ACOUSTIC ASPECTS OF A NON-CONVENTIONAL PISTONPHONE FOR CALIBRATING HYDROPHONES AT LOW FREQUENCIES

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1. INTRODUCTION

Usually, the calibration processes of hydrophones over the first hundreds of frequencies are carried out in large water tanks or in the sea deep water, where the free field conditions are satisfied. However, the complexity and the high costs of these operations can be avoided by employing laboratory devices as the pistonphones. In the literature, the aim of all kinds of pistonphones is to establish an uniform and identified pressure field in a small fluid volume, where is immersed the hydrophone(s) for calibrating. This uniformity is very important to avoid the existence of pressure gradients on the transducers sensitive faces and is obtained, with the desired accuracy, when the fluid volume dimensions are much smaller than the wave length related to the upper frequency of the pistonphone operation range. In some classical models of pistonphones [1], the acoustic chamber is completely full of one type of fluid or consists of a water or oil column and an air column. In both cases, a stiff piston or a moving coil driver imposes the acoustic input with the displacement measured by an optical sensor. In an absolute calibration pistonphone, relating the thermodynamic equations of the acoustic process to the source parameters the hydrophone sensitivity response is defined. In another classical model of pistonphone, the calibration is carried out by the reciprocity method using three transducers in a long length and small diameter tube. More recently, other systems to calibrate hydrophones at low frequencies have been patented, as for example: the calibration devices based on Helmholtz resonator theory [2], a pressure chamber with a hydraulic pump as a acoustic source [3] and an apparatus using PVDF films as reference transducers [4].

For the classical models of pistonphones, the driver sources, the watertight seal mechanisms and the displacement sensors are non-economical factors. For the reciprocity tube method the difficulty is to generate efficient low frequency sound in small chambers. From these restrictions, the present paper proposes a non-conventional pistonphone attending the low cost, manufacturing simplicity and accuracy requirements. In the system here described, the calibration curves are obtained by using a standard hydrophone in a comparison calibration process and adopting a commercial loudspeaker as the excitation source. The system was designed for production testing and field use in the largest possible frequency sub-bands from 10 Hz to 1 kHz. The hydrophones were mounted in a water-air chamber of dimensions established from the application of theoretical models to define the dynamical behaviour of the acoustic media. The initial data obtained from a prototype of the pistonphone and comparisons between the calculations and experimental results of the equipment response are presented.

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2. PISTONPHONE CONFIGURATION

According the basic requirements of the system, the pistonphone was designed in a typical configuration of the absolute calibration devices. As shown schematically in Figure 1, the proposed model consists of a water-air chamber and the acoustic input is produced by the response of a commercial loudspeaker combined with the dynamical behaviour of the air column. By using a standard hydrophone, the acoustic pressures values in the water and, consequently, the voltage sensitivity of the measured hydrophone is obtained. During the tests, the loudspeaker should be excited by a white noise input or by a sinusoidal signal with a frequency sweeping, amplified e filtered in the calibration frequency range. This excitation is converted to acoustic noise in the air column, transmitted to the water column and the electrical response of both hydrophones is applied to a spectral analyser in order to define the coherence function, the amplitude and phase transference functions between the two input channels. From these results, it is possible to define some of the main calibration conditions of the acoustic chamber, as the length of the water-air columns, the mounting position of the hydrophones and the frequency sub-bands where the calibration process is more accurate.

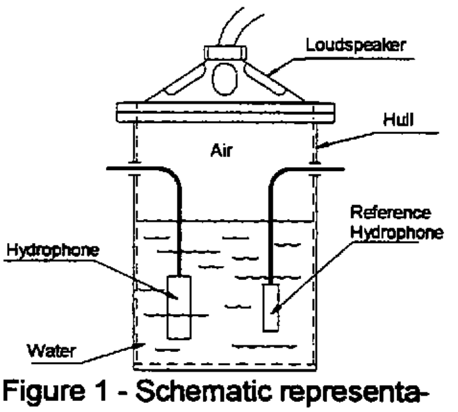

Figure 1 - Schematic representation of the pistonphone.

