then used on ships to actively stabilize the cable laying booms.

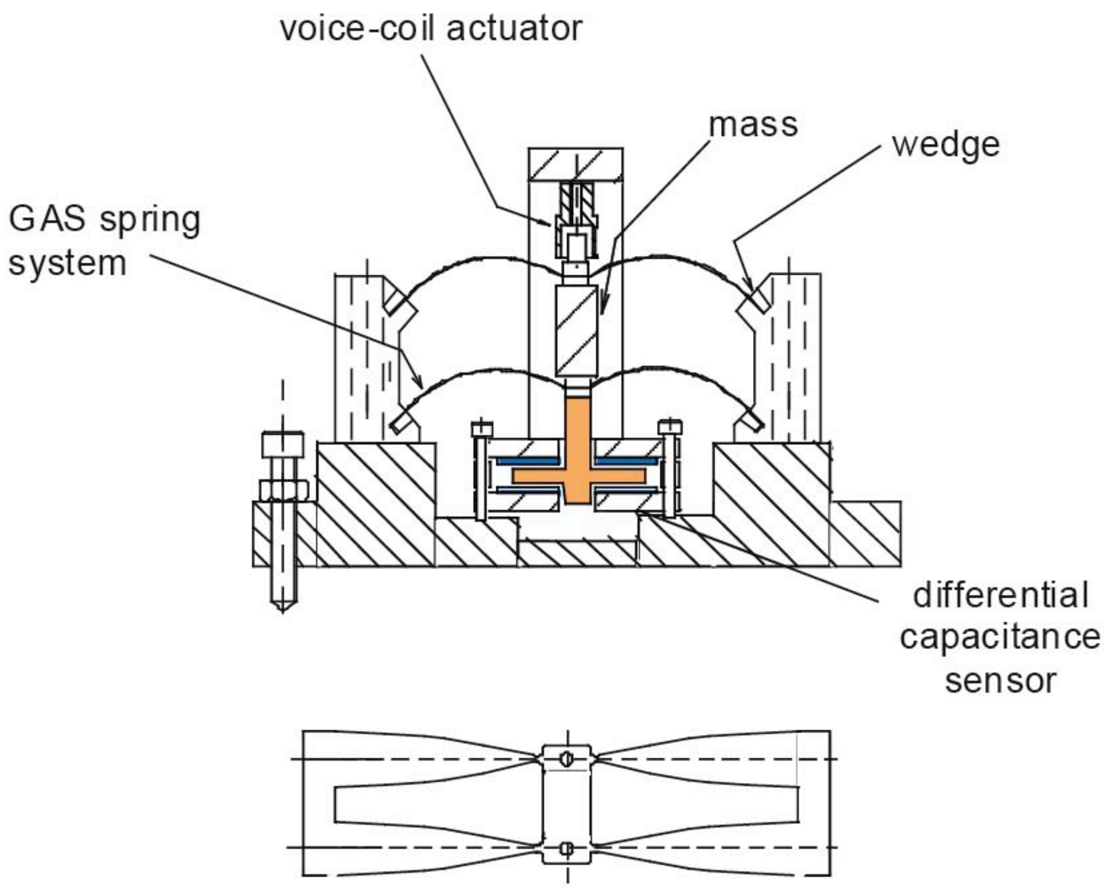

Figure 8, Vertical accelerometer based on two superimposed sets of twin GAS springs. The geometry constrains the movement to the vertical direction thus making it insensitive to orthogonal movements.

Tilt accelerometers

As already mentioned the development of UHV compatible tilt accelerometers for use in GW detectors was recently resumed at Virgo and at LIGO.

The Virgo specifications are less than 10^{-9} rad/s^2/√Hz @ 100 mHz, the LIGO specifications are an order of magnitude lower.

The Virgo group built a larger version of the 1997 tilt accelerometer, also based on Bendix flex joints and mostly confirming the well known low frequency noise problems and, as already mentioned, presenting noise much higher than the desired level.

It is now believed that the low frequency noise is dominated by the hysteresis in the flexure materials exacerbated by the Bendix geometry. Similar 1/f transmissibility noise has been recently observed in other systems and appears to be linked to the material's static hysteresis [18, 19].

Ongoing experiments by the author and his collaborators are showing the often-ignored dominating effects of static hysterisis on low frequency noise [20, 21].

Some of the physics behind these effects, based on Self Organized Criticality of dislocations in metal grains and their fractal behavior, was theoretically studied by Marchesoni [22].

To minimize the ill effects of hysteresis, a new design tilt meter, based on flexure design studied by J. Kamp [23] is now being attempted. The thin vertical blade design allows better flexure loading and is expected to introduce much less mechanical stiffness than the cross-blade Bendix flexure design. This geometry (figure 9) is expected to depress the hysteresis (and any other loss) contribution to the noise. Additionally, the volume of material involved in the flexure is much more confined, which should also help reducing noise. Most importantly, the flexure mount is designed to be easily replaceable, to allow the testing of different materials (including non metals) and of surface and thermal treatments of the flexure, all in the same instrument. This will allow to determine if the required level of sensitivity is possible with metals, and find the best solution, or if one needs to implement non metallic materials, like ceramics, mono-crystals and glasses. The flexure hinge of the instrument can also be replaced with a knife-edge hinge, copied from the old precision balances, for comparison.

