Proceedings of Meetings on Acoustics

Volume 18, 2012 http://acousticalsociety.org/

164th Meeting of the Acoustical Society of America

Kansas City, Missouri

22 - 26 October 2012

Session 3aEA: Engineering Acoustics

3aEA4. Wide band pressure and velocity (p-v) tympanometry with calibrated sound intensity micro-probes

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Wide band p-v tympanometry can be defined as the measurement of the acoustic immittance of the ear, possibly in normal air pressure condition of the ear canal, and in the full audio frequency range. The most important innovation pioneered by the p-v tympanometry regards the introduction of a different principle of measurement based on the direct acquisition of, both, pressure and velocity (p-v) signals at the ear canal entrance. The measurement can be done by using a pre-calibrated couple of dedicated micro-sensors: an ordinary microphone and an acoustic velocimetric micro-device. This paper will report about wide band measurements of ear immittance functions in the range [100, 1200] Hz, carried out by means of a modified tympanometric probe hosting a pre-calibrated sound intensity micro-probe, and their comparison, with data obtained by standard 226 Hz tympanometry.

Published by the Acoustical Society of America through the American Institute of Physics

Received 31 Oct 2012; published 2 Jan 2013

A. Introduction

Tympanometry is a technique which has been used in clinical audiometry since 1970s and is able, in battery with other tests, to detect possible pathologies of the middle ear and the tympanic membrane, by measuring the acoustic admittance of the ear canal [1,2]. This objective test may obtain serious benefits if pressure-velocity (p-v) microprobes, nowadays available thanks to the Micro Electro-Mechanical Systems (MEMS) technology, are used.

In a standard tympanometric test, collected data are presented as single-frequency tympanograms, showing the acoustic admittance as a function of the variation of static pressure in the external ear, induced by sealing and pumping the air volume inside the ear canal. The usual range of such a static pressure variation is $P=\left[-600,+400\right]$ daPa relative to the atmospheric pressure ($P=0$), while the stimulus is kept at a fixed 226 Hz frequency (single-tone tympanometry); the admittance magnitude corresponding to each P value is indirectly measured through a tympanometric probe, which has been previously calibrated over a 2 cc rigid cavity filled with air in standard pressure conditions. The traditional tympanometric test may be completed with other single-frequencies stimuli at 678, 800 and 1000 Hz (multi-tone tympanometry) albeit these “high frequency” tympanograms are yet to be fully interpreted for diagnostic purpose. It is worth to point out that at present, tympanometric signals are obtained only with a pressure microphone, so no direct measurement of the immittance function of the ear is accomplished: this process would require, in fact, the acquisition of the concatenated air particle velocity signal in addition to the acoustic pressure one.

The possibility of using well calibrated p-v sound intensity microprobes [3] has been recently demonstrated by two of the authors of the present paper [5], in connection with recent developments of wide band excitation tympanometry and the concept of Energy Absorbance (EA) [4]. The p-v approach to audiometric measures is possible thanks to the development of MEMS sensors, whose size makes them optimal to be used in such particular applications; it can be safely stated that this approach is the key to discover an entire new horizon to energetic audiometry.

After a brief summary of the ideal p-v model of the acoustic field in the ear canal and a short description of the standard tympanometry setup, a sample measurement of the EA performed with a p-v micro-probe at the “free” entrance of a normal ear canal is reported in Section B. The description of a prototype of a p-v tympanometric probe and its calibration procedure is reported in Section C, while section D accounts for the data comparison of standard and p-v tympanometry at 226 Hz. Finally some conclusions are drawn.

B. Ideal model of p-v fields inside the ear canal, aural immittance and energy absorbance

Fortunately enough, a big simplification in the nature of the acoustic field arises when the sound energy current enters the ear canal. In fact, the anatomical conformation of the human external ear is such that the air particle velocity $\mathbf{v}\left(x,y,z,t\right)$ can be safely considered as dependent on just one direction, because the ear canal is considered to flow ideally only along the longitudinal coordinate x i.e. $\mathbf{v}=\mathbf{v}\left(x,t\right)$. Moreover, from the experimental point of view, vector $\mathbf{v}$ can be considered as 1-D, which means that only 2 signals $\left\{p,v_x\right\}$, instead of 4 $\left\{p,v_x,v_y,v_z\right\}$, have to be measured by a p-v sound intensity probe, in order to perform aural immittance measurements.

