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Estimation of dynamic effects in low-frequency hydrophone calibration

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Three methods of estimation of dynamic effects in low-frequency hydrophone calibration by the hydrostatic exciter method are described. The advanced technique for the hydrophone calibration by hydrostatic exciter method is given. The main advantage of this technique is the possibility to excite the "variable hydrostatic" pressure up to 4-5 Hz with the precision frequency and displacement control.

The results of comparison of three methods are brought along with the results of the researches on the base of which the most effective method (in the sense of accuracy and simplicity of measurements) is chosen.

The possibility of calibration of hydrophones by this method at frequencies 0,001 to 2 Hz with uncertainty no more than 1 – 2 % is shown.

1. Introduction

There is a number of applications in underwater acoustics connected, in particular, with the investigation of sound waves generated by natural sources (earthquakes, tsunami etc.), in which the hydroacoustic transducers working at frequencies beginning from several milliherz are used.

On frequencies below 1-2 Hz the most precision methods of calibration are the various methods of a variable depth. One of this group of methods is so called method of the hydrostatic exciter [1]. In it the variable pressure is excited by the vertical harmonic displacement of a small water filled glass, which is connected by flexible tube with the main chamber in which the hydrophone being calibrated is immersed. On low frequencies the excited pressure is equal to:

$$p = \rho gh \cdot cos(2\pi ft) = P \cdot cos(2\pi ft) \qquad (1)$$

where: ρ – water density, g – gravity acceleration, h – amplitude of displacement, f – frequency, t – time, P – pressure amplitude. In further consideration the time component will not be take into account.

This method allows to carry out the precision calibration up to 0,5 Hz. In order to extend frequency range up to 1-2 Hz it is required to take into account the dynamic effects (inertia and resonance of system) which increase as a square of frequency and for which estimation there is a number of methods. Taking into account these effects the pressure amplitude will be:

$$P = \rho gh \cdot \left(1 - \frac{\omega^2 H_e}{g}\right) \cdot \left(1 + \frac{f^2}{f_r^2}\right) \qquad (2)$$

where $\omega = 2\pi f$ - circular frequency, H_e – the value having dimensions of length and describing the inertia effects, f_r - resonance frequency of system which in this case is close to the Helmholtz's resonator.

There are a several methods for the estimation of these dynamic effects.

2. Methods of the dynamic effect estimation

2.1. Two-levels method

If the level of water in the upper small glass is increased by Δh then the pressure amplitude P is:

$$P = \rho g h \cdot \left[1 - \frac{\omega^2 (H_e + \Delta h)}{g} \right] \cdot \left[1 + \left(\frac{f}{f_r} \right)^2 \right] \quad (3)$$

The output voltages of hydrophone immersed in the main chamber at these two levels will be:

$$U_1 = M \rho g h \cdot \left[1 - \frac{\omega^2 H_e}{g} \right] \cdot \left[1 + \left(\frac{f}{f_r} \right)^2 \right] \quad (4)$$

$$U_2 = M \rho g h \cdot \left[1 - \frac{\omega^2 (H_e + \Delta h)}{g} \right] \cdot \left[1 + \left(\frac{f}{f_r} \right)^2 \right] \quad (5)$$

M is the hydrophone sencitivity.

From (4) and (5) it follows:

$$H_e = \frac{g}{\omega^2} - \frac{\Delta h}{1 - \dfrac{U_2}{U_1}} \quad (6)$$

The basic lack of this method is the necessity of definition Δh. As the value U_2/U_1, as a rule, not too strongly differ from 1 (otherwise too large change of a level would be required, that makes system too inconvenient in operation), the definition Δh should be carried out with high accuracy. For example, at $U_2/U_1 = 0{,}9$ the 0,1 mm error in definition Δh leads to the 1 mm error in definition H_e, that results in the 0,4 % error in definition of pressure on 1 Hz and 1,6 % error on 2 Hz. In this case accuracy of 0,1 mm is rather high, since the speech is about a difference of levels and the measuring device should have an error no more than 0,05 mm. It is difficult for executing because of influence of meniscus on a surface of water, which is instable, and also because of probability of the top glass with water small deviations from a vertical. The application of contact or laser methods essentially complicates the equipment, but does not give a radical improvement.

Therefore large advantage should have the methods not requiring measurements of a level of water which is based on changing of dynamic effects with frequency. Two of them are considered below.

2.2. Two-frequencies method

Let's transform the expression (2) for the amplitude of pressure:

$$P = \rho g h \cdot \left[1 - \frac{\omega^2 H_e}{g} + \left(\frac{\omega}{\omega_r} \right)^2 - \frac{\omega^2 H_e}{g} \cdot \left(\frac{\omega}{\omega_r} \right)^2 \right] \quad (7)$$

Neglecting last addendum:

$$P = \rho g h \cdot \left(1 - \frac{\omega^2 H_e^1}{g} \right), \quad (8)$$

where:

$$H_e^1 = H_e - \frac{g}{\omega_r^2} \quad (9)$$

H_e^1 takes into account the dynamic effects connected both with the inertia, and with the resonance of system.