To evaluate and rule out other possible sources of low frequency noise, the instrument is designed to use different methods of sensing and actuation. Different requirement levels may require different readout schemes.

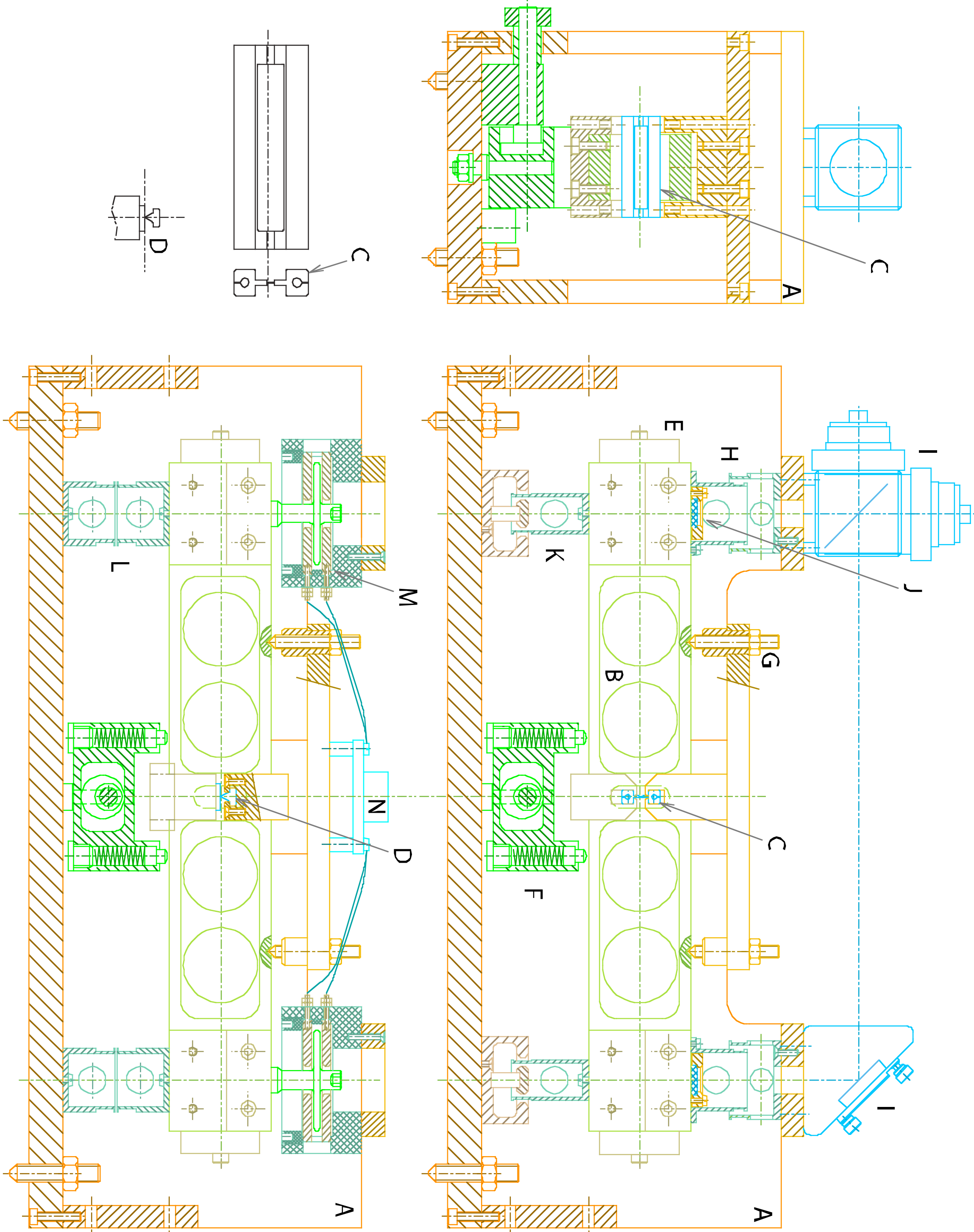

Figure 9: Different versions of the LIGO/Virgo developmental tilt accelerometer.

The top assembly illustrates the flexure hinge version with LVDT and interferometric tilt sensing and permanent magnet DC actuation. The bottom right assembly drawing illustrates the knife-edge hinge with capacitive tilt sensing and Amplitude Modulated Radio Frequency (AM-RF) actuation. In the bottom left insert expanded views of the flexure and the knife edge structure are shown.

A) instrument case, B) main balance arm, C) flexure hinge (note, in the side view in the insert, the monolithic design ensuring alignment of the two flexures of the hinge), D) knife-edge hinge, E) tuning mass, F) eccentric locking mechanism, acting against the G) end-stop screws. H) twin voice coil tilt sensing, I) Michelson tilt sensor using mirrors J) mounted on the end masses of the main balance arm. K) twin voice coil (permanent magnet) actuators, L) twin pairs of coils for AM-RF actuation. M) capacitive tilt sensing: the four capacitances are mounted in a Wheatstone bridge configuration connected by a N) transformer to a remote preamplifier.

