Eddy-current non-inertial displacement sensing for underwater infrasound measurements

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Abstract: A non-inertial sensing approach for an Acoustic Vector Sensor (AVS), which utilizes eddy-current displacement sensors and operates well at Ultra-Low Frequencies (ULF), is described here. In the past, most ULF measurements (from mHertz to approximately 10 Hertz) have been conducted using heavy geophones or seismometers that must be installed on the seafloor; these sensors are not suitable for water column measurements. Currently, there are no readily available compact and affordable underwater AVS that operate within this frequency region. Test results have confirmed the validity of the proposed eddy-current AVS design and have demonstrated high acoustic sensitivity.

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1. Introduction

Oceanographers and geophysicists have an ongoing interest in exploring underwater acoustic processes at infrasound frequencies, for example, for monitoring natural events and for communication.[1–3] At present, though, measurements at Ultra-Low Frequency (ULF) (from mHertz to 10 Hertz) are difficult due to sensing limitations.

Existing, or prototyped, underwater acoustic vector sensors (AVS)[4–7] are often designed as neutrally buoyant rigid bodies having built-in inertia-type sensing elements, such as accelerometers or moving coil geophones. These sensors operate from tens, or hundreds, of Hertz to approximately 10,000 Hz; they lose considerable sensitivity at ULF, primarily due to the fundamentals of inertial sensing.

Here a non-inertial-sensing concept for an AVS, specifically designed to operate at ULFs, is presented.

2. Inertial and non-inertial sensing

A typical AVS consists of a neutrally buoyant (or nearly so) body that surrounds an imbedded accelerometer or geophone.[4–7] The body oscillates due to incident acoustic wave with velocity V_0, which is equal to the fluid particle velocity of the incident wave; the body is often modeled as a neutrally buoyant sphere.[6,9] The essential part of the imbedded transducer is a proof mass. As the body moves in response to the incident wave, the proof mass also moves in proportion to its inertia, thus "inertial sensing."

Gabrielson *et al.*[6] and McConnel[7] presented a thorough analysis of such a system. A simplified mechanical diagram of an inertial sensor is shown in Fig. 1(a).[7] Here m_S is the mass of the buoyant body, m_0 is the mass of the displaced fluid, m_a is the added mass of fluid, M_t is the transducer proof (inertial) mass, and C_t and R_t are the

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14. ABSTRACT

A non-inertial sensing approach for an Acoustic Vector Sensor (AVS), which utilizes eddy-current displacement sensors and operates well at Ultra-Low Frequencies (ULF), is described here. In the past most ULF measurements (from mHertz to approximately 10 Hertz) have been conducted using heavy geophones or seismometers that must be installed on the seafloor; these sensors are not suitable for water column measurements. Currently, there are no readily available compact and affordable underwater AVS that operate within this frequency region. Test results have confirmed the validity of the proposed eddy-current AVS design and have demonstrated high acoustic sensitivity.

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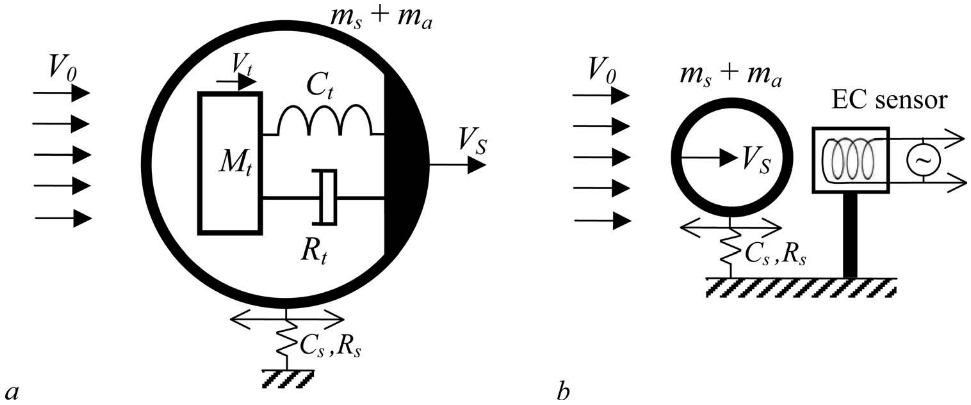

Fig. 1. Mechanical diagrams of inertial, (a), and non-inertial, (b), acoustic vector sensors with external suspension (compliance C_S and damping R_s).

compliance and the damping constant of the proof mass suspension, respectively. The buoyant body is constrained with a compliant suspension having the compliance C_s and damping constant R_s.