Measuring output voltage of a hydrophone on two strongly enough distinguished frequencies, we receive:

$$U_1 = M_1 \rho g h \cdot \left(1 - \frac{\omega_1^2 H_e^1}{g} \right) \quad (10)$$

$$U_2 = M_2 \rho g h \cdot \left(1 - \frac{\omega_2^2 H_e^1}{g} \right) \quad (11)$$

Suppose that the frequencies are chosen so, that $M_1 = M_2$, then from (10) and (11) it is derived:

$$H_e^1 = \frac{g}{\omega_1^2} \cdot \frac{1 - \dfrac{U_1}{U_2}}{1 - \dfrac{U_1}{U_2} \cdot \dfrac{\omega_2^2}{\omega_1^2}} \quad (12)$$

This method has the essential advantage before previous, since it does not require measuring the water surface levels. And the measurement (or direct giving) frequency can be executed with high accuracy.

Besides, here influence both of inertia and resonance of system is estimated at once. As well as in the previous method the high accuracy of measurement of voltage is necessary here. However using of modern devices (for example, precision ADC) allows to carry out these measurements with an error 0,1 - 0,2 %.

The main lack of this method is the assumption $M_1 = M_2$. If it not so, it is necessary to make some assumption, for example, that M changes as well as at a chain of the first order (for many of hydrophones it is carried out precisely enough). In this case:

$$M = \frac{M_0 \omega\tau}{\sqrt{1+(\omega\tau)^2}}, \qquad (13)$$

where M_0 – hydrophone sensitivity on high frequency, τ - the first-order chain time constant.

In order to determine τ it is necessary to carry out measurement for one more frequency and the system of the equations becomes nonlinear. However, its decision does not produce the large difficulties.

2.3. Zero frequency method.

This method doesn't have the basic lacks of the two previous, though as well as in the first case it requires a separate measurement of the resonant frequency.

If we have the device (mechanical generator) stimulating vertical moving of a small upper glass that is capable to work on enough high frequencies (up to 4 - 5 Hz) and to change frequency fluently, then it is possible, by changing frequency, to achieve equality of inertial and hydrostatic pressure on some frequency f_0. In this case:

$$1 - \frac{\omega_0^2 H_e}{g} = 0 \qquad (14)$$

From (14):

$$H_e = \frac{g}{\omega_0^2} \qquad (15)$$

In this case the amplitude of pressure is expressed as:

$$P = \rho g h \cdot \left[1 - \left(\frac{f}{f_0}\right)^2\right] \cdot \left[1 + \left(\frac{f}{f_r}\right)^2\right] \qquad (16)$$

This method requires neither measurement of a level, nor exact measurement of a voltage. It is required only to determine a minimum of an electrical signal when f_0 is being measured.

The additional projector built-in to the main chamber is used for the measurement of f_r. By increasing the frequency of projector radiation the frequency f_r at which the signal from a hydrophone is maximal is determined. As the frequency f_r is much higher than the top border of working frequency range, the high accuracy is not required in its determining.

3. Comparison of methods

The comparative researches of the methods of estimation of dynamic effects described above were carried out. In Table I the values of the dynamic multiplicand D are given. D is:

$$D = 1 - \frac{\omega^2 H_e^1}{g} \qquad (17)$$

It should be mentioned that the value f_r was 14 Hz, Δh for the first method was 23,5 mm, ω_2/ω_1 for the second method was equal to 16.

Table I. Results of comparison of various methods of the dynamic multiplicand D estimation.

		Two-levels method	Two-frequencies method	Zero frequency method
H_e^1 [cm]		2,578	2,601	2,666
D	1 Hz	0,896	0,895	0,893
	2 Hz	0,585	0,582	0,571

The data submitted in the table I show, that if for frequency 1 Hz the difference between all of the methods is 0,2 - 0,3 %, for frequency 2 Hz the difference increases up to 2 - 3 %.

4. Conclusion

Three ways of an estimation of dynamic effects in low-frequency hydrophone calibration is considered. The most precision is that one based on smooth changing of frequency with the purpose of achievement of a minimum of a signal. It allows to achieve a measurement uncertainty no more than 1 – 2 % on frequencies up to 2 Hz. More simple and economic is the method based on measurements on two (three) frequencies. On frequencies below 1 Hz it allows to reach the same accuracy as zero frequency method does. The low frequency limit for all the methods is connected only with the properties of a hydrophone itself and it can rich at least 0,001 Hz.

Reference

1. A. Golenkov, Absolute calibration of infra sonic pressure detectors in an air and water resonator with hydrostatic excitation. Measurement Techniques, Journal 5, pp. 444-449, (1965).