For the dimensional aspects, the requirement of a 10 Hz initial frequency leads to a 15 inches diameter loudspeaker and from the need for calibrating a considerable diversity of commercial hydrophones is specified a 365 mm inner diameter. In respect to the height of the acoustic media, Albul et al. [5] assert that the sound field in a pistonphone chamber remains homogeneous if the sizes of the water and air parts do not exceed 1/6 the length of the sound wave in the water and air respectively, corresponding to the upper frequency of the operation band. However, due to the dimensional requirement for the chamber, the height of the water-air columns is initially established as a function of the near field and acoustic radiation impedance criteria. To apply the first criterion, it should be noted that the propagation of the highest frequencies in the band could excite longitudinal and transversal acoustic waves in the chamber. Then, from the development of an acoustic field with waves propagating even in a non-stationary state, the dynamical responses of the air and water volumes is out of phase to the loudspeaker cone, in a non-rigid mode. While for the air volume the excitation is imposed by the loudspeaker (real source), for the water volume the acoustic input is produced by the air-water interface (virtual source). It is important to observe that the propagation of acoustic waves in lengths close to the loudspeaker dimensions or close to the internal dimensions of the chamber hull can make the non-spherical divergence zones continue until points very distant of the real and virtual acoustic sources. For this situation, the pistonphone chamber could be probably excessively long. Otherwise, it is convenient that the transversal profile of the acoustic pressure field, immediately above the water surface, is the more homogeneous as possible and the hydrophones are mounted at a depth where the sound pressure on their sensitive faces do not present phase variations.

Although, in an acoustic propagation medium, there is not an exact region of transition from the Fresnel to Fraunhofer zone, the phase and amplitude criteria related to a circular plane piston (proved by USA Standard Institute - Z24.24) can be considered as a good approximation to define the spherical divergence zone, as follows:

$$Y \geq \frac{\pi r^2}{\lambda} \qquad \text{and} \qquad Y \geq a \qquad (1)$$

In the equations above, $\underline{Y}$ is the axial distance between the source (real or virtual) and the point where the spherical diffraction begins, $\underline{r}$ means the source radium (for the air is the loudspeaker effective radium and for the water volume is the chamber inner radium) and $\underline{\lambda}$ represents the wavelength concerned with the upper frequency. By comparing the criterions expressed in (1), can be concluded that the water surface should be at a minimum distance of 249.2 mm from the loudspeaker and the hydrophones need to be positioned at a depth not less than 182.5 mm from the interface air-water. Should be registered that for the virtual source modelling are adopted elastic and dynamical parameters equivalents to the air volume closed in the pistonphone.

For the criterion of the acoustic radiation impedance, it is suitable to consider that should have a minimum volume of air molecules to permit a maximum transference of acoustic power from the driver transducer to the air column, considering each frequency of the pistonphone operation range. Then, once the effect of the acoustic radiation reactance (X_r), over the total mechanical impedance of a loudspeaker, corresponds to the loading of the cone by a cylindrical volume of air with transversal section identical to its effective area, the acoustic radiation masslike is expressed by

$$m_r = \frac{X_r}{2\pi f} = \pi\, r^2\, \rho_0 \frac{8r}{3\pi} \qquad \text{where } \rho_0 \text{ is the density of the acoustic medium.} \qquad (2)$$

It should be noticed that the last term of the equation above means the minimum height of the air column for a maximum of the acoustic radiation efficiency. In relation to the loudspeaker, this height should be higher than 140 mm, consequently smaller than the air column based on the near field criteria (not less than 250 mm). For the water volume, although the hydrophones should be submerged at about 183 mm as the minimum quota, is specified a total height of 335 mm according the requirement to calibrate different models of hydrophones.

