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A laser pistonphone designed for absolute calibration of infrasound sensors from 10 mHz up to 20 Hz

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Abstract

There has been an increased demand for traceable calibrations at infrasonic frequencies in support of geophysical monitoring applications, an example being the Comprehensive nuclear Test Ban Treaty Organization, which provides a global international coverage for nuclear testing ban, and requires for the International Monitoring System. In this paper, a new laser pistonphone design is presented with the objective of establishing primary standards for sound pressure at very low frequencies down to 10 mHz. The piston is a modified accessorized loudspeaker driver whose diameter is equal to the diameter of the front pistonphone cavity. The volume velocity of the piston is measured through a laser interferometer and the current version was designed to have an upper frequency limit of 20 Hz, to overlap with the closed coupler reciprocity method of calibration. Particular attention has been given to the sealing to avoid the pressure leakage loss. The dimensions of the front cavity were designed to allow the calibration of a large variety of sensors, including microphones, barometers, manometers and microbarometers. Examples of calibrations for several sensors are presented and also an uncertainty budget for the Brüel & Kjær type 4160 laboratory standard microphones, commonly used for primary calibrations. Finally, the metrological performance of the laser pistonphone is demonstrated by comparing the calibration results with those obtained with alternative methods.

Keywords: Infrasound, Calibration, Laser pistonphone, Microphones, microbarometers, Barometers, Acoustics

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1. Introduction

Infrasound consists of acoustic waves where the frequency is less than 20 Hz, and typically inaudible to humans. The characteristic wavelengths of these signals reach 100s or even 1000s of kilometres if the source has sufficient energy. Recently, the demand for measurements at infrasound frequencies has emerged in connection with the monitoring volcanoes, tsunamis, avalanches, wind turbines or even for road transport [1–6]. Another key application is to cover the needs of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), a United Nations organization which provides global oversight for the ban on nuclear testing. To ensure compliance with the provisional treaty, CTBTO deploys different types of sensors within the global International Monitoring System (IMS), and continuously monitors key geophysical parameters including infrasound using microbarometers as infrasound sensors. To meet its needs, CTBTO requires specifications and tolerances for its network of infrasound sensors including their frequency response in the 0.02 Hz - 4 Hz band [7].

Driven by the need for control, compliance with tolerance, and confidence in the quality of measurement results, the metrological confirmation of sensors in laboratory and in-situ for infrasound measurement is an important issue, especially when sensors remain on site in highly variable environmental conditions, and the resulting data contributes to decision making of international importance. This quality control process is based on different principles and methods, including sensor calibration and the estimate of the associated measurement uncertainty. By comparing the sensor used to make practical measurements with a known reference sensor when both are exposed to the same stimulus, the response of the sensor under test is obtained. The reference sensor itself is calibrated against a realisation of the pertinent physical quantity, in this case the infrasonic sound pressure. The calibration response is then the difference between the infrasound pressure indicated by the device under test, and the applied known infrasound pressure. Uncertainty is the bounds within which the measured value is considered to lie within specified level of a statistical confidence interval centred around the calibration result.

In the field of airborne acoustics, the accepted means of realising primary measurement standard for acoustic pascal is via the calibration of so-called laboratory standard microphones using the reciprocity method described in the international standard IEC 61094-2:2009 [8]. This method is based on the use of closed couplers, and the National Metrology Institutes (NMI) have verified and published Calibration and Measurement Capabilities (CMCs) at frequencies up

to 25 kHz and down to 2 Hz [9]. While the reciprocity method is used to determine the sensitivity of laboratory standard microphones in an extended band of audible frequencies, the primary calibration for infrasonic frequencies below 2 Hz has in general not been widely studied, and does not feature at all in the CMC database maintained by BIPM (Bureau International des Poids et Mesures) [10]. CMCs are of course found for static pressures, which is realised through methods such as pressure balances [11], but although sound pressure and static pressure share the same units, they are in fact different quantities [12, 13]. Recognizing these challenges, the Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV) of BIPM highlighted in its latest strategic document for the period between 2021 and 2031 [14] the need to establish traceability to very low acoustic frequencies down to 0.02 Hz.

A pistonphone device where a calculable sound pressure is created in a notional sealed volume, by the sinusoidal movement of a piston with known displacement, can be used for the absolute calibration of microphones and other infrasound sensors [15]. These devices are sometimes referred to as laser pistonphones when laser interferometry is used to determine the displacement of the piston.

In this paper, a new laser pistonphone design is proposed with the objective of establishing primary standards for sound pressure at very low frequencies down to 10 mHz. To achieve this, a new membrane-sealing structure was developed to avoid the pressure leakage loss. The device was designed to have an upper frequency limit of 20 Hz, to overlap with the frequency range of reciprocity calibration. The device is intended as the basis for realising primary measurement standard at very low frequencies. Therefore, the metrological performance is discussed and the calibration results are compared to those obtained with alternative methods.

2. Overview of devices for calibration of infrasound sensors

Some devices for the calibration of acoustic sensors covering the infrasound frequency range are described in the literature. These include (a) the CS18 SPL-VLF calibration system developed by SPEKTRA covering the frequency range 0.1 Hz to 31.5 Hz [16] (b) the GRAS 42AE low-frequency calibrator covering the frequency range 0.01 Hz to 250 Hz [17] (c) the high pressure microphone calibrator type 4221 covering the frequency range 0.01 Hz to 95 Hz [18] (d) the CEA (Commissariat à l'Énergie Atomique et aux énergies alternatives) generator developed to meet the metrological requirements of the CTBTO

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IMS monitoring network and covering the frequency band of 10^{-4} Hz up to 100 Hz [19] (e) the generator of the University of Pennsylvania producing infrasound pressure in the frequency range from 0.001 Hz to 30 Hz and using two reference sensors, a microphone and a differential pressure sensor [20] (f) the pressure-generator system developed at the National Center for Physical Acoustics and Sandia National Laboratories also to meet the metrological requirements of the CTBTO IMS monitoring network, covering the frequency range 0.01 Hz to 10 Hz and based on a large volume of approximately 1.4 m^3 allowing the calibration of several sensors inserted inside this volume [21, 22] (g) and the low frequency calibrator developed at the National Measurement Institute in Australia working in the frequency range 0.1 Hz to 20 Hz [23]. All these devices are of interest for secondary calibration of infrasound sensors but are not by themselves sufficient to ensure the traceability to the SI for infrasound measurements as they all require a primary measurement standard calibrated through a primary reference procedure in the frequency range of interest.