Conclusions

The requirements for accelerometers and tilt-accelerometers for use in GW detectors are quite different from the needs for geophysics measurements, which do not require UHV compatibility, and require little depression of sensitivity to signal in orthogonal directions. The different requirements spawned a parallel development line of development and different design criteria, which is now spilling back new solutions and ideas into the geophysics seismometer field.
Both fields will profit from extended collaboration in the future.

Data and Resources

Some of the data and schematics shown in this paper were provided to the author by various scientists, as referred.
The other data and schematics shown were produced by the author and his collaborators within the Virgo and LIGO collaborations.

Acknowledgments

The author gratefully acknowledges the support of the United States National Science Foundation, under the cooperative agreement PHY9210038 and PHY-0107417.
He also acknowledge the Italian INFN (Istituto Nazionale di Fisica Nucleare) for the support during the years spent on the development of the Virgo instruments.
LIGO-DCC number P080064-00-Z.

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Figure Captions

Figure 1: Virgo accelerometer LVDT sensitivity. [4]

Figure 2, Virgo vertical accelerometer.

The test mass (A) is constrained to motion in the vertical degree of freedom by two flexures (B). The weight of the test mass is supported by the vertical component of the tensioning force of the spring (C). The LVDT position sensor is made of an excitation coil (D) sandwitched between two, oppositely wound, receivers coils (E). The coil (F) of the actuator and the LVDT excitation coil are coaxially mounted on the test mass. The actuator's permanent magnet, the LVDT secondary coils are solidly mounted on the instrument's case. The tuning screw (H) changes the vertical resonant frequency of the instrument by changing the horizontal compressional force applied on the flexures.

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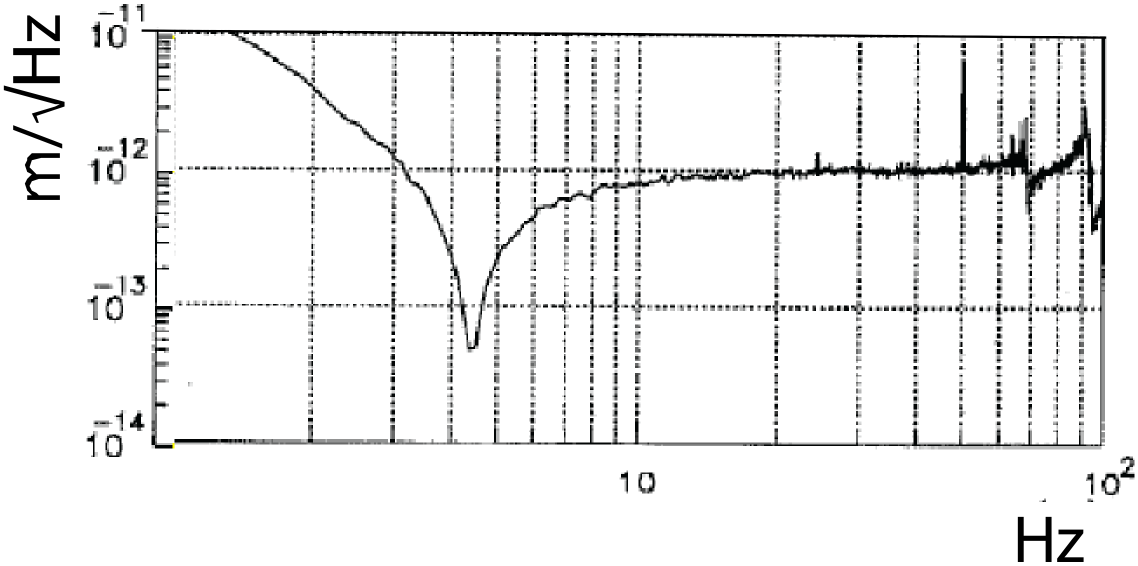
Figures:



