Low-frequency with passive

Conventional geophone topologies and their intrinsic physical limitations, determined by the mechanical construction, limit their velocity sensing capabilities. Therefore, Magnetic Innovations has developed a novel, patent pending topology with a passive magnetic spring, that overcomes these limitations. The compact, robust and passive design offers new improvement possibilities for semiconductor and seismic industries.

• *Johan Dams* •

In many industrial applications, especially for vibration isolation purposes, absolute velocity sensing is critical for the high level of precision and accuracy required. In lithographic and high-level inspection applications for example, absolute velocity is measured to determine disturbances of the payload caused by moving parts and external disturbances. Absolute velocity sensing is utilized in this case to accurately position and control a complex lens system. Absolute velocity measurements are also necessary in seismological research applications related to earthquake prediction or the detection of oil/gas fields; see Figure 1. A geophone, or seismometer, is a commonly used device for such measurements.

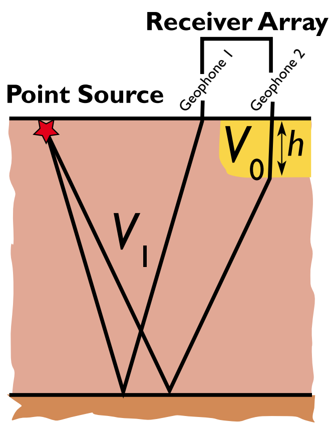

Figure 1. The principle of seismic measurement.

An important property of a geophone is the resonance frequency, which should be low to allow measurement of low-frequency signals. A large bandwidth is required as well, in order to measure high-frequency signals simultaneously. Geophones exhibiting a low resonance frequency are commercially available. However, they often have a limited bandwidth and large dimensions, or need an external power supply, which makes them too expensive for a number of applications. The main characteristic of the majority of the geophones available nowadays is the presence of mechanical springs, which limit the performance of the device.
Magnetic Innovations has developed an electromagnetic solution including a passive magnetic spring in order to resolve these limitations and to provide a very compact high-bandwidth geophone with a low resonance frequency.

Geophone principles

The elementary topology of a geophone is a mass suspended by mechanical springs, as illustrated in Figure 2.

geophone magnetic spring

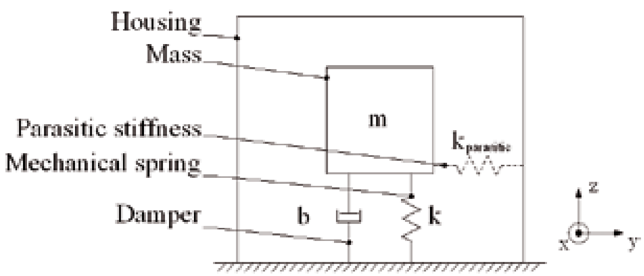

Figure 2. Mechanical geophone representation.

When a velocity, in the z-direction, is imposed on the geophone, both the suspended mass and the geophone housing start to move according to the imposed velocity for frequencies lower than the resonance frequency. For frequencies above the resonance frequency, the mass will no longer follow the movement of the housing and remain stationary. The mass *m*, depicted in Figure 2, is implemented by means of either magnets or coils. Therefore, two topologies of electromagnetic geophones can be defined, i.e., moving coil and moving magnet. Figure 3 shows a topology with a moving magnet, where the coil part is stationary, and the opposite, a moving coil topology, where the magnet is stationary.

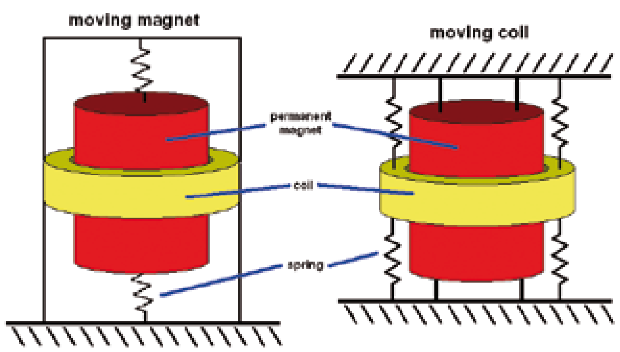

Figure 3. Geophone topologies: moving magnet (left) and moving coil.

Electromagnetic principles

Electromagnetic geophones, schematically presented in Figure 3 are based on Faraday's law. The movement of the magnetic circuit relative to the coil, or vice versa, causes a change of the magnetic flux linked by the coil, thus an emf (with an amplitude dependent on the velocity of the magnet) is induced in the coil.
Research on geophones has primarily been focused on increasing the flux rate of change, therefore the induced emf and by that the geophone sensitivity (*S*) given by

$$S(s) = \frac{U(s)}{v(s)} \qquad (1)$$

where U is the generated voltage by the geophone and v the imposed velocity. These improvements have led to geophones with a large sensitivity and improved signal-to-noise ratio. However, these developments did not solve the physical problems caused by mechanical springs if one is to obtain a low resonance frequency.