The reciprocity method used for the calibration of laboratory standard microphones partially addresses this need as it has been studied intensively in recent years to extend the frequency range to the lowest frequencies. In particular, significant effort was carried out to clarify and improve the calculation of the acoustical transfer impedance of couplers and its correction for the effects of heat conduction at low frequencies [24, 25], leading to the publication of an amendment of the IEC standard 61094-2 [26]. Thus, pressure reciprocity calibration of laboratory standard microphones extending to 2 Hz is now the norm in many NMIs and further studies are in progress to extend the method to significantly lower frequencies [27]. However, some underlying drawbacks remains at frequencies below 2 Hz such as: (a) the control of unintentional pressure leakage in the coupler affecting the acoustic transfer impedance, (b) the analytical models of impedance of microphones where heat conduction in the cavity behind the diaphragm and the pressure-equalizing tube of the microphone contribute significantly to the acoustic impedance of the microphones at low frequencies which in turn has a strong influence on the acoustic transfer impedance, (c) the increasingly low signal-to-noise ratio with decreasing frequency, which greatly limits the practical implementation of reciprocity calibration.

Other studies were carried out in the recent years on alternative primary reference procedures to overcome the limitations inherent in reciprocity calibration. To the knowledge of the authors, all of them are based on the method of the calculable

pistonphone where the microphone to be calibrated is exposed to a calculable sound pressure produced within a closed volume of a pistonphone. The laser pistonphone is an example of a calculable pistonphone introduced by the National Physical Laboratory (NPL) in the 70s [28], improved in the 80s in an updated version [29] and used as the basis for some of NPL measurements down to 1 Hz in the international key comparison CCAUV.A-K2 [30, 31]. The main disadvantage of the NPL device is its lack of sealing, limiting the operating frequency range to approximately one-tenth of a Hertz. More recently a small number of other calculable pistonphones have been developed at institutes around the world. In 2004, the National Metrology Institute of Turkey (UME) developed a laser pistonphone with similar specifications to the NPL devices, with validated performance in the frequency range 20 Hz to 250 Hz [32]. The National Institute of Metrology of China NIM developed a laser pistonphone in the 2010s based on the same operating principle as the NPL pistonphone [33]. A laser interferometer measures the displacement of a piston in a cylindrical cavity. The diameter of this piston is 0.1 mm smaller than that of the cavity to which the sensors are coupled. The sealing is managed with this adjustment and without O-rings, therefore requiring corrections of leaks that appear at very low frequencies and limiting the operating range to approximately 1 Hz. The authors subsequently improved and characterized the device with a modification of the piston drive system and an analytical model for the leakage, which made it possible to operate at frequencies down to 0.001 Hz [34, 35]. In 2016, the authors demonstrated the performance of the device by providing calibration equivalences with the pressure reciprocity method for amplitude sensitivities at frequencies down to 1 Hz [36]. The Shandong University of Technology published the specifications of a device based on the low-speed servomotor and the pistonphone technique. Specifically, a membrane-sealing structure between the piston and chamber was developed so that the pressure leakage loss and friction are avoided. A tiny pinhole was machined on the chamber to allow for static pressure equilization, while maintaining a controlled leakage time constant of about 20 s. This device does not use laser interferometer. Instead, the estimation of the volume velocity of the piston is based on a theoretical modelling of the driving system. Three corrections are required for the sound pressure calculation (a) for the pressure leakage, (b) for the heat conduction and (c) for the wave motion effects, reaching a correction around 0.5 dB at 0.1 Hz. For this device, it should be noted that the metrological performance of the system was not validated in terms of equivalence with

other methods of calibration. For the last two devices described, it should be noted that the analytical treatment of the leakage remains a important source of uncertainty and the model considered by the authors for heat conduction corrections, based on Gerber's paper [37] has been strongly challenged recently [24, 25]. In 2020, the National Metrology Institute of Russian Federation (VNIIFTRI) improved their pistonphone 3202 developed in the 60s to cover the frequency range 0.001 Hz to 50 Hz [38] but it should be noted that this device remains poorly documented, particularly with regards to metrological performance and demonstration of equivalences with other methods of calibration. Finally, the Korea Research Institute of Standards and Science (KRISS) presented their laser pistonphone in a conference paper [39]. The device is similar to the NPL laser pistonphone and calibration equivalences have been demonstrated for modulus and phase at frequencies down to 2 Hz.

3. General principle of the laser pistonphone

A pistonphone is a device in which a sound pressure is generated in a fixed air volume by the motion of one or more pistons, creating a well-defined volume velocity. The laser pistonphone is a specific kind of calculable pistonphone where the volume velocity produced by the motion of the piston is derived from dynamic displacement measurements by laser interferometry, and the known frontal area, where almost an always rigid piston is assumed.

Then simply, the microphone to be calibrated is exposed to this known sound pressure and its output voltage measured (strictly, the open-circuit output voltage). The method is absolute in that no prior measurement with, or reference to another microphone is necessary. The dimensions of the closed volume are constrained to allow the assumption to be made that the sound pressure is uniformly distributed within. The pressure sensitivity M_p of the microphone is then determined directly from its open-circuit output voltage $U_{m,0}$ (in volt) and the applied sound pressure p_m (in pascal),

$$M_p = \frac{U_{m,0}}{p_m}. \quad (1)$$

Alternatively, a microphone system comprising of a microphone, a preamplifier and optionally an amplifier stage, may be calibrated by the same principle, except that the system output voltage replaces the open-circuit output voltage of the microphone in equation (1).

The generated sound pressure p_m that is applied to the diaphragm of the microphone is calculated from an evaluation of the acoustic transfer impedance

Z_T of the coupler and a measurement of the piston displacement δ_x .

The acoustic transfer impedance is the constant of proportionality between the sound pressure at the microphone diaphragm and the volume velocity driving the cavity. In the case of a sinusoidally driven rigid piston, the volume velocity is given by the product of the piston area S_p , the piston displacement and a factor $j\omega$ where ω is the angular frequency:

$$p_m = j\omega S_p \delta_x Z_T. \quad (2)$$

If the piston is not rigid, calculation of the volume velocity requires the surface integral of displacement to be determined, e.g. with scanning interferometry.