3. DYNAMICAL BEHAVIOUR OF THE CALIBRATING CHAMBER

3.1 Longitudinal Modal Response of the Acoustic Media

Usually, the modal acoustic behaviour of closed cylindrical chambers has been investigated from propagation models applied to pure longitudinal waves in pipes. This class of models can only be employed for devices where the pipe diameter is too small when compared with the wavelength of the upper operation frequency and for ratios pipe length / inner diameter >> 1. Then, to analyse the longitudinal modal propagation of the pistonphone were adopted models with boundary conditions more associated to the volumetric cavities geometry, once, for the acoustic chamber, the ratio previously mentioned is 1.6 for air-water total column, 0.7 for the air column and 0.9 for the water column. Then, to define theoretically the longitudinal acoustic modes of the calibration media, besides the simple one-dimensional model, the Helmholtz Modified model [6], the model for a Stiff Piston in Closed Chambers [7] and the Coupled Impedance model [8] were applied.

By comparing the models [9], was proved that the Coupled Impedance model is the most accurate for cylindrical closed chambers with ratio fluid column / inner diameter lower than 5.5 and when excited by a compliant acoustic source as a loudspeaker. This model, unlike the others mentioned above, considers not only the dynamical properties of the acoustic media but also the acoustic source properties, whereas the mechanical impedance of the loudspeaker could be sufficient to affect the global dynamical behaviour of the acoustic chamber. In this point of view, the total input impedance of the chamber is the series combination of the impedances of the loudspeaker cone (Z_C) and of the acoustic media (Z_A). Then for frequencies where the wavelength does not introduce delays in the cone displacement can be written;

$$Z_T = Z_C + Z_A \tag{3}$$

With Im $\{Z_T\} = 0$ and assuming that the final part of each fluid column is on a stiff baffle (for the air the baffle is the water and for the water the baffle is the chamber bottom), the equation above becomes;

$$\frac{cos\ \mathrm{KL}\ sen\ \mathrm{KL}}{sen^2\ \mathrm{KL} + (\alpha\,\mathrm{L})^2 cos^2\ \mathrm{KL}} = \underbrace{\frac{m}{S\rho_0 L}}_{1}\mathrm{KL} - \underbrace{\frac{sL}{S\rho_0 c^2}}_{2}\frac{1}{\mathrm{KL}} \tag{4}$$

where, S̲ and L̲ are respectively the internal area of the chamber and the column height of the medium analysed, ρ_0 is the acoustic absorption coefficient of the media, c̲ is the sound speed in the fluid considered, m̲, s̲ and w̲ represent respectively the total moving mass of the coil-cone set, the longitudinal stiffness coefficient of the cone and the driven frequency. K̲ is the wavenumber. If the water is the physical system modelled, the ratio to the masses (term 1) is defined in the equation (4) where the loudspeaker effective mass plus the mass of the air column is divided by the water mass. Concerning the elasticity of the acoustic system (term 2), the series combination of the cone stiffness and the air column stiffness is divided by the water column stiffness.

The Coupled Impedance model has a graphical solution from the intersection of the two curves defined in equation (4) and provides the main frequencies for the longitudinal resonance modes of the acoustic media. Each intersection point of the curves defines a particular resonance mode of the fluid and from the intersection of the hyperbolic curve with the horizontal axe, which argument is *KL*, is established the first resonance frequency of the loudspeaker. By using a light and compliant loudspeaker (when compared to the air mass in chamber) there is an acoustic state nearly configured by a displacement anti-node and a pressure node in the interface cone-

air. In the interface air-water the acoustic state is nearly defined by a displacement node and a pressure anti-node. In case of a heavy and stiff loudspeaker, the displacement node and pressure anti-node conditions nearly represent the acoustic state in both interfaces. For the hydroacoustic chamber, the air-water interface should actuate as a light and compliant source and, consequently, the dynamical state at this region corresponds to a pressure node and a displacement anti-node. As the bottom of the water column consists of the chamber hull, the boundary conditions are a displacement node and a pressure anti-node.
When applied for the loudspeaker-air volume system, the Coupled Impedance model resulted in a pure longitudinal mode with a fundamental frequency of about 127 Hz for the acoustic medium and of 35 Hz relative to the mechanical resonance of the loudspeaker.