Mechanical principles

The main specifications for geophones are the bandwidth, sensitivity and phase response. For the phase response it is important that the phase shift decreases to zero, especially for motion control applications where a phase shift results in a delayed velocity signal.
Figure 4 shows a general representation of the bandwidth and the magnitude response of a geophone, where the line

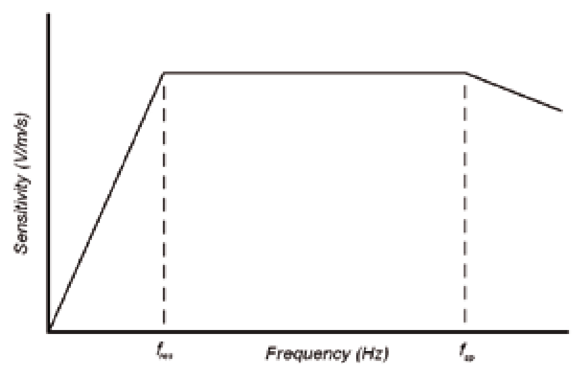

Figure 4. Response curve of a geophone.

between the resonance frequency (f_{res}) and the spurious frequency (f_{sp}) indicates a constant sensitivity.

The bandwidth of a geophone is defined as the frequency range between the resonance frequency and the spurious frequency. In this range the sensitivity, S, is constant. The resonance frequency is determined by

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad (2)$$

where k is the spring constant and m is the mass, which were depicted in Figure 2. The spurious frequency is usually defined by properties of the mechanical spring, i.e. mechanical springs have instead of a spring constant in vertical direction, z, a parasitic constant in horizontal direction, y, as well. This horizontal spring constant, significantly higher than the vertical spring constant, introduces an additional resonance at a higher frequency, which is often visible in the frequency response of the sensor.

The main challenge during geophone development is to obtain a low resonance frequency and a high bandwidth by increasing the spurious frequency. Next to that, geophones with a low resonance frequency have large dimensions and need external circuitry such as a power supply, which is not desirable for passive velocity measurement. To demonstrate the main challenge, the factors that influence the resonance frequency, as given in (2), have to be analyzed.
In order to obtain a low resonance frequency, the ratio between the spring constant, k, and the mass, m, should be small. So, the mass needs to be increased in order to obtain a lower resonance frequency. By enlarging the mass, or the force F, the preload of the mechanical spring, x, indicated in Figure 5, is increasing according to Hooke's law for springs, given by

$$F = -kx \qquad (3)$$

The second option to decrease the resonance frequency is to reduce the spring constant. However, this results in a larger preload of the mechanical spring as well (due to the constant mass). Lowering the resonance frequency to 0.5 Hz for example as shown in Figure 5 results in a preload of 1 m, which normally would result in mechanical failure of the spring.

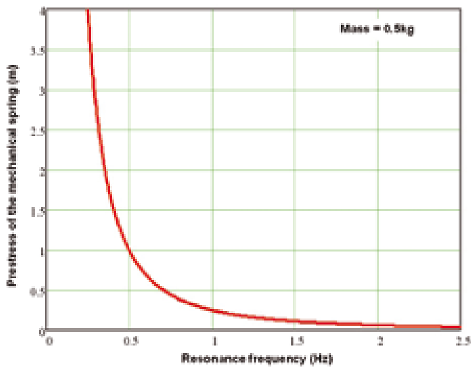

Figure 5. Preload of the spring with constant mass as function of f_{res}.

To overcome the mentioned drawbacks of existing geophones a solely permanent magnetic spring was developed by Magnetic Innovations to dramatically reduce the preload of the mechanical spring.

Sensor topology

The new geophone design is presented in Figure 6 and consists of three permanent magnet rings, a coil, and a set of mechanical leaf springs. The design incorporates moving magnets to avoid stress on the coil terminal leads during movement.

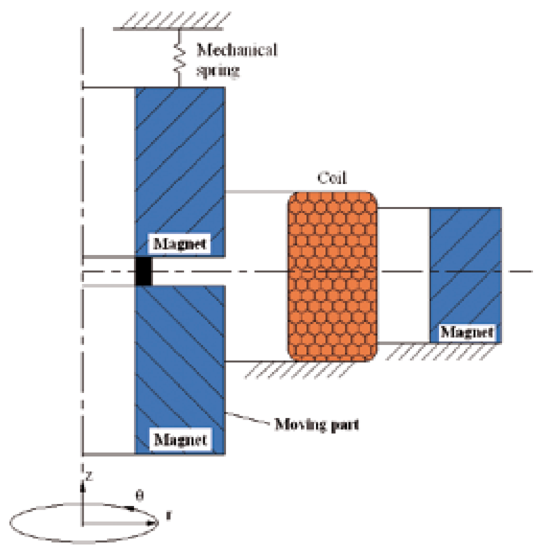

Figure 6. Geophone with passive magnetic spring.