The acoustic transfer impedance can be calculated when the coupler has a simple geometry enabling its volume, V to be determined. When the characteristic coupler dimensions are significantly smaller than the acoustic wavelength, λ (typically when $\sqrt[3]{V} \ll \lambda$), then the sound pressure can be assumed to be uniformly distributed within the coupler [8]. Then, assuming adiabatic compression and expansion of the gas and that the coupler is perfectly sealed, the acoustic impedance of the coupler Z_c is $\kappa P_s / (j\omega V)$, where κ is the ratio of specific heats for air and P_s is the static pressure inside the coupler. Values for κ in humid air can be derived from equations given in IEC 61094-2:2009 - Annex F [8]. From the equivalent circuit in Figure (1), Z_T is then given by:

$$\frac{1}{Z_T} = \frac{1}{Z_p} + j\omega \frac{V}{\kappa P_s} + \frac{1}{Z_m}, \quad (3)$$

where Z_p and Z_m are the acoustic impedances of the piston and the microphone to be calibrated respectively. At frequencies of interest, the acoustic impedance Z_m of the microphone can be considered as a pure acoustic compliance $Z_m = \kappa P_s / (j\omega V_{e,m})$ where $V_{e,m}$ is the equivalent volume of the microphone as described in the standard IEC 61094-2:2009 - Annex E [8]. The acoustic impedance of the piston can be more complex to evaluate depending on its configuration. It should be noted also that at low frequencies (i.e. below 1 or 2 Hz, depending on the microphone) heat conduction in the cavity behind the diaphragm and the pressure-equalizing tube of the microphone contribute significantly to the acoustic impedance of the microphones and makes this quantity difficult to evaluate. Therefore, the volume of the coupler should be dimensioned sufficiently large so as to minimize the load losses in the piston and the coupled sensors and thus minimize these sources of uncertainties.

The evaluation of the impedance Z_T in equation (3) assumes adiabatic conditions in the coupler. However, in practice, the influence of heat conduction at the walls of the coupler causes increasing departure

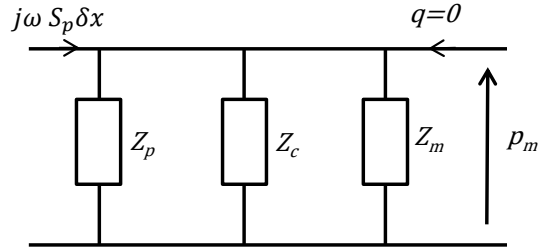


Figure 1. Equivalent circuit of the pistonphone for evaluating the sound pressure over the exposed surface of the diaphragm of the microphone.

from purely adiabatic conditions as the frequency is reduced, especially for small couplers. At frequencies where the sound pressure can be considered to be uniformly distributed within the coupler and under the assumption that the walls remain at a constant temperature, the influence of the heat conduction losses can be calculated and expressed in terms of a complex correction factor Δ_H to the geometrical volume V in equation (3) [8]. Significant efforts were carried out recently to clarify and improve the formulation of this correction [24,25], leading to the publication of an amendment of the IEC standard 61094-2 [26]. Based on these recent studies, the correction factor for heat conduction considered in this paper is given by:

$$\Delta_H = \kappa - (\kappa - 1)E_P, \quad (4)$$

where E_P is a complex quantity derived from the fundamental solution of the Fourier equation for heat conduction and which depends on the coupler geometry. For finite cylindrical couplers, the quantity E_P is given by

$$E_P = \sum_{m=0}^{+\infty} \sum_{n=1}^{+\infty} \frac{8/\pi^2}{(m+1/2)^2 \lambda_n^2} F_{m,n}, \quad (5)$$

with

$$F_{m,n} = \left(1 + \frac{\lambda_n^2 R^2 + (m+1/2)^2 \pi^2}{(1+2R)^2} X_P^2 \right)^{-1}, \quad (6)$$

and where $R = \ell_0/(2a)$ is the length to diameter ratio of the coupler; a is the radius of the coupler; λ_n are the roots of $J_0(\lambda_n) = 0$; $J_0()$ is the cylindrical Bessel function of the first kind, zero order; $X_P = A(1-j)/(V\sqrt{2})\sqrt{\alpha_t/\omega}$; A is the total area surface of the cavity and α_t is the thermal diffusivity of the enclosed gas.

4. Design concept

The laser pistonphone described in this paper was designed specifically for the calibration of a large variety of infrasound sensors including microphones, barometers, manometers and microbarometers widely disseminated in the world for atmospheric infrasound monitoring especially in the International Monitoring System (IMS).

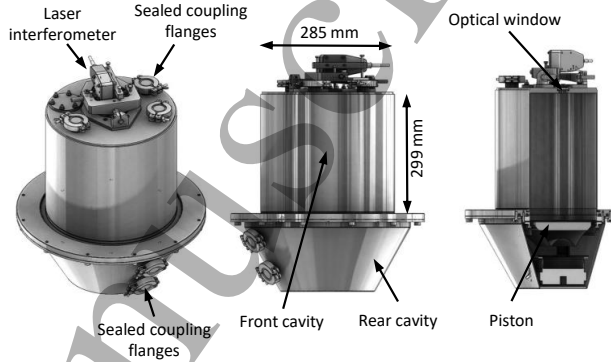


Figure 2. 3D digital view of the primary standard.

In order to conform as much as possible to the assumptions of the acoustic impedance model described previously, particular attention has been given to the cylindricity of the pistonphone cavity. The chosen nominal dimensions of the main cavity (front cavity) are: a diameter of 0.285 m in order to be aligned with the dimensions of the piston and a length of 0.298 m for a good compromise between volume, signal-to-noise ratio, and manufacturing cost. Figure (2) shows the views of the 3D digital model of laser pistonphone.

Equipment coupling systems (such as static or dynamic pressure sensors or temperature probes) are designed in such a way that the cavity remains as cylindrical as possible. The geometries of the mechanical parts are flush-mounted with the base of the cylinder of the front cavity. Figure (3) details the geometric plane on which the sensors are coupled via ports, as well as the alignment platform of the interferometer. Based on the experience acquired with the different versions of infrasound generators [19], the sealing or tightness of the cavity has been carefully studied. The solution selected for sealing the various entry ports is the use of vacuum flanges (ISO-KF25). A generic port for future sensors is reserved, with a diameter of 40 mm. Two solenoids are systematically coupled in order to automatically equalize the static pressure of the front and rear cavities. The three sensor ports allow the simultaneous connecting of up to three sensors, including a mixture of microphones, microbarometers, or static pressure sensors.

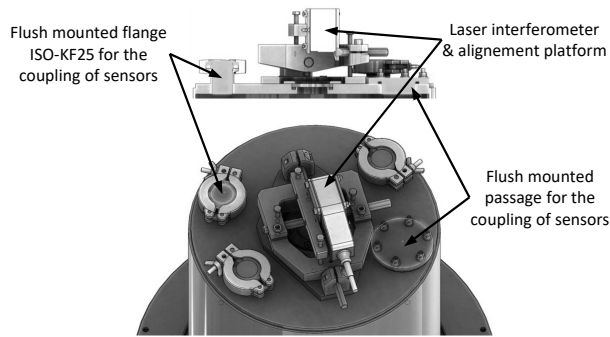


Figure 3. Base of the cavity of the laser pistonphone with flush mounted coupling systems.