The inertial approach described here allows for measurement of the relative velocity between the proof mass and the sphere, that is, the sensor output is proportional to $V_S - V_t$. Following McConnel,[7] the normalized (with respect to particle velocity V_0 in the incident acoustic wave) velocity response of the inertial sensor can be expressed as

$$\frac{V_s - V_t}{V_0} = \left(\frac{m_0 + m_a}{m_s + m_a}\right)\left[\left(1 - 2j\frac{\omega_s}{\omega}\zeta_s - \frac{\omega_s^2}{\omega^2}\right)\left(1 - 2j\frac{\omega_t}{\omega}\zeta_t - \frac{\omega_t^2}{\omega^2}\right) - \frac{M_t}{m_s + m_a}\left(\frac{\omega_t^2}{\omega^2} + 2j\frac{\omega_t}{\omega}\zeta_t\right)\right]^{-1}, \tag{1}$$

where $\omega_t = \sqrt{(M_t C_t)}$ and $\omega_s = \sqrt{((m_s + m_a)C_s)}$ are the resonance frequencies of the proof mass and buoyant body (including the added mass); $\zeta_t = R_t/2\omega_t M_t$ and $\zeta_s = R_s/2\omega_s(m_s + m_a)$ are the damping ratios of the proof mass and the buoyant body suspensions, respectively.

Using formula (1) it can be shown that the response of the inertial sensor will be significantly degraded at frequencies below the proof mass resonance frequency, see Fig. 2.

The AVS velocity response can, however, be significantly improved by utilizing non-inertial sensing, that is, with direct measurements of the buoyant body motion from a displacement sensor positioned outside the body, as illustrated in Fig. 1(b). The velocity response of this non-inertial sensor is determined by the following formula:

$$\frac{V_s}{V_0} = \left(\frac{m_0 + m_a}{m_s + m_a}\right)\left[\left(1 - 2j\frac{\omega_s}{\omega}\zeta_s - \frac{\omega_s^2}{\omega^2}\right)\right]^{-1}, \tag{2}$$

and clearly provides a dramatic improvement in the low frequency response, as illustrated in Fig. 2.

In calculating the velocity responses, as per formulas (1) and (2), the following values for a typical geophone were used; a proof mass of $M_t = 24$ grams, a resonance frequency of $\omega_t/2\pi = 14$ Hz, a damping ratio of $\zeta_t = 0.34$, and a total weight of 110 grams. In order to satisfy the neutral buoyancy condition, given the geophone's total weight, the radius of a spherical housing had to be no less than 3 cm. Hence, the sphere would have a total dynamic mass of $m_s + m_a = 170$ grams. For both inertial and non-inertial sensors

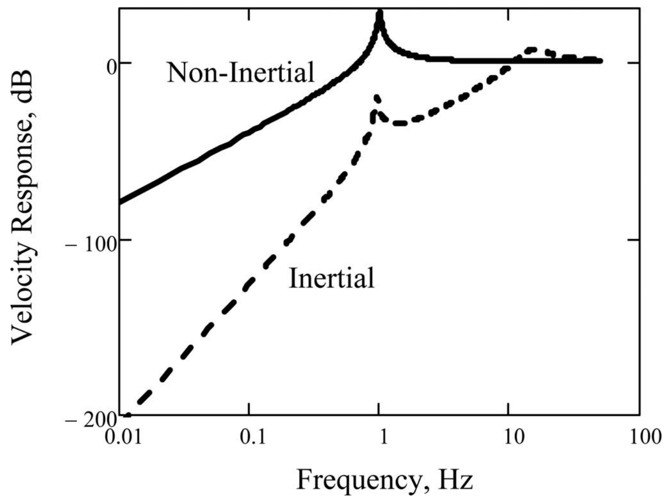

Fig. 2. AVS velocity responses for inertial (dashed line) and non-inertial (solid line) sensors, per Eqs. (1) and (2).