Since the medium resonant frequency is near the correspondent value obtained from the one-dimensional model for a 1/4 wavelength, can be evidenced that the loudspeaker acts upon the air column as a light and compliant acoustic source.

Concerning the water volume, resonant modes are defined from the fundamental frequency of 1117 Hz comprising frequencies near its first four pure odd harmonics, to know: 3339 Hz, 5506 Hz, 7706 Hz and 9940 Hz. Notice that, for the air column, there is one longitudinal resonant frequency in the pistonphone operation range. For the water volume, all the frequencies values obtained from the Coupled Impedance Model are above 1 kHz. However, it could not be asserted preliminary if the occurrence of any resonance mode, longitudinal or transversal, would affect the transfer process of acoustic power from the system loudspeaker-air column to the water column. For each particular resonance mode, this depends on the form as the pressure field is being distributed in phase at the air-water interface.

3.2 Transversal Modal Response of the Acoustic Media
It should be noted that acoustic media in cavities of similar dimensions to the chamber here analysed present a three-dimensional profile for the dynamical response, configured by longitudinal, diametrical and circular modes. In this sense, the model for Acoustic Propagation in Cavities [7] was adopted to define the volumetric modes in the air and water columns. From this model, for a cylindrical cavity opened at one extremity, the longitudinal, diametrical and circular resonance frequencies, pure or coupled are given by

$$f(i,j,k)=\frac{c}{2\pi}\left(\frac{\lambda_{jk}^2}{r^2}+\frac{i^2\pi^2}{4L^2}\right)^{1/2} \qquad (5)$$

where, <u>L</u> and <u>r</u> represent respectively the height and the inner radium of the acoustic media. i = *0, 1, 3,...* is the number of longitudinal nodes. j = *0, 1, 2, ...* is the number of diametrical nodes and k = *0, 1, 2,...* the number of circular nodes. λ_{jk} is the natural frequency parameter (for values see [6]). Notice that by determining the pure longitudinal modes, where $j = k = 0$, $\lambda_{jk} = 0$, the relation (5) becomes identical to the equation of the one-dimensional model for a 1/4 wavelength. Then, for the three-dimensional model, only the results related to the longitudinal and transversal coupled modes (i, j and $k \neq 0$) or to the pure transversal modes ($i = 0$, j and/or $k \neq 0$) were considered. For the last case, the frequency values are naturally independent of the medium height. For the air volume, only the two first pure diametrical modes plus the (1,1,0) and the (1,2,0) modes are in the desired operation band, respectively with the follow frequency values: 551, 913, 649 and 976 Hz. As expected for the water column the resonance frequency values were higher than 1 kHz, once the water and air wavelength ratio is higher than the two media height ratio and the chamber inner diameter is constant. However, is important to mention that as the elastic and dynamical properties of the loudspeaker affect the longitudinal resonance pattern of the media, one supposes that the transversal resonance values, pure or coupled to the longitudinal modes, also can be affected by the dynamical behaviour of the acoustic source.

3.3 Modal Response of the Pistonphone Hull

The resonance of the air volume at frequencies of the pistonphone operation range enables the transference of the energy of vibration from the air column to the water volume through the cylindrical wall of the measuring chamber. This situation can be more problematic specially if the resonance frequencies of the hull modal response are near the modal frequencies of the air column, when the consequences of the transference of energy can be more intensive and harmful to the calibration process. The transversal excitation of the water column, from the hull vibration, is able to generate spurious noises with pressure amplitude high enough to disturb the acoustic field on the sensitive faces of the hydrophones and causing distortions in the voltage sensitivity curves. Aiming to obtain the natural frequencies of the pistonphone hull, were applied two classical mathematical models proved experimentally [8]. The first one, based on the Flügge theory for cylindrical shells, is more accurate to the two first circunferencial modes. The second model, by Sharma, has a suitable applicability to the circunferencial modes of third order. Both solve the pure longitudinal modes and longitudinal and transversal coupled modes with the same accuracy.