The membrane displacement measuring system is a Renishaw RLE system composed of an RLU laser unit and a RLD10-3P detector head. The RLU laser unit contains the laser source and signal processing electronics providing the position feedback signals in either digital or analogue quadrature format. The RLD10-3P detector head is the core of the optical measuring system containing the interferometer, reference optics, fringe detector, laser shutter and beam steerer. To complete the interferometer configuration, a plane mirror is attached to the piston to allow the reflection of the laser beam of the interferometer. The peculiarity of this system is the use of a double beam that makes it possible to reduce the errors of lens aplanatism and doubles the spatial resolution. The adjustment system has been developed specifically for the calibration setup. Specifically, it must be insensitive to temperature variations, have four degrees of freedom, and be able to remain locked in a nominal operating position for indefinite periods of time. The main advantage of using an optical device to measure the displacement of the membrane is simplicity of traceability over the entire operating frequency range of the laser pistonphone. In fact, the reliability of the measurement depends mainly on the stability of the wavelength of the laser source and the geometric stability of the cavity. Whatever the frequency of the displacement field of the membrane, only this optical stability is involved in the interferometer's uncertainty. The calibration of the interferometer is traceable to the SI, the laser source has a wavelength of 632.9900 ± 10^{-4} nm.

The internal dimensions of the front cavity were measured as 284.9980 ± 0.1576 mm for the diameter and 299.0684 ± 0.1247 mm for the height with a ZEISS ACCURA II 3D-dimensional measuring machine. These dimensions ensure that the sound

pressure remains uniformly distributed within the cavity up to a frequency of 20 Hz where $\lambda > 60\sqrt[3]{V}$.

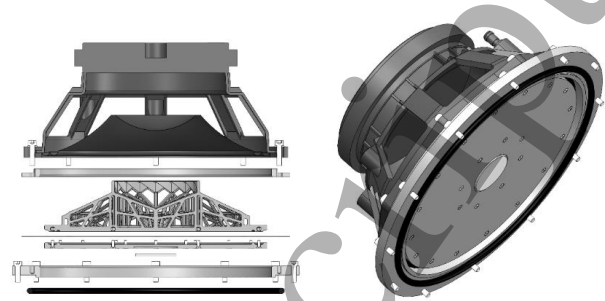


Figure 4. Details of the piston: an accessorized loudspeaker.

The piston is a specially modified PHL Audio Type 4061 loudspeaker where its 285 mm diameter matches the diameter of the front cavity. Figure (4) shows an exploded 3D view of the assembly. A structural mesh, 3D printed in a nylon material (PA12) by Selective Laser Sintering technique is glued to the dome of the loudspeaker to stiffen the structure and create a flat surface, onto which a 3 mm thick neoprene membrane is attached. This membrane is also clamped at the circumference by two metal rings that accordingly ensure sealing and maintain its state. The loudspeaker assembly is attached to the front cavity and an O-ring provides sealing between the two parts. A sealed hood covers the loudspeaker assembly forming the back cavity with a volume of approximately 10 litres. The stiff structure of the piston makes its acoustic impedance Z_p very high minimizing its effect in the total acoustic impedance Z_T as described in equation (3). The contribution of the acoustic impedance Z_p in the total acoustic impedance Z_T was measured in the frequency range 0.01 Hz - 0.1 Hz with the laser interferometer and a static pressure sensor SETRA Type 278, calibrated at DC and known to have a flat frequency response in the frequency range of interest (see Figure (7)). The acoustic impedance Z_p is then deduced from equations (2) and (3) once the sound pressure p_m is known in the coupler. Figure (5) presents the contribution $Z_p/(Z_p + Z_T)$ of the acoustic impedance Z_p in the total acoustic impedance Z_T in amplitude and phase as function of frequency, reaching to corrections of 0.1 dB for the amplitude and more significantly 3 degrees for the phase at 0.01 Hz. The acoustic impedance of this piston is expressed in the model in equation (3) as a complex impedance with a lumped parameter representation with an acoustic mass $m_a = 1.3 \cdot 10^8$ kg/m⁴, an acoustic compliance $c_a = 6.3 \cdot 10^{-8}$ m⁵/N and an acoustic resistance $r_a = 2.1 \cdot 10^9$ Ns/m⁵.

Figure (6) shows an illustration of the con-

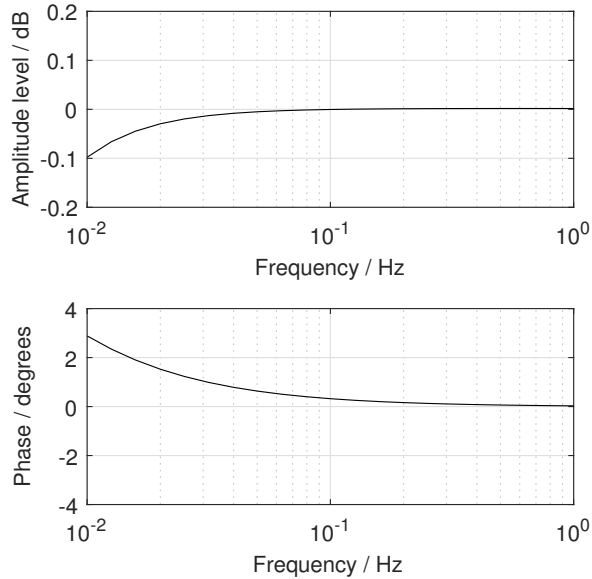


Figure 5. Contribution $Z_p/(Z_p + Z_T)$ in level of the amplitude (upper graph) and phase (lower graph) as function of the frequency of the acoustic impedance Z_p in the total acoustic impedance Z_T in level of the amplitude and phase as function of frequency.

trol/command device of the laser pistonphone. The generation of the signal that drives the loudspeaker (piston), as well as the digitization of the signals produced by the sensors and by the interferometer, are carried out by using a VTI Instruments CMX09 chassis with an EMX-1434 waveform generator and a 24-bit EMX-4350 digitizer. The pure sine signal thus generated is amplified by an AE TECHRON 7224 power amplifier whose frequency response goes to DC. This signal then drives the loudspeaker. An SMX-2002 relay board controls the two solenoid valves that are used to equalize the static pressure within the front and back cavities respectively, in case of significant changes in external static pressure during the setup of the system. Throughout the measurement sequence, the environment variables are monitored by using temperature, hygrometry, and static pressure probes. The laser pistonphone is placed on an active vibration isolation system Accurion I4 for isolating measurements from building vibrations and other disturbances. The apparatus is controlled with bespoke software developed alongside the equipment. The amplitude and phase of the sensor signals were computed with a sine fitting algorithm, as explained in [24], inspired by IEEE Standard 1057:2017 [40]. This algorithm provides a least squares method for fitting digitized waveform data to a sinewave in the case where the frequency of the sinewave is known.