The moving part is formed by the two inner magnets that are interconnected and suspended by mechanical springs, where the stationary part encompasses the outer magnet and the coil. All the magnets are placed in such a way that a low spring constant, which remains constant along the stroke, is obtained. The coil is positioned to obtain a constant sensitivity. Passive magnetic levitation, however, is intrinsically unstable. In the new design therefore, stability is enforced by applying cylindrical leaf springs which enable only one degree of freedom (DOF), i.e., movement along the *z*-axis.
The characteristics and magnetic behavior of the sensor were optimized by means of extensive magnetic modeling. The optimized magnetic spring constant is very low, which in combination with the mass and leaf spring results in a resonance frequency using (2), to be < 1 Hz, which is low in comparison with the majority of the passive commercially available geophones.
The geophone is represented by a second-order system, as presented in Figure 2, with a mass, *m*, spring, *k*, and a damper, *b*, which leads to the Newton equation

$$m\ddot{x} = F - b\dot{x} - kx \qquad (4)$$

where *F* is an external force and *b* is the damper constant. The constants, *m*, *b* and *k*, determine the behavior of the system.

Velocity dependency

Another important property of the sensor, as stated in (4), is the damping, *b*, which is a velocity dependent property. Damping is required to condition the signal generated by the geophone.
Equation (4) can be rewritten to a characteristic equation

$$ms^2 + bs + k = \frac{F}{x} \qquad (5)$$

This second-order system's free response, described by (5), can be characterized by the damping ratio ζ, which is defined by

$$\zeta = \frac{b}{2\sqrt{mk}} \qquad (6)$$

Three cases can be distinguished:
- critically damped,
- overdamped,
- underdamped.

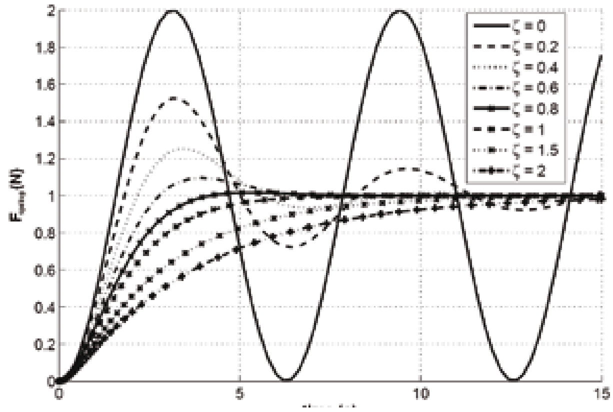

Figure 7. Step response for different values of ζ of the model.

Figure 7 shows a time response plot where ζ is varied from ζ = 0, an undamped system, to ζ = 2, an overdamped system. The value ζ = 1 represents a critically damped system.

As Figure 7 shows, overdamping results in a long settling time where underdamping results in overshoot of the signal. There are various mechanical options to implement a damper within a system. However, the damping achieved within this system has to be contactless and without any external equipment. Therefore, eddy current damping is integrated into the sensor design.
With the movement of the magnets, eddy currents are induced in an electrical conductor. These eddy currents circulate in the electrical conductor and generate a magnetic field opposing the applied magnetic field. The interaction of the two magnetic fields causes a velocity dependent repelling force. By using eddy current damping within the sensor, no external circuitry is required to provide damping, in contrast with competitor geophones. Sensor signal integrity is therefore less compromised and remains at its original sensitivity.

Results

For practical performance verification purposes the sensor, with an attached reference sensor, was mounted on a platform which was connected to a shaker. This shaker was controlled by a spectrum analyzer that had the signals from both the reference sensor and the new sensor as inputs. By using a reference sensor the exact characteristics of the shaker were not needed, only exact specifications of the reference sensor. By means of the reference sensor data the frequency response of the measured sensor can be determined.
Figure 8 shows calculated response data and measured data, indicating a resonance frequency of 0.9 Hz and a sensitivity of 36.6 Vs/m.