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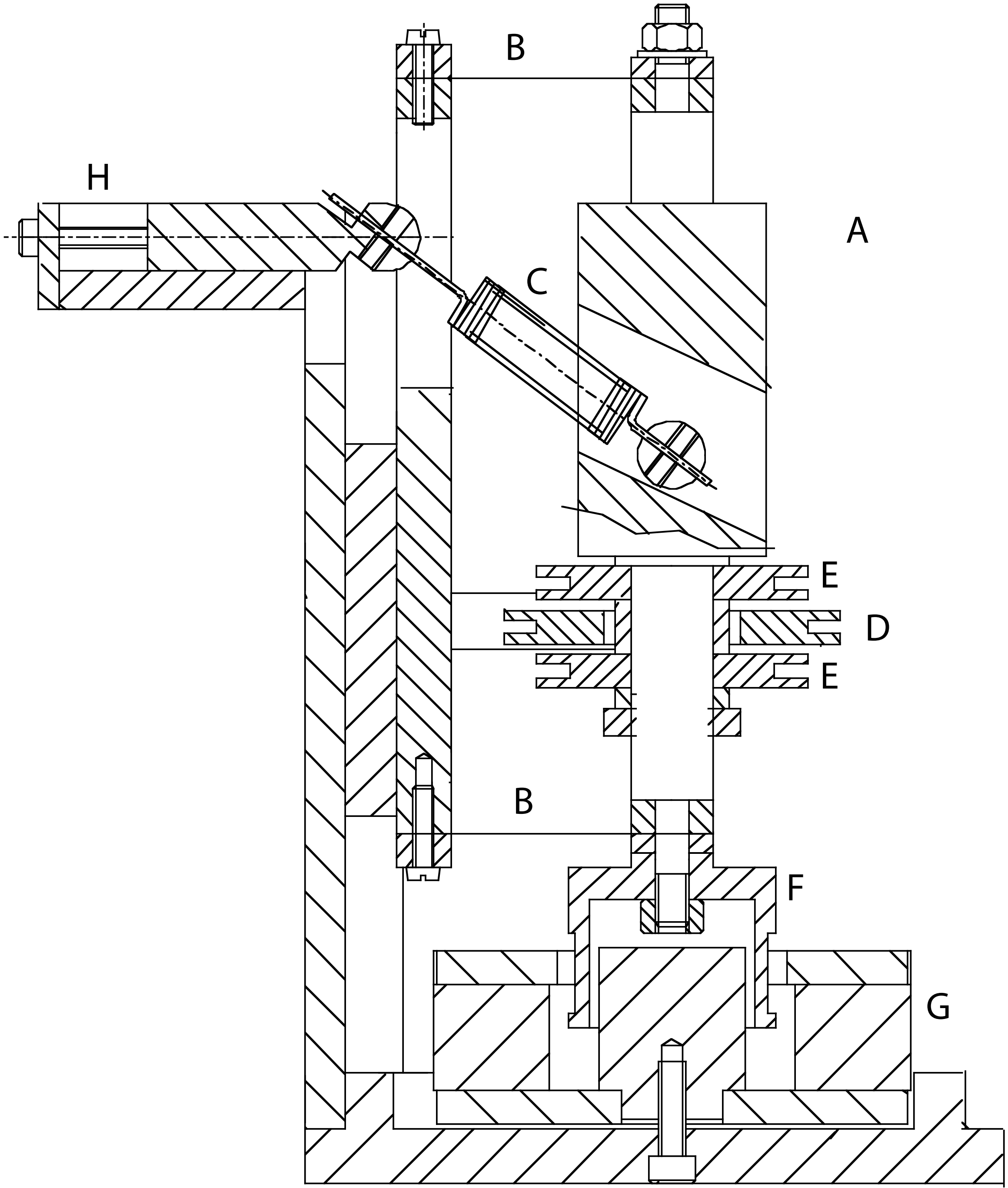
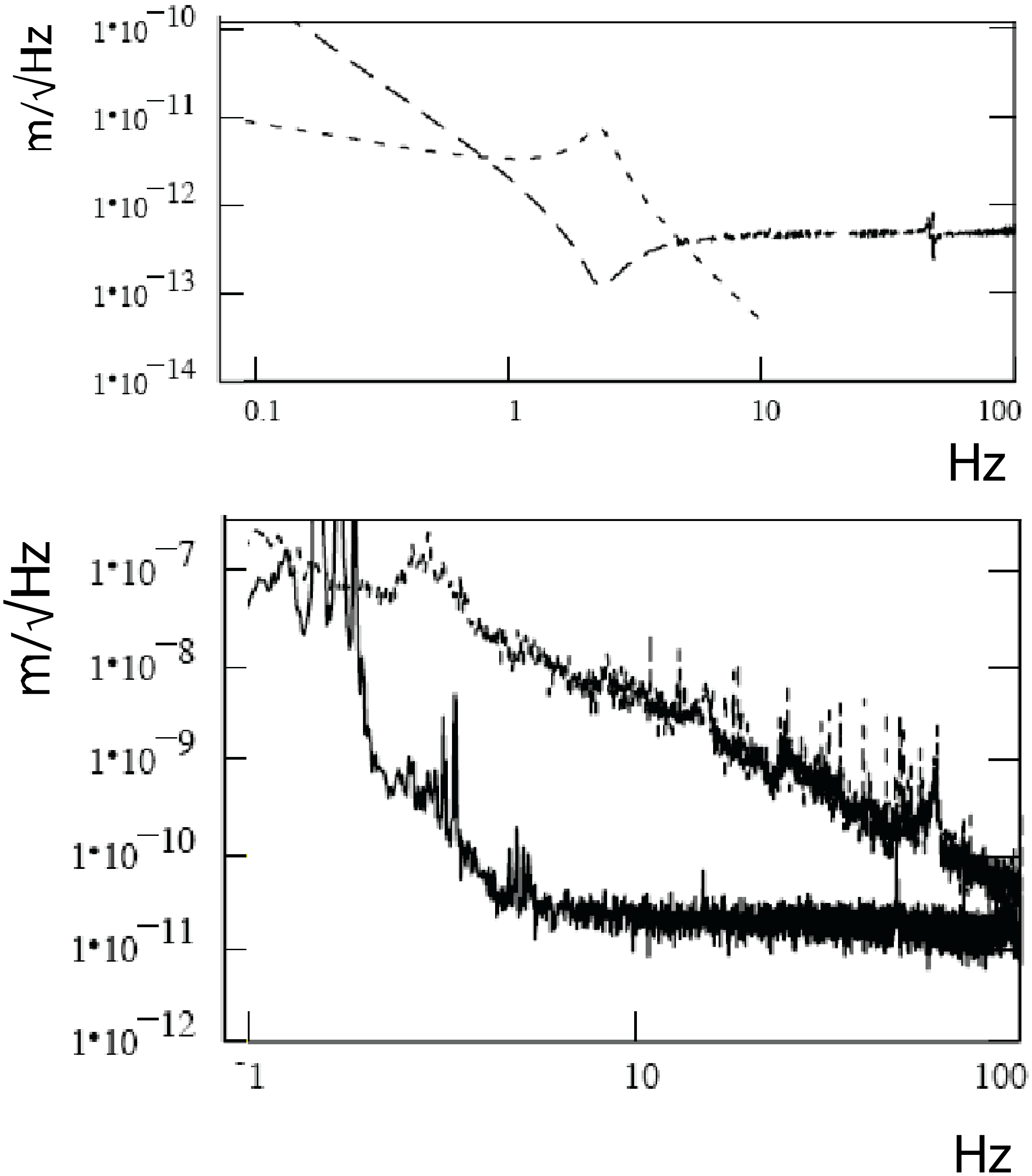