The pistonphone hull was made from carbon steel with a 5 mm wall thickness, 185 mm mean radium and 565 mm total length. By applying the two models to the chamber geometry were defined six resonance modes which frequency values are smaller than 1 kHz, to know: 371 Hz, 457 Hz, 548 Hz, 852 Hz, 937 Hz and 997 Hz. Should be noted that some theoretical frequency values of the chamber hull are extremely near the theoretical ones determined to the air column. This coincidence gives rise to the possibility of distortion occurrences in the hydrophones calibration curves, mainly around the frequency values mentioned.

4. EXPERIMENTAL RESULTS

The pistonphone analysed in this work resulted in a first prototype showed in Figure 2. Its external configuration is represented in Figure 3 where the main subsystems are: 1- pistonphone hull, 2- adjustable cap for tight closing and 3- frame of the pistonphone hull and suspension elements [10,11]. Besides the pistonphone portability, the metallic structure was designed to isolate the acoustic chamber of the vibration excitations from the ground motion. For this objective, was adopted a suspension system formed of four viscoelastic isolators with a lower cut frequency of 18 Hz and a minimum efficiency of 85 %.

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Figure 2 - Prototype of the Pistonphone

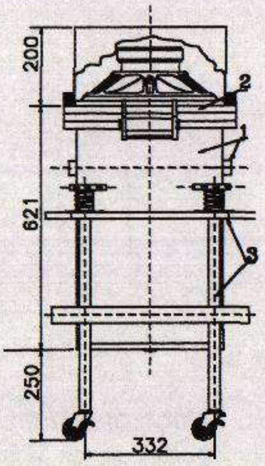

Figure 3 - External configuration

For the initial tests here presented, a water column of 335 mm was established and two cylindrical hydrophones type ITC 4046 were used. The sensitivity curves supplied by the hydrophones manufacturer denote that the transducers have the same plan response profile up to 6 kHz, despite a maximum amplitude difference of about 1 dB in some frequencies. Both hydrophones were mounted at a water depth of 183 mm and apart 100 mm and 90mm to each other and to the wall respectively. To investigate the acoustic behaviour of the calibration chamber, the hydrophones were used to obtain the frequency spectrum of the media and the loudspeaker driven by a white noise signal filtered from 10 Hz to 1010 Hz.

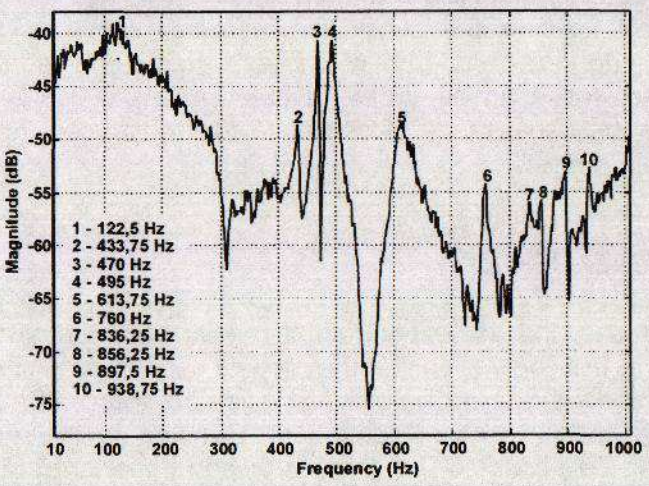

Figure 4 - Frequency spectrum of the Pistonphone (hydrophones at 183 mm depth).