From the theoretical point of view, the two scalar fields of acoustic pressure $p\left(x,t\right)$ and the *x*-component of air particle velocity $v\left(x,t\right)$ can be modeled starting from the velocity potential $\phi\left(x,t\right)$ of a general plane wave field and by time and space derivation. In formulas this reads:

$$\phi\left(x,t\right)=ac[e^{i(kx-\omega t)}+Re^{i(kx+\omega t+\vartheta)}] \tag{1}$$

$$p\left(x,t\right)=-\rho_0\Re\left(\phi_t\right)=\Re\left\{i\omega a z_0[e^{i(kx-\omega t)}-Re^{i(kx+\omega t+\vartheta)}]\right\} \tag{2}$$

$$v\left(x,t\right)=\Re\left(\phi_x\right)=\Re\left\{i\omega a[e^{i(kx-\omega t)}+Re^{i(kx+\omega t+\vartheta)}]\right\} \tag{3}$$

where a is the air particle displacement, c the sound velocity, ρ_0 the density of air when no sound is present, $z_0 = \rho_0 c$ the air characteristic impedance, ω and k the circular frequency and wave number respectively, R and ϑ the amplitude and (absolute) phase of the reflected wave with respect to the incident one. From (2) and (3) the frequency dependent specific acoustic immitance of sound inside the ear canal can be straight obtained via the Fourier transformation F as

$$Y(x,\omega) := \frac{F(v)}{F(p)} = G(\omega) + iB(\omega) = |Y(\omega)| e^{i\Delta\phi(\omega)} \tag{4}$$

where $|Y|$ is the magnitude of the admittance depending on both the acoustic conductance G and susceptance B, and $\Delta\phi$ is the phase lag of the pressure signal with respect to the velocity one for each frequency component ω.

A further simplification is obtained considering that aural immitance measurements are usually performed with a tympanometric probe which is sealed to the ear canal through a rubber tip (see Figure 1). In this standard setup, the measurement point x is located in a position inside the body of the probe and so, in order to measure the effect on the impedance measured at x due to the acoustic load "external" to the probe (i.e. the sound field inside the ear canal "after" the rubber tip), the probe itself needs to be calibrated. This is usually done at 226 Hz over a standard rigid cavity of 2 cc, sometimes involving more than one volume so that a better accuracy is achieved.

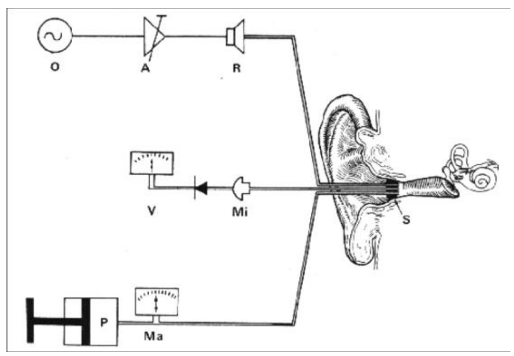

Figure 1. Scheme of a standard tympanometric probe. One can see the pressure gauge (Ma) and the pump (P) that change the static pressure inside the sealed ear canal during the tympanometric test. The 226 Hz stimulus is generated by a miniature speaker (R) and its response is recorded by the pressure microphone (Mi).

Recent advancements in wideband absorbance tympanometry [4], while extending the experimental model based on equation (4) in the frequency range [226, 8000] Hz, also introduce the concept of Energy Absorbance (EA) in audiometry [Ref. 4, footnote 2, p. 3718] on the basis of the transmission lines analogy. This point of view has been fully developed in [5] where the rigorous expression of the *energy current immittance* has been given as

$$\bar{\sigma} = \eta + i\mu \tag{5}$$

and the relationship between the *energy conductance* η (i.e. the real part of $\bar{\sigma}$) and the Energy Absorbance (EA) has been made explicit as:

$$EA = 1 - \frac{1-\eta}{1+\eta}. \tag{6}$$

The important thing to appreciate here is that all equations (4), (5) and (6) define directly measurable quantities, once a p-v calibrated probe is made available to the observer. In particular, *EA* in Eq. (6), can be calculated for any band center frequency f_k from the ratio of active intensity I to the mean energy density W normalized to the sound speed. Starting from expressions (2) and (3), it can be shown in fact that:

$$I = \frac{1}{2} z_0 (a\omega)^2 (1 - R^2); \quad W = \frac{1}{2} \rho_0 (a\omega)^2 (1 + R^2); \quad \eta \equiv \frac{I}{cW} = \frac{1-R^2}{1+R^2} \tag{7}$$

Detailed calculations leading to the above results can be found in Ref. [5], pp. 276-279, where also the signal processing procedure able to attain the frequency distribution of the time-averaged energy conductance η is fully accounted ([5], p. 273). Like an example, figure 2 is here re-edited from [5] just to show the oversimplified measurement setup used for obtaining the EA results reported in figure 3, which shows the frequency distribution of EA calculated for $1/12$ octave bands (left scale), as well as its overall value for a normal ear (right scale).