identical suspensions were used, having a resonance frequency of $\omega_s/2\pi = 1$ Hz, and a damping ratio of $\zeta_s = 0.02$. For a neutrally buoyant sphere, the ratio $(m_0 + m_a)/(m_s + m_a)$ is exactly unity.

The non-inertial sensing approach offers additional improvements over conventional inertial sensing. For example, restrictions on the minimum size of the buoyant body are removed, as no sensing mechanism is required inside. Non-inertial sensing eliminates any wiring to the body, which often interferes with oscillatory motion.

Furthermore, at very low, and ultra-low frequencies, it is much more advantageous to measure acoustic particle displacement, ξ, rather than velocity or acceleration, since the response of the non-inertial displacement sensor increases as frequency decreases, $\xi \sim V/\omega$.

3. Eddy-current displacement sensing

Various non-contact direct displacement sensing techniques exist: laser-based interferometric or time-of-flight sensors, capacitive, inductive, optical, and eddy-current (EC) sensors. For the application of interest here, EC sensors have many advantages. EC sensors work well in water and are insensitive to varying static pressures within the water column; they are stable with temperature, have no moving parts, and have a very small form factor (thus, weight), they are relatively inexpensive, extremely sensitive, and typically possess very low electronic noise floors, even at frequencies down to DC.

An EC sensor consists of an electric coil (probe coil), which is energized by a high-frequency (hundreds of kHertz to MHertz range) carrier signal, which then creates an EC field to any nearby, electrically conductive, nonmagnetic surface. The eddy currents generate a secondary magnetic field that interacts with the field produced by the probe coil. The magnetic field interactions are highly dependent on the distance between the probe and the target. As the separation distance changes, the electronics sense the change in the field and produce a voltage output that is proportional to the change in distance between the probe and the target. Top quality EC sensors can measure subnanometer displacement amplitudes over a broad range of frequencies.[10–12] The low minimum detectable signal levels are achieved, in part, from heterodyne measurements; that is, the measured signal modulates a high-frequency carrier, essentially eliminating 1/f noise.

Another advantage of the non-inertial EC sensor is that it does not need to employ the mechanical motion of the proof mass, as commonly done with inertial sensors. Hence, an EC sensor does not have associated mechanically induced thermal noise.

Lacking these two major noise sources at low frequencies, the EC sensor noise is primarily determined by the thermal noise[13] of the probe coil and is proportional to the coil resistance R, which is quite low, typically only a few ohms. As a result, high-performance, commercial off-the-shelf EC displacement sensors have a displacement resolution of approximately 0.013 $\mathrm{nm}/\sqrt{\mathrm{Hz}}$ (0.028 $\mathrm{nm}/\sqrt{\mathrm{Hz}}$ below 10 Hz, MicroEpsilon model DT3703).[10]

4. Experimental verification of an ultra-low frequency, non-inertial prototype acoustic vector sensor

A proof-of-concept, non-inertial, acoustic vector sensor (AVS) was built around the Micro-Epsilon 3700 series EC displacement sensor (diameter 4 mm, length 20 mm) and a hollow, near neutrally buoyant, aluminum sphere (19 mm in diameter). These components were housed in a plastic cube (each side of length 12.7 cm), with the sphere suspended as a pendulum on two thin strings, Fig. 3. Calibration measurements were conducted at the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, using the Low Frequency Facility (LOFAC) System L test vessel[15] also shown in the Fig. 3. This large, horizontally mounted, stainless steel tank has an internal diameter of 38 cm and a length of 243 cm. It is terminated at both ends with independently controlled low-frequency sound projectors. The tube is also equipped with an array of six reference hydrophones, which are positioned along the length. The measured EC sensor output, normalized by $P/\rho c$ (where P is the amplitude of the acoustic pressure measured by the reference tube hydrophone adjacent to the sensor and ρ and c are water density and sound speed), is shown in Fig. 4(a). As expected, the sensor displacement response increases as the frequency decreases. The narrow peak in the response, slightly below 1 Hz, is due to the resonance of the sphere's suspension.