Figure 2.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1•10−9
1•10−10
1•10−11
1•10−12
1
10
100
Hz

Figure 3.

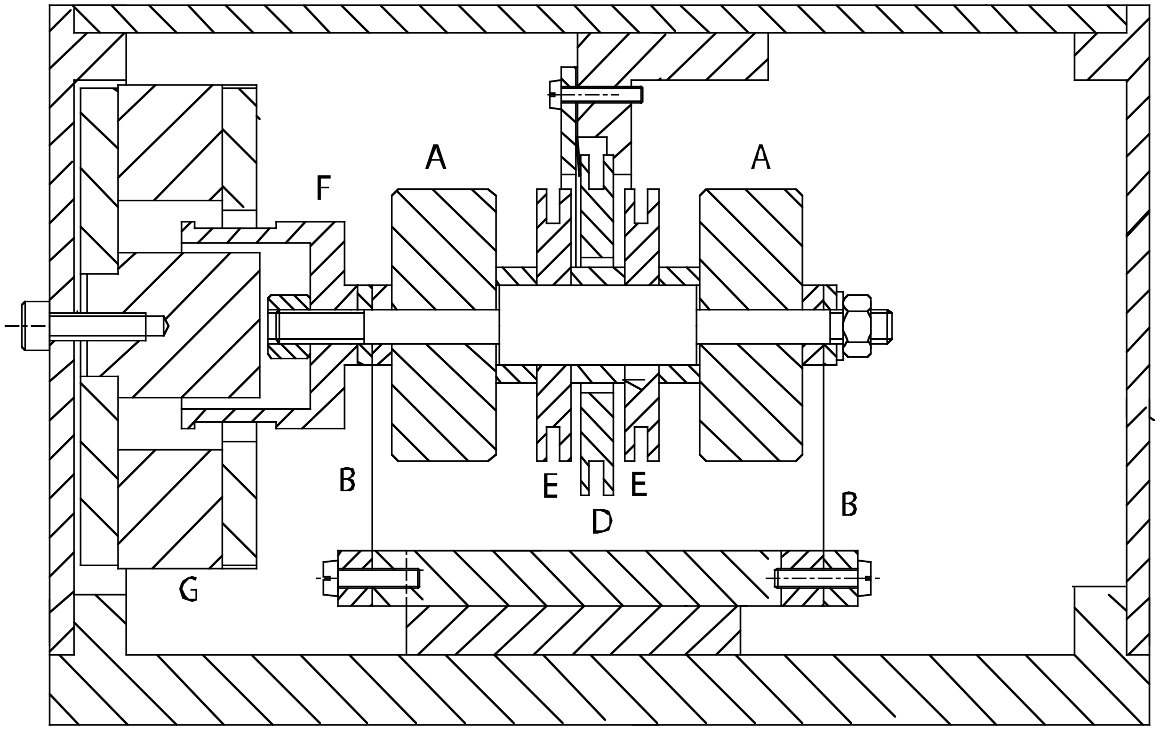

Figure 4.