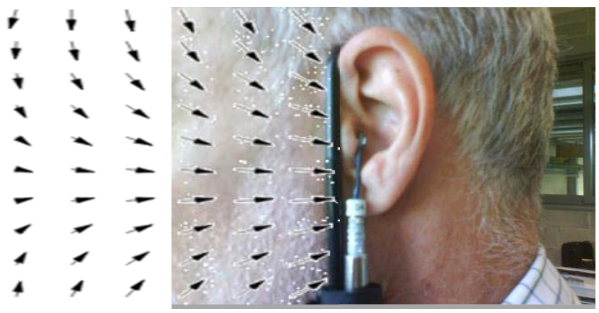

Figure 2. From [5]: the simplistic setup used for measuring the EA of a normal ear with a commercial p-v micro-probe. The sound energy current of the stimulus (log sweep) is qualitatively represented by arrows entering the ear.

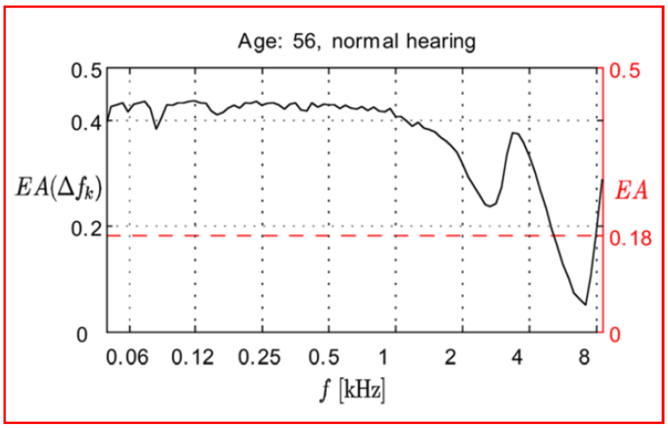

Figure 3. From [5]: the 1/12 octave band frequency distribution of EA in Eq. (6) is graphically rendered by the black continuous line read on the left scale. The 18% overall value of EA is reported on the right scale by the dotted line.

C. A prototype probe for p-v tympanometry and its calibration

Results of figure 3 were obtained with a commercially available sound intensity micro-probe which was previously calibrated using a progressive plane wave (PPW) reference field as completely accounted in [3]. The calibration procedure is summarized below for completeness.

The PPW calibration setup is illustrated in figure 4. A bi-conical loudspeaker a) is used for generating wide band [20 Hz - 12 kHz] frequency sweeps travelling as a progressive plane wave along the anechoic guide b) to the measurement point c) 12.5 m apart. The correction curve $\Gamma(\omega) \in \mathbb{C}$ is calculated as

$$\Gamma(\omega) = \frac{Y^0}{Y_{meas}(\omega)} = \frac{P_m^0(\omega)}{\rho_0 c V_m^0(\omega)} \in \mathbb{C}; \quad Y^0 = \frac{1}{\rho_0 c} \in \mathbb{R} \tag{8}$$

where Y^0 is the theoretical admittance of the reference field and $Y_{meas} = V_m^0 / P_m^0$ is the admittance measured with the uncalibrated p-v probe. As detailed in [3], once $\Gamma(\omega) \in \mathbb{C}$ has been obtained in the reference field from Eq. (8), it must be applied to the acoustic specific admittance measured in whatsoever field conditions with the same (uncalibrated) p-v probe to obtain the corrected (calibrated) admittance

$$Y_{cal}(\omega) = \Gamma(\omega) Y_{uncal}(\omega). \tag{9}$$

Any p-v measurement process $\{P(\omega), V(\omega)\}$ is then finalized by applying the calibrated admittance $Y_{cal}(\omega)$ to the pressure spectral density $P(\omega) = F(p)$ to get the spectral density $V(\omega)$ of the concatenated velocity calibrated both in modulus and phase, i.e.

$$V(\omega) = Y_{cal}(\omega) P(\omega) \quad \in \mathbb{C}; \qquad v(x,t) = F^{-1}(V) \quad \in \mathbb{R}. \tag{10}$$

Clearly, the above described procedure implements a comparison calibration methodology, and therefore results are affected, in principle, at least by the same systematic error typical of the pressure sensor assembled in the p-v micro-probe. In fact, the reference signal $p(x,t)$ picked up with the p-v probe is only checked for sensitivity against a reference B&K microphone at 1000 Hz.