Because the Micro-Epsilon EC sensor had a known DC sensitivity of 5 V/mm, it was possible to determine the absolute value of the measured sphere displacement within the tank. Fig. 4(b) provides an example of the spectral output of the EC sensor for a signal at 0.25 Hz. Also shown (dashed line) is the ambient spectral noise floor, as measured within the tube.

5. Summary

The non-inertial acoustic vector sensor concept appears to have many attributes, particularly with acoustic applications at low and ultra-low frequencies. The prototyped sensor has reasonable acoustic sensitivity, works well in water, is temperature stable,

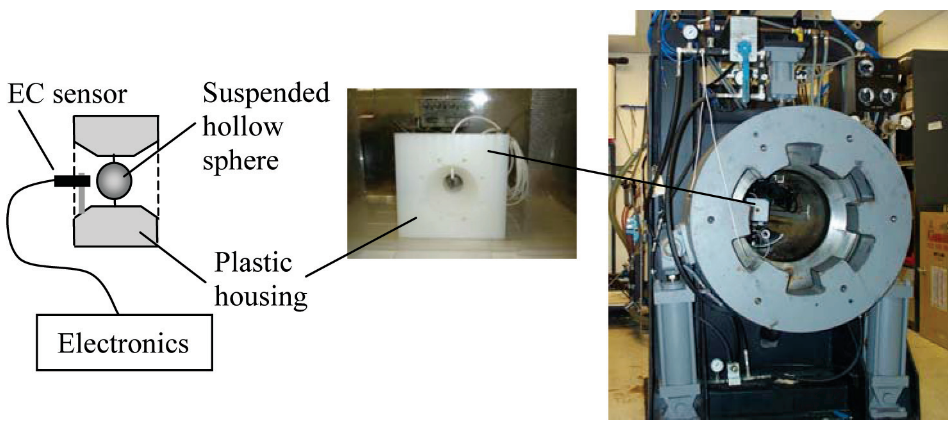

Fig. 3. (Color online) Proof-of-concept EC sensor prototype diagram and photograph within the low frequency calibration tube.

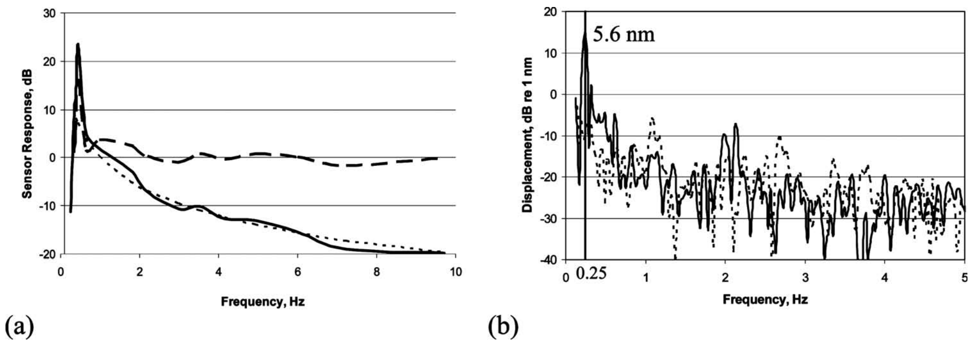

Fig. 4. (a) EC sensor normalized frequency response (P/ρc – corresponds to zero dB): solid line, displacement response $\xi(f)$; dashed line, particle velocity response $\sim f\ \xi(f)$; dotted line, $1/f$ curve; (b) Spectral response (solid line) of the prototyped EC displacement sensor showing signal at frequency 0.25 Hz. Dashed line, tube environmental noise spectrum measured in absence of the signal.

and has an excellent form factor. Measurements completed at the LOFAC System L test vessel, NUWC Division Newport, confirmed the ability of the EC sensor to detect acoustic signals below 1 Hz at displacement levels of fractions of nanometers.