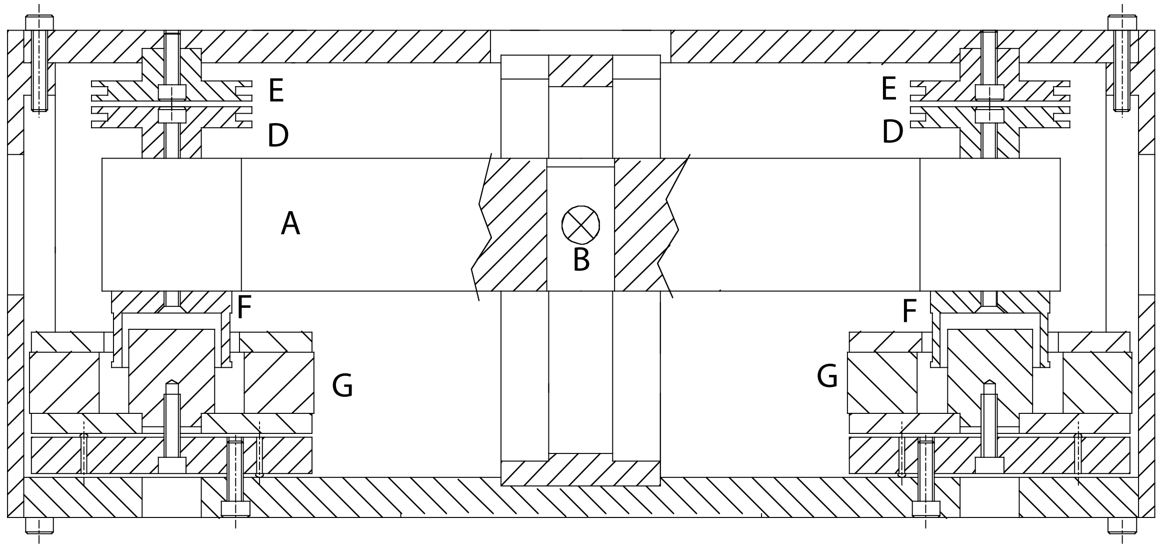

Figure 5.

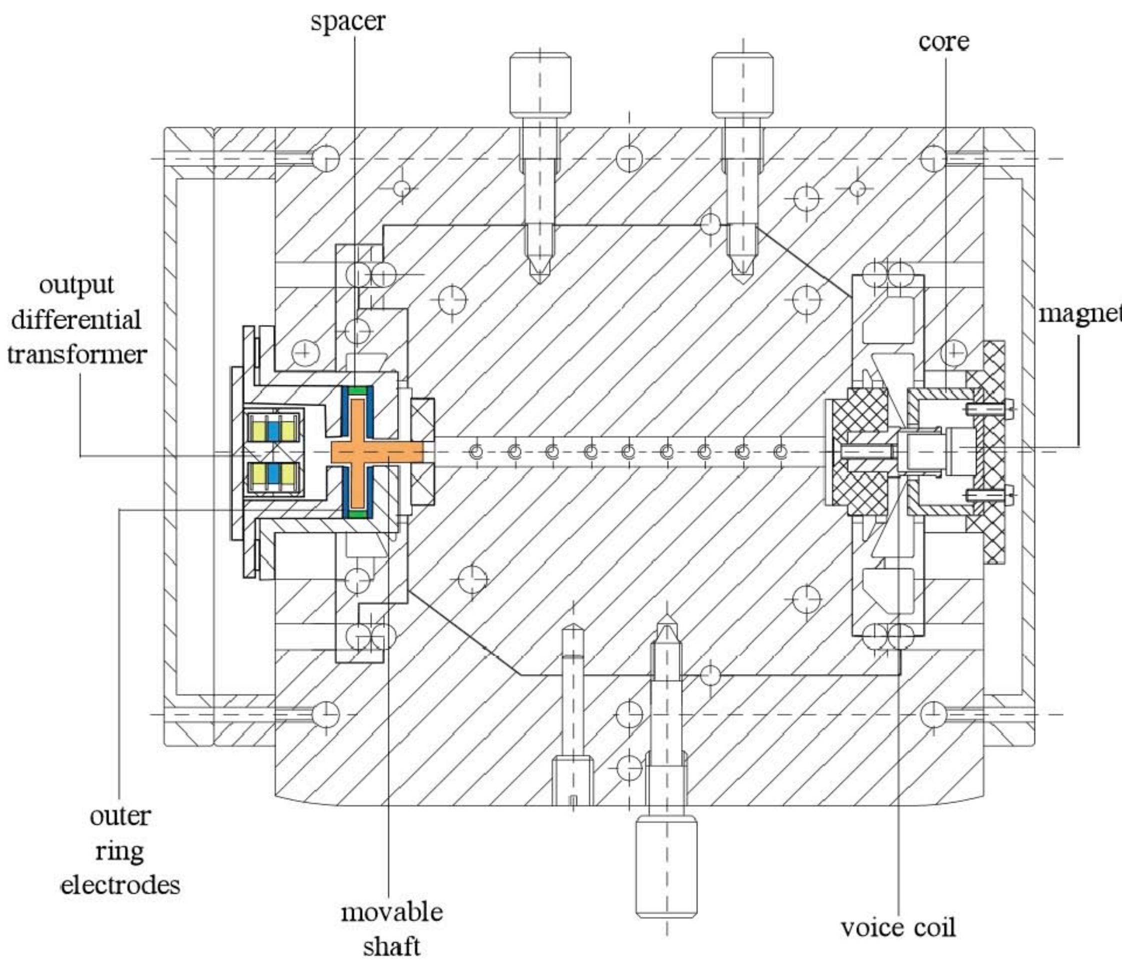
spacer
core
output
differential
transformer
magnet
outer
ring
electrodes
movable
shaft
voice coil

Figure 6.