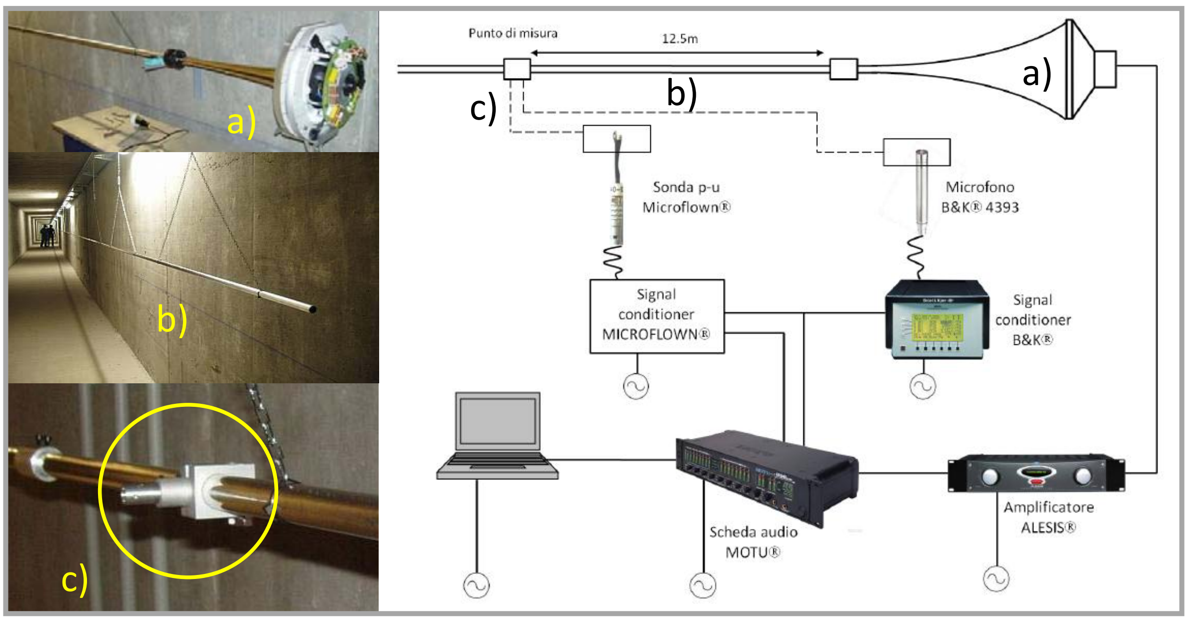

Figure 4. The reference field for calibration is generated in the form of a plane progressive wave travelling along the 48 m long, thermostatic and anechoic guide installed in the Larix Lab of Ferrara University b). A bi-conical loudspeaker a) allows the calibration to be performed, with a single measurement session, both at low and high frequency in the range [20, 10000] Hz. Both the transfer function of the pressure and velocity sensors under test are measured at the calibration point c) 12.5 m apart from the source in order to calculate $\Gamma(\omega)$ from equation (8).

Typical calibration results which can be obtained using the PPW calibration method described above are represented as magnitude and phase of the correction curve $\Gamma(\omega)$ in figure 5.