In Figure 4 can be observed the occurrence of important frequency peaks in the acoustic chamber, mainly at frequencies higher than 433.75 Hz. Besides a peak at 122.5 Hz, close to the longitudinal resonance frequency of the air volume (127 Hz) as predicted by the Coupled Impedance model, also others experimental frequency values are in good concordance with the theoretical frequency values. These are related to the transversal resonance modes of the air volume and to the hull resonance modes. Furthermore, comparing the spectrum curve with the curve of coherence function of the two hydrophones output, see Figure 5, is verified that the occurrence of resonance modes in the media does not obligatorily disturb the calibration process.

Concerning the acoustic modes where for both hydrophones the pressure field on the sensitive faces is homogeneous, notice that the acoustic coherence is high and consequently is possible

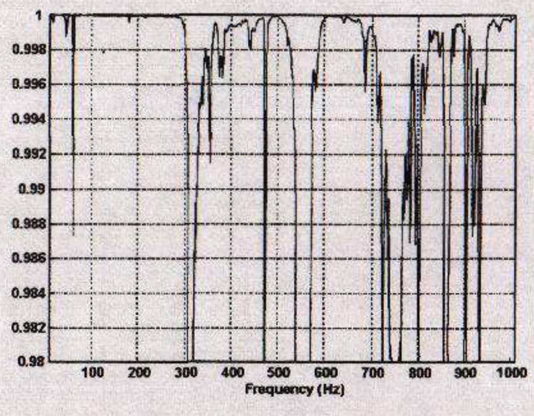

Figure 5 - Coherence function between ITC 4046 hydrophones (at 183 mm depth).

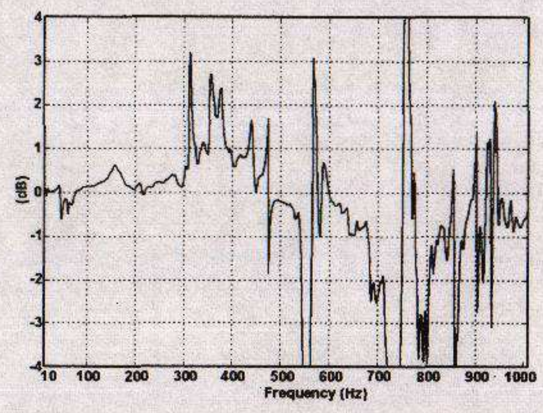

Figure 6 - Sensitivity curve of the hydrophone being calibrated related to the reference hydrophone (at 183 mm depth).

to define the frequency sub-bands for which the comparison calibration process is carried out with the desired accuracy. For the testing conditions, comparing Figure 5 with the Figure 6, where is showed the sensitivity curve of the hydrophone being calibrated in relation to the sensitivity curve of the reference hydrophone, can be verified that the calibration process has a major accuracy and provide suitable results in the frequency sub-bands with a difference of sensitivity lower than 1 dB, as follows: 10 Hz up to 300 Hz, 387-432 Hz, 455-472 Hz, 485-520 Hz, 600-670 Hz and from 985 to 1010 Hz.

At last, once the frequency sub-bands are regularly distributed from 10 Hz to 1 kHz, by using an interpolation technique, may be possible to define the sensitivity response curve of the hydrophone being tested over the entire pistonphone bandwidth. Moreover, when combined this curve with the sensitivity curves obtained, for example, from calibration tanks, could be determined the hydrophone response over the usual range of operation for transducers used individually or in arrays.

5. CONCLUSIONS

The good agreement between the calculations and the experimental results obtained to the pistonphone introduced in this paper, leads to the conclusion that the models used to predict the modal behaviour of the acoustic media and adopted to define the dimensions of the calibration chamber have the suitable accuracy to design this type of equipment. Concerning the techniques of signal processing adopted, should be observed that them provided important subsidies for a better understanding of the acoustic energy transference from the loudspeaker-air column set to the water column. It was proved that the resonant behaviour of the pistonphone hull was responsible by some noise patterns in the sensitivity curve of the hydrophone calibrated. Should be also noted that, despite the pistonphone has attended the operational requirements, other tests has being carried out to define more suitable measuring conditions and to make possible larger calibration ranges or an upper limit frequency higher than 1 kHz.

6. REFERENCES

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