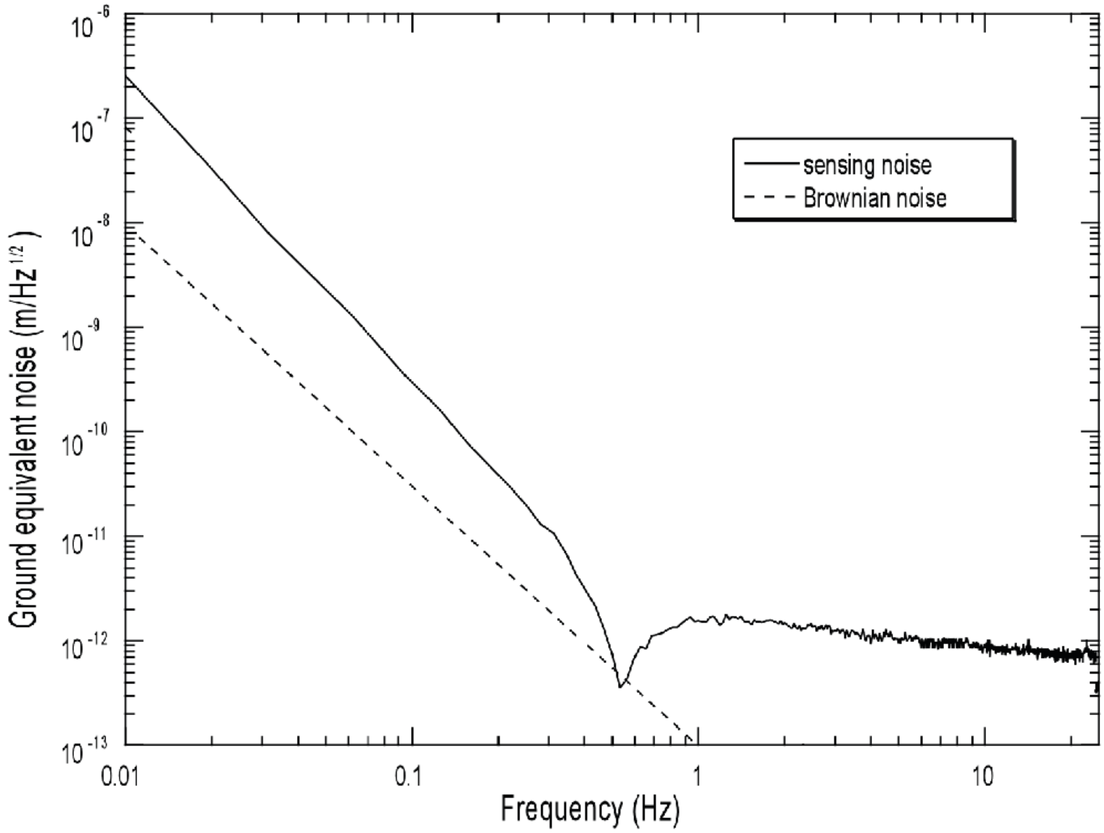
sensing noise
Brownian noise
Ground equivalent noise (m/Hz $^{1/2}$)
Frequency (Hz)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.01
0.1
1
10

Figure7.

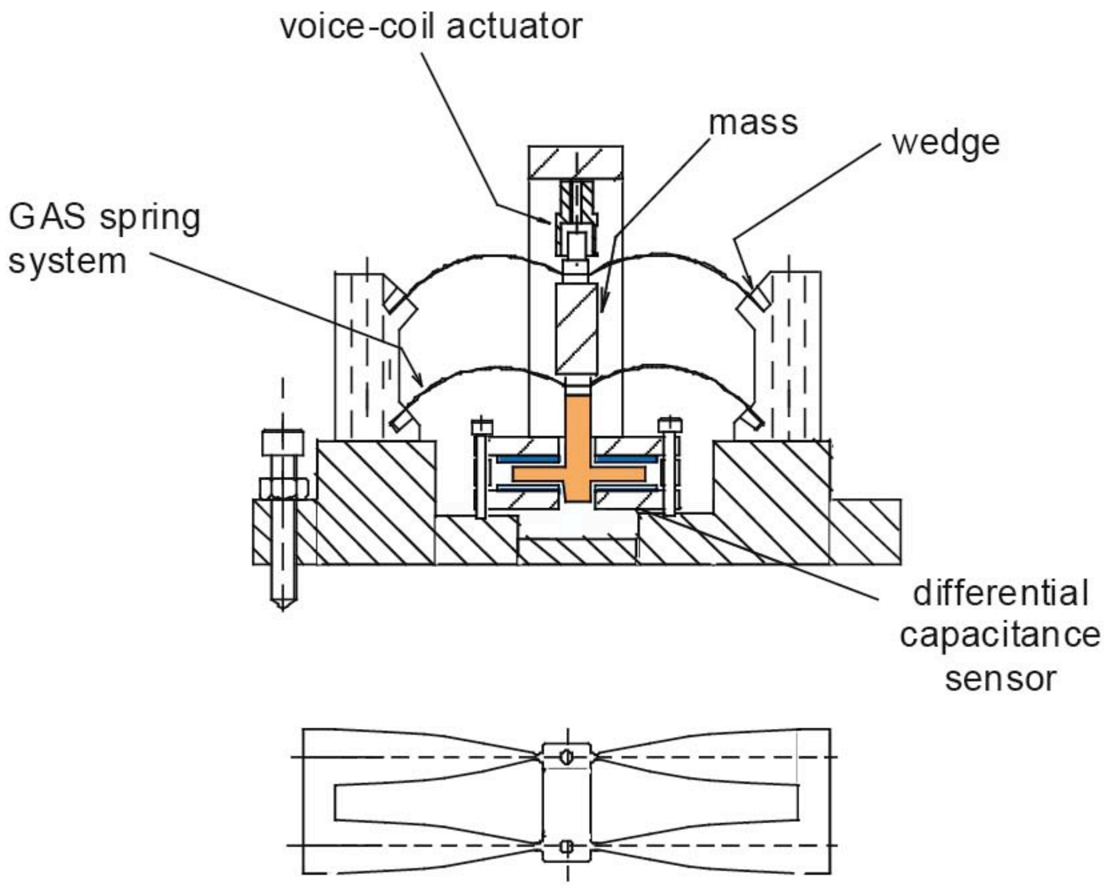
voice-coil actuator
mass
wedge
GAS spring
system
differential
capacitance
sensor