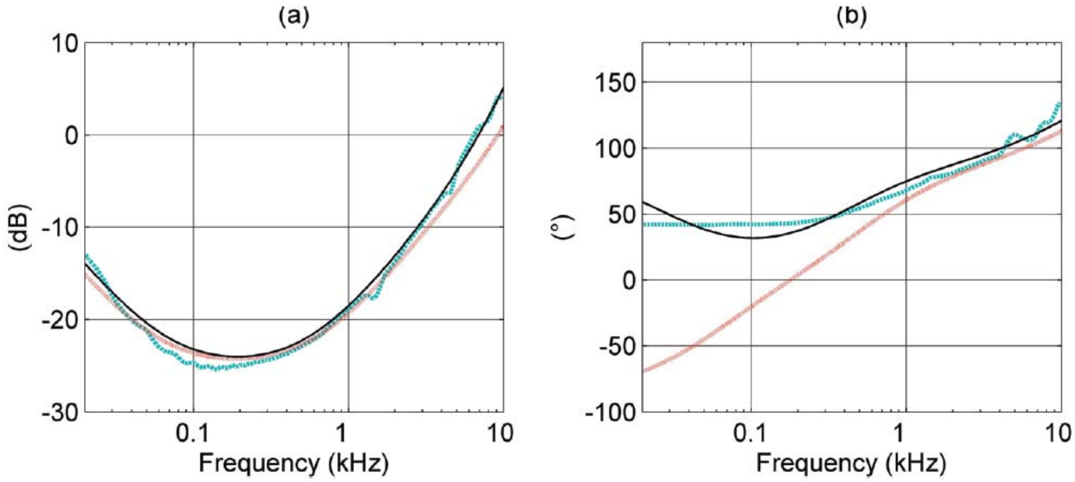

Figure 5. Experimental results for the magnitude a) and phase b) of $\Gamma(\omega)$ calculated from Eq. (8) are visualized by the blue dotted line. The black continuous line is a best-fit to experimental data obtained using the analytical model curve provided by the p-v probe manufacturer, while the red line represents the probe's nominal calibration curve.

Tympanometric p-v probe and immitance reference level

A first prototype of p-v tympanometric probe was built by starting from a standard one: after having removed its microphone and the static pressure pump, the body was modified so that it could host a commercial p-v sensor (Microflown® PU Match model) previously calibrated with the PPW method summarized above. A common in-ear headphone, used to generate the acoustic stimulus, was installed at the rear of the probe while its front was terminated with a rubber tip in order to easily plug the probe into the ear canal entrance. Particular care was taken in the alignment of the velocity sensor along the axis of the tympanometric probe, since the velocity sensor is very delicate and has cosine directivity. Figure 6(b) shows the transparent plastic tube which holds the PU Match while the precise alignment of the velocity sensor inside the body of the tympanometric probe is shown in 6(a).

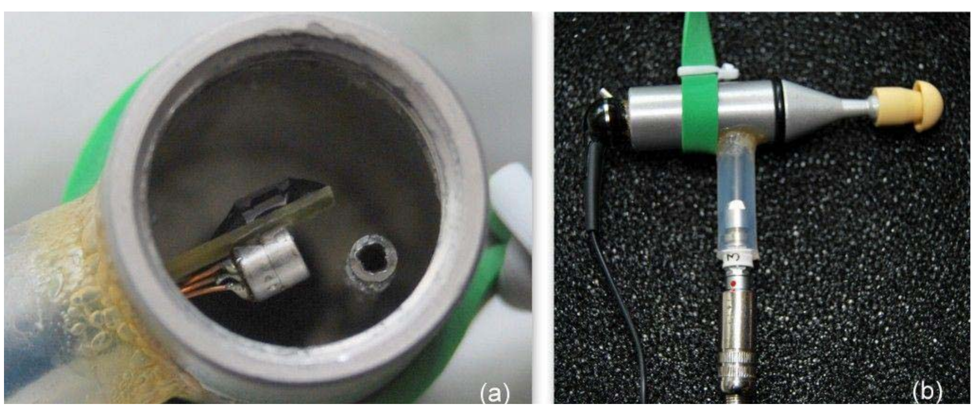

Figure 6. (a) Detail of the p-v sensor inside the prototype probe; (b) Overview of the p-v tympanometric probe.

Data acquisition and analysis instrumentation was carried out by a National Instruments I/O interface (NI USB-4431) and a laptop running customized Matlab® routines. The p-v tympanometric system (figure 7(a)) allows to record synchronous signals from the pressure and velocity sensors in response to a wide frequency range stimulus, a swept sine within the range [20, 8000] Hz. The p-v responses are then convoluted with the inverse stimulus obtaining the pressure and velocity impulse responses (IRs) p and v, from which, the immittance function is calculated using equation (4). Clearly, the set $\{p, v\}$ of concatenated IRs allows the computation of any other more elaborated quantity, like the ones in equations (5), (6) and (7).