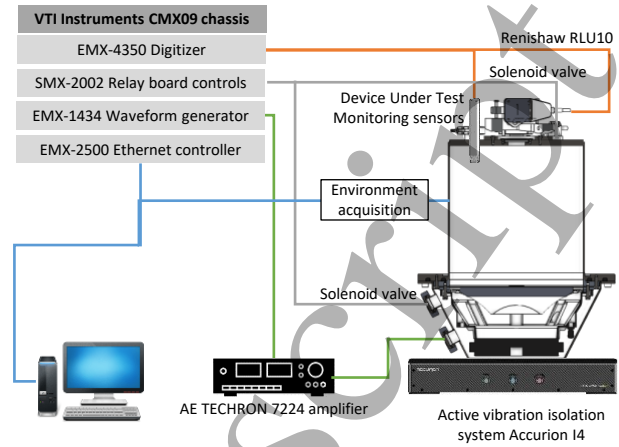


Figure 6. Synoptic diagram of the functioning of the calibration bench.

5. Experimental results and uncertainty analysis

The laser pistonphone was designed specifically for the calibration of a large variety of infrasound sensors including microphones, barometers, manometers and microbarometers. Figure (7) presents the pressure sensitivities as function of frequency in magnitude level and phase for some particular types of sensors that can be calibrated with the laser pistonphone. These include the Brüel & Kjær type 4160 and type 4180 laboratory standard microphones, respectively the one-inch and half-inch microphones commonly used for primary calibrations by the reciprocity technique, and the Brüel & Kjær type 4193 microphone which is designed specifically for low frequency applications. The working principle of these condenser microphone is based on a fixed charge. This charge is established with a very stable external polarisation voltage applied via a high-value resistor to prevent charge leakage, all placed within the preamplifier. It should be noted that the combination of the capacitance of microphone and the large resistance acts as a high pass filter, limiting the use of these microphones for infrasound applications. However, the lower cut-off frequency of this combination can be reduced by (a) using a suitably high resistance in the preamplifier (typically 15 G Ω for a Brüel & Kjær type 2669 preamplifier) and/or (b) using a special adaptor (e.g Brüel & Kjær type UC0211) in between the microphone and preamplifier that adds capacitance to the microphone. Note however, that using such an adaptor has the effect of reducing the microphone's sensitivity (by 16 dB for the Brüel and Kjær type UC0211), thus reducing its usefulness for applications which does not require the microphone to have a flat frequency response.

Microphones have also a small vent allowing

A laser pistonphone designed for absolute calibration of infrasound sensors from 10 mHz up to 20 Hz

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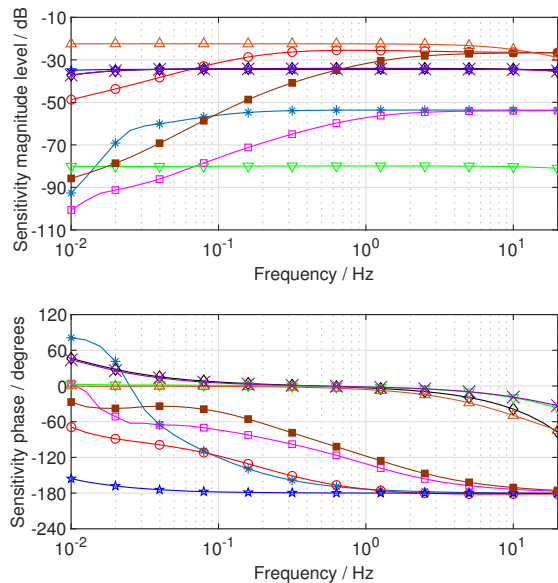


Figure 7. Pressure sensitivity magnitude level in dB ref. 1V/Pa (upper graph) and sensitivity phase in degrees (lower graph) as function of the frequency for a microphone B&K Type 4193 with a low frequency adaptor UC0211 and a preamplifier B&K Type 2669 (blue Asterisks); a microphone B&K Type 4160 (vent unexposed to the sound field) with a preamplifier B&K Type 2669 (red circles); a microphone B&K Type 4160 (vent exposed to the sound field) with a preamplifier B&K Type 2669 (brown solid squares); a microphone B&K Type 4180 (vent exposed to the sound field) with a low frequency adaptor UC0211 and a preamplifier B&K Type 2669 (pink squares); a microphone B&K Type 4147 with a conditioner B&K Type 2631 (blue stars); a microbarometer Martec Type MB2005 (black diamonds), a microbarometer Seismowave Type MB3 (violet crosses), a manometer MKS Baratron type 616A (orange Upward-pointing triangles) and a barometer SETRA type 278 (green downward-pointing triangles).

pressure equalisation between the front and back of the diaphragm which can affect the frequency response at lower frequencies. This may be a side vent, a rear vent, or intrinsic venting via a screw thread, depending on the model of microphone. The vent is essential, as static pressure changes otherwise create large and disturbing signals (over-loads of amplifiers) and might significantly displace the diaphragm from its intended position. At low frequencies, the frequency response of the microphone is strongly influenced by the pressure equalisation time constant and by the position of the external vent opening. When the vent is exposed to the sound field, this acts as a high pass filter causing the sensitivity to decrease below the cutoff frequency. In contrast, if the vent is isolated from the sound field, the response does not fall with decreasing frequency. For microphones having a rear vent, the laser pistonphone allows the microphone to be calibrated with the pressure equalisation vent exposed to or isolated from the sound field. The Brüel &

Kjær type 4160 is a rear-vented microphone, where the responses are found to be very different in the two cases. The microphone power supply used in the calibrations is a modified Brüel & Kjær type 2829 where the internal high pass filters is bypassed (short-circuited) giving an overall flat frequency response down to DC.

Although long out-of-production, the Brüel & Kjær type 4147 microphone with its special conditioning unit Brüel & Kjær type 2631 known as a Microphone Carrier System, is of specific interest for infrasound applications. This device works on the principle of the modulated radio frequency method introduced by Peter Baxandall in the 1960s instead the usual DC polarisation voltage [41]. The microphone capsule is used as the tuning capacitor in a radio frequency circuit with a high frequency signal (typically around 8 MHz). Changes in the capsule capacitance (caused by sound waves moving the diaphragm) modulates the tuning of the radio frequency oscillator in proportion to the incident sound pressure. A demodulation circuit then extracts the audio signal corresponding to the sound pressure. The advantage of the radio frequency mode design is that it can have a frequency response that extends to DC [41,42]. Unfortunately, the old age of the device available for experimentation resulted in a lack of stability. However, this technology remains of interest for infrasound applications, and will be investigated further.