Figure 8.

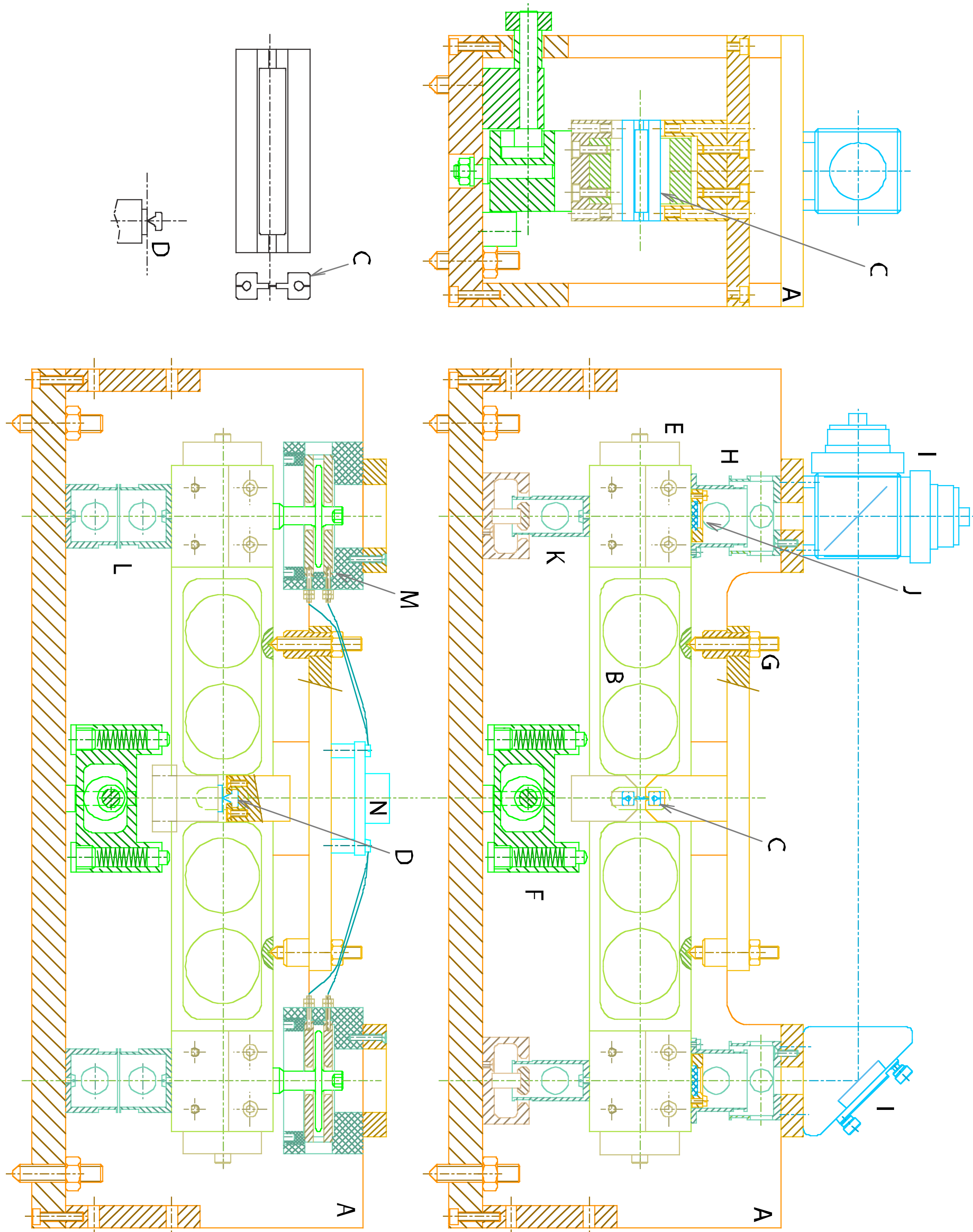

Figure 9.