Difficulties remain in configuring the proof-of-concept EC sensor into a rugged, fieldable, ULF AVS. Of primary concern is the ability to design a suitable, extremely low resonant suspension, or mounting scheme, that allows for measurement of all three orthogonal components of acoustic particle displacement. In addition, an AVS would require the incorporation of a pressure-sensing hydrophone, with comparable sensitivity. The authors are examining these sensor issues, as well as others, and look forward to presenting their findings in the near future.

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References and links

[1] J. D. Wilson and N. C. Makris, "Quantifying hurricane destructive power, wind speed, and air-sea material exchange with natural undersea sound," Geophys. Res. Lett. **35**, L10603, 1–5 (2008).

[2] L. A. Ostrovsky and A. J. Bedard Jr., "On generation of infrasound by large objects falling into water," in *Proceedings of Geosciences and Remote Sensing Symposium, IGARSS '02* (IEEE International, New York, 2002) Vol. 2, pp. 873–872.

[3] M. Lopatka, B. Nicolas, G. Le TouzéMaciej Lopatka, X. Cristol, B. Chalindar, J. Mars, and D. Fattaccioli, "Robust underwater localization of ultra low frequency sources in operational context" Proceedings of the 3rd International Conference on Underwater Acoustic Measurements, Nafplion, Greece, (21–26 June 2009).

[4] B. A. Cray and V. F. Evora, "Highly directive underwater acoustic receiver," U.S. Patent No. 6697302 (February 2004).

[5] M. J. Berliner and J. F. Lindberg, in *Acoustic Particle Velocity Sensors: Design, Performance, and Applications*, edited by M. J. Berliner and J. F. Lindberg, AIP Conf. Proc. No. 368 (AIP, Woodbury, NY, 1996), 448 pp.

[6] T. B. Gabrielson, D. L. Gardner, and S. L. Garret, "A simple neutrally buoyant sensor for direct measurement of particle velocity and intensity in water," J. Acoust. Soc. Am . **97**(4), 2227–2237 (1995).

[7] J. A. McConnell, "Analysis of a compliantly suspended acoustic velocity sensor," J. Acoust. Soc. Am. **113**(3), 1395–1405 (2003).

[8] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics*, 2nd ed. (Butterworth-Heinemann, Oxford, England, 1995), pp. 30–31.

[9]S. Temkin, *Elements of Acoustics*, (Acoustical Society of America, New York, 2001), p. 446.
[10]Micro-Epsilon America, available at http://www.micro-epsilon.com (last viewed 4/6/2011).
[11]S. Tumanski, "Induction to coil sensors—a review," Meas. Sci. Technol. **18**, R31–R46 (2007).
[12]R. Blaser, "High resolution standard proximity sensor," Proceedings of the 36th Aerospace Mechanisms Symposium, Glenn Research Center, (May 15–17, 2002), available at http://www.vibro-meter.com/pdf/hrsps-info.pdf.
[13]F. Schloss, "Accelerometer noise," Sound Vibr. **1993**, 22–23.
[14]T. B. Gabrielson, "Modeling and measuring self-noise in velocity and acceleration sensors," in *Acoustic Particle Velocity Sensors: Design, Performance, and Applications,* edited by M. J. Berliner and J. F. Lindberg, AIP Conf. Proc. No. 368 (AIP, Woodbury, NY, 1996), pp. 1–48.
[15]R. Drake, available at http://www.navsea.navy.mil/nuwc/newport/usrdiv/Pages/Low FrequencyFacility.aspx (last viewed 4/6/2011).