Finally, the laser pistonphone allows the calibration of barometers or microbarometers suitable for infrasound measurements.

Example calibration results are presented in Figure (7) for (a) a range of working standard and laboratory standard microphone systems with different vent configurations, (b) the microphone carrier system, (c) a SETRA Type 278 barometer presenting a flat frequency response but a very low sensitivity requiring high sound pressures to be used in calibration, (d) a MKS Baratron Type 616A manometer with a high sensitivity and a flat frequency response below 1 Hz and (e) a Martec Type MB2005 and Seismowave MB3 microbarometers commonly used for infrasound monitoring of geophysical events and presenting a flat frequency response and a high sensitivity. However, it should be noted that the MB2005 and MB3 have significant volumes in comparison to the volume of the laser pistonphone, that is difficult to estimate leading to a high measurement uncertainty. Therefore an alternative comparison calibration method may result in a lower uncertainty for this type of device.

The calibration device examples presented in this paper is a non-exhaustive list. The substantial volume of the laser pistonphone provides some flexibility for the coupling of sensors, and the high level of infrasound

pressures that can be generated (up to 50 Pa) makes it possible to calibrate a variety of sensors with a range of sensitivities.

The principal objective of this device is to establish primary standards for sound pressure at frequencies as low as 10 mHz and to disseminate the traceability to the SI through the calibration of transfer standard sensors. For this purpose, the best measurement uncertainty is an important consideration and is obtained over a wide bandwidth with the Brüel & Kjær type 4160 microphone with vent isolated from the sound field. The measurement uncertainty in the pressure sensitivity when estimated in accordance with the ISO/IEC Guide 98-3, arises from seven main sources: (a) measurements of the sensor output voltage, (b) piston properties, (c) coupler properties, (d) imperfection of theory, (e) sensor parameters, (f) processing of results and (g) repeatability of measurements. The details of the standard uncertainty components are described below as an example for the calibration of a Brüel & Kjær type 4160 microphone.

a) Measurements of the sensor output

The sensor outputs are measured with a 24-bit EMX-4350 digitizer. Its stability and linearity has an associated uncertainty of systematic and random nature, including inherent and ambient noises and other type of interference such as cross-talk. Generally, measurements are undertaken with a sound pressure of 15 Pa (or sound pressure level of approximately 117 dB), providing a sufficient signal-to-noise ratio. The sum of the component uncertainties are estimated experimentally and by comparison with a calibrated voltmeter considering both DC and AC signals from 2 Hz up to 20 Hz. The standard uncertainties for these components are estimated lower than 0.01 dB for the amplitude and lower than 0.1 degree for the phase.

b) Piston properties

The piston generates an infrasound pressure at the frequency provided by the EMX-1434 waveform generator and at an amplitude that does not exceeding the linear operating range of the piston assembly, so that distortion remains negligible. The order of magnitude of the displacements of the piston is approximately 40 μm when working with acoustic pressures of 15 Pa, producing harmonic distortion do not exceeding 0.5 %. Therefore, the uncertainty component on the frequency comes essentially from the waveform generator. The diameter of the piston has been measured with an uncertainty of 0.2 mm and the uncertainty on the piston displacement measurement is less 0.02 % which remains non-significative in this application. The piston volume velocity is determined from the

displacement measured at a single point, assuming the piston to be rigid. Special attention has been given to stiffening the loudspeaker structure to support this assumption. This also ensures that the acoustic impedance of the piston is significantly higher than that of the pistonphone cavity to minimize its contribution to the total acoustic impedance of the coupler, but some residual contribution remains especially at lower frequencies. The combination of these standard uncertainties is estimated to be less than 0.015 dB at 0.01 Hz and 0.01 dB at 20 Hz for the amplitude, and less than 0.4 degree at 0.01 Hz and 0.06 degree at 20 Hz for the phase.

c) Coupler properties

Uncertainties on the coupler dimensions affects the acoustic impedance of the coupler. The dimensions also influence the heat conduction process. The volume of the cavity has been determined from traceable measurements of the height and diameter at a number of positions within the cavity with uncertainties lower than 0.05 mm. The tolerances on the shape of the cylinder cavity were measured at 0.16 mm for the diameter and 0.13 mm for the height. The coupler was designed to be sealed and no venting tube is used in this device. The unintentional leakage was characterised by monitoring the stability of static over-pressure and is assumed to be negligible. Uncertainties on environmental parameters also affect the calculation of the acoustic impedance of the coupler. These uncertainty components were determined from the uncertainties of traceable sensors measuring environmental parameters. The combination of these standard uncertainties is estimated lower than 0.01 dB for the amplitude and lower than 0.12 degree for the phase.

d) Test device parameters

The acoustic impedance of the device under test forms a part of the total acoustic impedance of the coupler. To a first approximation, the acoustic impedance of the sensor can be expressed in terms of the equivalent series-connected acoustic compliance, acoustic mass and acoustic resistance, and is a function of frequency. Acoustic impedance is often expressed as a complex equivalent volume, and it is generally sufficient for this application to consider only the low-frequency value of the real part of the equivalent volume. For some sensors, additional coupled volumes also need accounting for. This might include the front cavity of a microphone or a coupling tube fitted to the sensor. However, in almost all cases, these added volumes are negligible compared to the large volume of the

A laser pistonphone designed for absolute calibration of infrasound sensors from 10 mHz up to 20 Hz 10

Frequency (Hz)	0.010	0.016	0.032	0.063	0.126	0.251	0.50	1.00	2.00	3.98	7.9	15.8	20.0
Componentes of type B uncertainties in dB×1000													
Measurements of sensor output	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Piston properties	14.4	9.7	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
Coupler properties	7.1	7.1	7.2	7.2	7.2	7.2	7.3	7.3	7.3	7.5	8.3	10.8	12.3
DUT parameters	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Imperfection of theory	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Processing of results	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Componentes of type A uncertainties in dB×1000													
Repeatability of measurements	75.4	58.2	40.0	27.9	20.0	14.7	11.2	8.9	7.4	6.4	5.8	5.3	5.2
Expanded uncertainties in dB ($k = 2$)	0.16	0.12	0.09	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.04

Table 1. Uncertainty budget for the pressure sensitivity magnitude level of type LS1 microphones determined by the LNE laser pistonphone.