Vibration isolation results

In collaboration with MI-Partners, three sensors in combination with three moving magnet actuators were

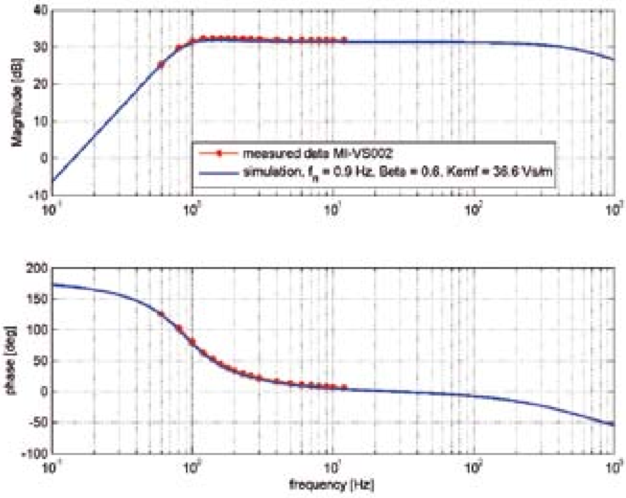

Figure 8. Frequency response of the sensor.

applied in a vibration isolation platform (Figure 9), resulting in 3 DOF (Z, Rx and Ry) vibration cancellation. Passive platform resonance frequency was tuned at 2.5 Hz utilizing springs. During closed-loop operation the applied velocity sensors were used to suppress all measured movement, to which of course the 2.5 Hz resonance frequency of the platform is a dominant contributor.

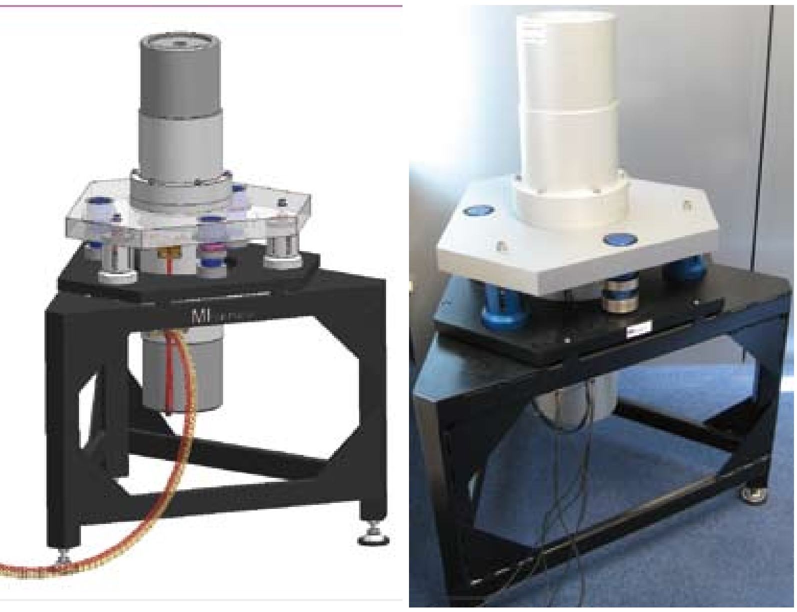

Figure 9. Vibration isolation platform (drawing on the left, actual construction on the right) with three velocity sensors.

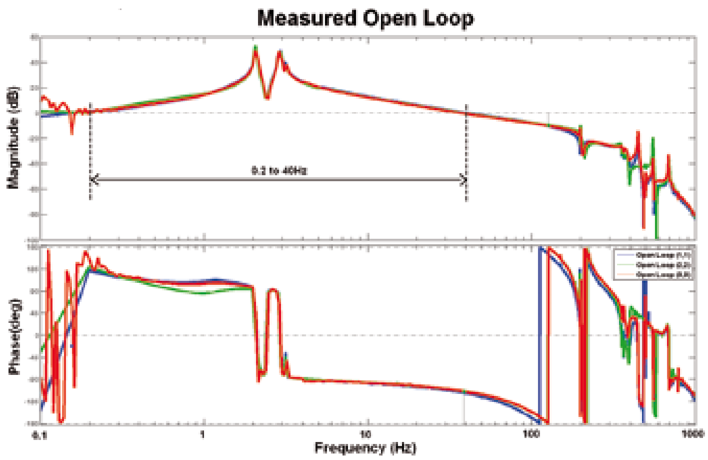

Figure 10. Measured open-loop system transfer functions with three sensors.

The measured open-loop system transfer functions listed in Figure 10 are according to simulations and indicate active vibration suppression between 0.2 and 40 Hz. All listed resonance frequencies in Figure 10 are platform related and no sensor spurious frequency was detected.

Application-oriented versions

Because the size, resonance frequency, spring constant, mass and damping coefficient can be easily varied in the design, application specific sensors can be developed with optimum characteristics for different market areas.

Author’s note

After many years of designing electromechanical actuators for lithography machines, resulting in several patented applications, Johan Dams co-founded Magnetic Innovations in 2007 in Veldhoven, the Netherlands. Magnetic Innovations specializes in the design of PMSM motors, linear motors, generators, passive magnet systems, sensors and actuators.
During experimental verification of the sensor design, the Electromechanics and Power Electronics department at Eindhoven University of Technology, under supervision of Professor Dr. E.A. Lomonova, developed an analytical model of the sensor. This work will be published in ‘Actuators and Sensors’ (author A.J.J.A. Oome).

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