Frequency (Hz)	0.010	0.016	0.032	0.063	0.126	0.251	0.50	1.00	2.00	3.98	7.9	15.8	20.0
Componentes of type B uncertainties in degree×100													
Measurements of sensor output	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7	7.7
Piston properties	40.8	17.1	7.0	5.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Coupler properties	0.1	0.1	0.1	0.1	0.1	0.2	0.3	0.6	1.2	2.3	4.6	9.2	11.5
DUT parameters	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Imperfection of theory	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.4	3.7
Processing of results	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	3.0	3.0	3.0	3.0
Componentes of type A uncertainties in degree×100													
Repeatability of measurements	93.9	60.9	32.8	18.6	11.6	8.0	6.3	5.4	4.9	4.7	4.6	4.5	4.5
Expanded uncertainties in degree ($k = 2$)	2.06	1.28	0.70	0.43	0.32	0.27	0.25	0.24	0.24	0.24	0.25	0.30	0.33

Table 2. Uncertainty budget for the pressure sensitivity phase of type LS1 microphones determined by the LNE laser pistonphone.

cavity. The exception is microbarometers, where the internal volume of the sensor is significant. When calibrating microphones, the uncertainty in the polarisation voltage is also a parameter to be considered. For almost all sensors that might be calibrated, the combination of these uncertainties is estimated lower than 0.005 dB for the amplitude and lower than 0.02 degree for the phase.

e) Imperfection of theory

The dimensions of the coupler cavity were chosen to be sufficiently small that the uncertainty component associated with the assumption on the uniformity of the sound pressure within the cavity does not exceed 0.01 dB and 0.1 degree at frequencies below 20 Hz. The model for heat conduction is based on that given by [24] and is assumed to be valid within 0.005 dB for the amplitude and 0.05 degree for the phase in the frequency range of interest.

f) Processing of results

The calibration results are provided at the actual environmental conditions as the temperature, pressure and humidity coefficients of the typical sensors considered in this application are currently unknown in the full frequency range of interest. The laser pistonphone is operated in a temperature-controlled environment that maintains the reference ambient temperature of $23 \pm 1^\circ\text{C}$. However, measurements are conducted at the prevailing atmospheric pressure. The atmospheric pressure is maintained during the measurement cycle for each frequency by closing the solenoid valve of the cavity but repeatability measurements are performed at different time where

the atmospheric pressure can differ within a maximum variations fixed at 15 hPa. Thus the results are provided at the averaged environmental conditions. The sensors are considered to have no significant dependence on humidity. Taking into account the rounding errors on the calibration results, the combination of these standard uncertainties is estimated to be less than 0.003 dB for the amplitude and less than 0.03 degree for the phase.

g) Repeatability of measurements

The uncertainty due to repeatability is based on typical levels of sample standard deviations. The measurements are repeated at least five times. The standard deviation of a specific set of measurements is required to be below that allowed for in the uncertainty budget, otherwise the uncertainty is increased. The uncertainty due to repeatability depends strongly on the frequency and the type of sensor to be calibrated. It should be noted that for the specific case of microphones with the vent outside of the sound field, the vent is then exposed to ambient noise, outside the coupler. Despite the use of the sine fitting algorithm [24], some uncertainty contribution from ambient noise remains at the lowest frequencies. These uncertainties are between 0.08 dB at 0.01 Hz and 0.005 dB at 20 Hz for the amplitude and between 1 degree at 0.01 Hz and 0.05 degree at 20 Hz for the phase.

Table (1) and Table (2) give a quantitative summary of the considered uncertainty components and the estimate expanded measurement uncertainty in the determination of the pressure sensitivity for a

Brüel & Kjær type 4160 with the vent isolated from the sound field. Table (1) is for the amplitude and Table (2) for the phase. The overall uncertainty is estimated between 0.16 dB at 0.01 Hz and 0.03 dB at medium frequencies for the amplitude and between 2 degree at 0.01 Hz and 0.24 degree at medium frequencies.

6. Validation

Any calibration method must be shown to be fit for purpose so that confidence is established in the results it produces. For this reasons, method validation and verification are essential requirements for metrology applications and are especially required for ISO/IEC 17025 accreditation. Primary calibration methods are especially difficult to validate, where intercomparison with peer laboratories is the established practice. However, when unique capability is being established for the first time, even this approach is not possible. Fortunately, in the case of low-frequency acoustic calibration, alternative absolute calibration methods have been conceived and implemented, including reciprocity calibration. The technique considered in this paper for the validation of the newly developed calibration capability, is a comparison with other available calibration methods, with the objective of demonstrating equivalences between these calibration results.

However, there is no alternative validated method covering the full frequency range of interest, i.e. 10 mHz to 20 Hz. Thus, two alternative and well-established methods are considered for this validation: (a) reciprocity calibration which is the method currently used worldwide for the primary pressure calibration of laboratory standard microphones and which is described in the international standard IEC 61094-2 [8, 26], and (b) the use of a differential capacitance manometer calibrated in static pressure (DC) against a primary static pressure reference standard. For this comparison, the frequency response of the differential capacitance manometer is assumed to be flat up to a few hertz and its sensitivity phase is expected to converge to 0 degrees at DC.

The amplitude and phase results from these validation measurements are presented in Figure (8). Good agreements can be observed between the calibrations obtained with the laser pistonphone (blue points and black crosses and error bars) and the reference calibration data (the shaded areas representing the reference calibration result and the expanded measurement uncertainties for a coverage factor $k = 2$). Deviations in the phase sensitivity of the Brüel & Kjær type 4160 microphone, are seen to increase with decreasing frequency

down to the 2 Hz lower limit of the reciprocity calibrations. This deviation could be explained by the inherent limitations in reciprocity calibration at low frequencies. In reciprocity calibration the phase sensitivity is especially sensitive to unintentional leakage which occurs when using usual couplers, and to the formulation of the acoustic impedance of the microphones where account for heat conduction losses and the influence of the vent from the back cavity of the microphones is needed. The increase in the pressure sensitivity magnitude level and the lag in the sensitivity phase are typically the effect of heat conduction in the back cavity of the microphone. It should be noted that the order of magnitudes of these effects measured with the laser pistonphone are in good agreement with those expected by Rasmussen by simulation in the report [43] using a lumped parameter model of the microphone.

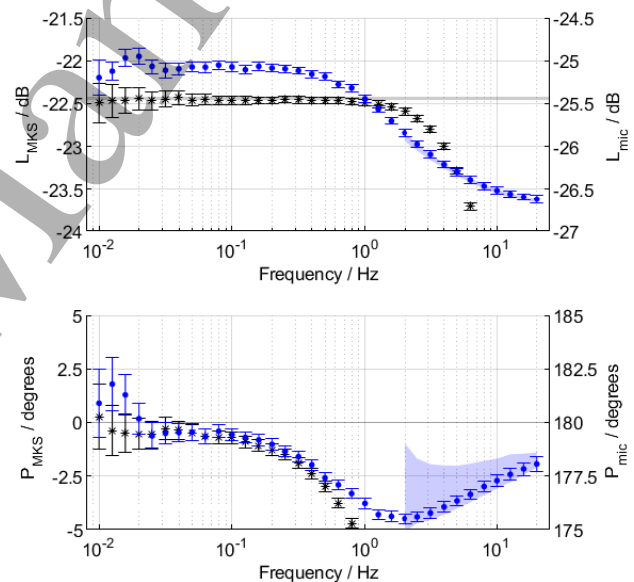


Figure 8. (a) open circuit pressure sensitivity (blue points) and expanded measurement uncertainties ($k = 2$) (blue error bars) for magnitude level in dB ref 1V/Pa (upper graph) and phase in degrees (lower graph) for a B&K type 4160 microphone calibrated with the laser pistonphone in the frequency range 10 mHz to 20 Hz. The blue shaded area represents the reference open circuit pressure sensitivity \pm the expanded measurement uncertainties ($k = 2$) calibrated by the reciprocity technique in the frequency range 2 Hz to 20 Hz. These data refer to the right axis scale. (b) pressure sensitivity (black crosses) and expanded measurement uncertainties ($k = 2$) (black error bars) for magnitude level in dB ref. 1V/Pa (upper graph) and phase in degrees (lower graph) for a differential capacitance manometer MKS Baratron Type 616A calibrated with the laser pistonphone in the frequency range 10 mHz to 20 Hz. For the magnitude level, the black shaded area represents the reference pressure sensitivity \pm the expanded measurement uncertainties ($k = 2$) calibrated at DC against a primary static pressure reference standard. These data refer to the left axis scale.

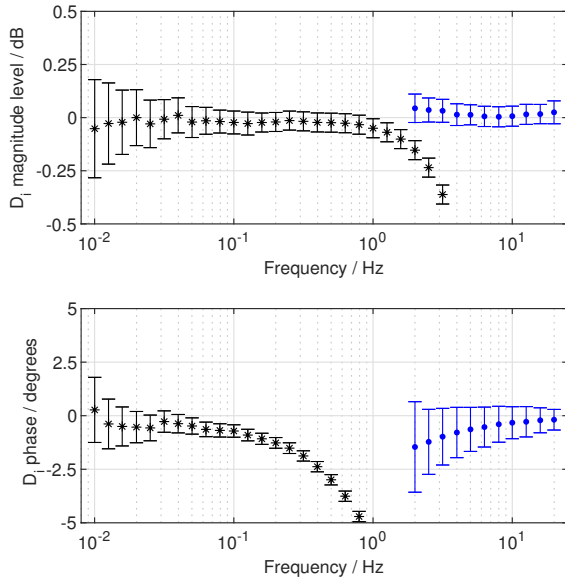


Figure 9. Degrees of equivalence for pressure sensitivity magnitude level (upper graph) and phase (lower graph) with uncertainty bars corresponding to coverage factor $k = 2$. The black cross data refer to the differential capacitance manometer MKS Baratron Type 616A and the blue point data refer to the microphone B&K Type 4160.

The equivalence of these calibrations are presented more explicitly in Figure (9) showing the Degrees of Equivalence D_i (DoE), defined as the difference between the calibration result M_p and the reference value M_{ref} and the associated uncertainty $U(D_i)$, defined as the combined uncertainties of the reference value $U(M_{ref})$ and the calibration result $U(M_p)$ (assuming that the uncertainty terms associated with the calibration result and the reference value are uncorrelated). Equivalences between calibrations are demonstrated when the combination of the degree of equivalence with its associated uncertainty overlaps the reference value, i.e. $D_i = 0$. Thus, a successful performance is demonstrated for the comparison with the Brüel & Kjær type 4160 microphone both in amplitude and phase in the full frequency range covered by the reciprocity technique, i.e. 2 Hz – 20 Hz. For the differential capacitance manometer, the successful performance is demonstrated at the lowest frequencies where its frequency response is assumed to be flat and where its sensitivity at static pressure can be considered as the reference value, i.e. up to 0.79 Hz in amplitude and 0.04 Hz in phase. Outside of these frequency ranges, there remains some intermediate frequencies where equivalences cannot be demonstrated due to an absence of reliable reference calibrations. Indeed, this is the fundamental rationale for undertaking the development of the laser

pistonphone device. Nevertheless, demonstration of equivalence in the regions where this is possible, establishes confidence overall in the calibration results produced by the laser pistonphone.

7. Conclusion

The objective of this paper is to present a new laser pistonphone design for establishing primary standards for sound pressure at very low frequencies down to 10 mHz. A pistonphone is a device in which a sound pressure is generated in a cavity with a fixed air volume by the motion of a piston, creating a well-defined volume velocity. The generated sound pressure is calculated from an evaluation of the acoustic impedance of the cavity and a measurement of the volume velocity. The recent progresses achieved in the modelling of acoustic impedance of cylindrical cavities [24, 26] made it possible to consider this development with a better confidence in both the method and the theory at frequencies where heat conduction losses are significant.

Calibrations of a large variety of infrasound sensors were carried out. These included microphones, barometers, manometers and microbarometers. Infrasound pressures of up to 50 Pa can be produced in the pistonphone, which provided adequate signal-to-noise performance, even for sensors with low sensitivities. This is reflected in the sensor-dependent measurement uncertainties that could be achieved, which for the best-performing sensors is 0.03 dB in amplitude and 0.24 degree in phase. These uncertainties are obtained at medium to high frequencies and rise up to 0.16 dB for the amplitude and 2 degrees for the phase at 10 mHz.

Performance validation of the laser pistonphone as a calibration device required special attention, in order to establish confidence in the results produced. The approach taken was to assess equivalence with an independent validated method. In fact, two methods were considered, as no single validated method exists covering the operating frequency range of 10 mHz to 20 Hz. These alternative methods were the reciprocity method at frequencies 2 Hz – 20 Hz, and the use of a differential capacitance manometer calibrated at static pressure (DC) against a primary static pressure reference standard, where this reference sensitivity is extrapolated to almost 1 Hz. These equivalences were demonstrated in amplitude and phase at the lowest and higher frequencies where the reference sensitivity data are considered as valid. There remained some intermediate frequencies where equivalences cannot be demonstrated due to the limitations of the reference calibration techniques, but the performance at the extremities of the frequency range is good

justification for accepting the performance across the full operational frequency range, at least until further alternative methods are available to cover the intermediate frequencies.

The laser pistonphone therefore provides a new calibration capability to establish traceability for infrasound pressure and enable it to be disseminated for measurements at very low frequencies. Many immediate applications for this primary calibration capability are emerging, in particular to support the operation of global networks for environmental monitoring and research in areas such as climate change and non-proliferation of nuclear weapons. Based on this work, LNE is now able to provide low-frequency calibration of infrasound sensors to users.

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