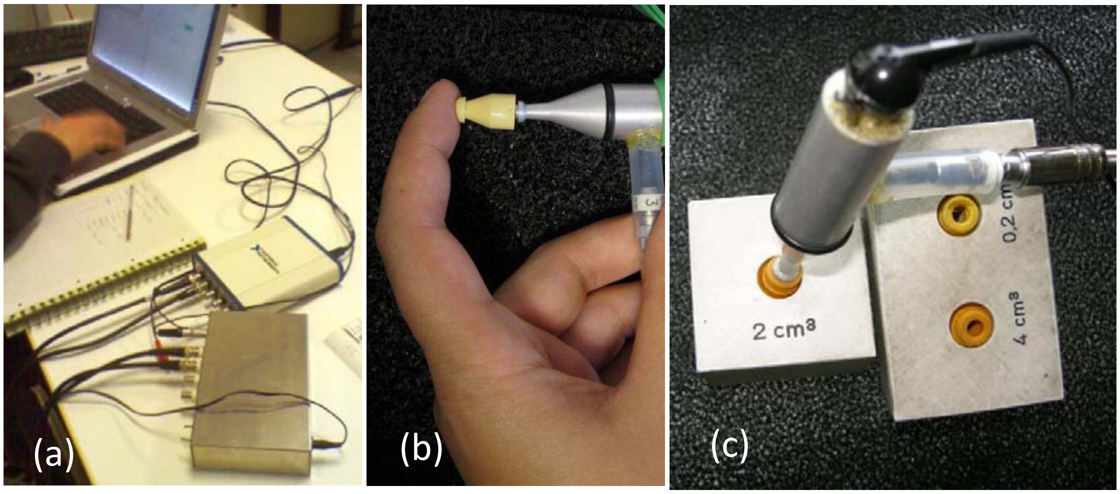

Figure 7. The p-v tympanometric system is a laptop based dual channel analyzer (a), able to record both the IRs of pressure and velocity signals captured with the p-v tympanometric probe and to calculate the specific immitance Y and other energetic quantities. The magnitude $|Y|$ is displayed by the system in dB relative to the frequency dependent baseline obtained by plugging the probe (b). In this way the "Equivalent Volume" of standard tympanometry corresponds in the p-v one, to the reading in dB of a 2 cc rigid cavity at the frequency of 226 Hz (c).

As in standard tympanometry, the p-v tympanograms need to be referenced to a baseline. This task can be accomplished, in p-v tympanometry, by measuring the modulus of the acoustic admittance when the p-v tympanometric probe is plugged up (see figure 7(b)) and then reading the immittance level $L_{|Y|}$ defined as

$$L_{|Y|} = 20\log\left(\frac{|Y(\omega)|}{|Y(\omega)|_{Plugged}}\right) \quad \text{dB} \tag{11}$$

where $|Y(\omega)|_{Plugged}$ is clearly a frequency dependent baseline used as dB reference. Figures 8 and 9 show respectively the graph of $|Y(\omega)|_{Plugged}$ for the prototype probe, and the reading in dB of $|Y(\omega)|$, defined according to equation (11) and measured when the 2 cc rigid cavity is in atmospheric pressure conditions.

It is worth noting that the "Equivalent Volume" of standard 226 Hz tympanometry which is relative to the 2 cc rigid cavity (see figure 10) corresponds in p-v tympanometry to about -6.7 dB as evidenced in figure 9. The choice of a rigid cavity is based on the hypothesis that for such a system the admittance is only due to the acoustic capacitance (compliance) of the air volume inside the cavity, a condition similar to the one met during standard tympanometry measurements for static pressure $P = +200$ daPa, whose value (called Equivalent Volume) is usually used for zeroing the tympanometric scale given in cc. In order to demonstrate the goodness of the pure compliant behavior of air inside a rigid cavity, figure 11 shows the real and imaginary part of the admittance, i.e. the acoustic conductance G and susceptance B appearing in equation (4), measured for a 2 cc rigid cavity: one find $G(226\,\text{Hz}) \simeq 0 \quad \text{ms}^{-1}\text{Pa}^{-1}$, which confirms that practically no acoustic energy is absorbed by the rigid wall of the cavity, thus meaning that energy can be only stored like (compliant) susceptance, whose value is $B(226\,\text{Hz}) \approx 3.6\times10^{-4}\ \text{ms}^{-1}\text{Pa}^{-1}$. It is important to recall here that all the operations described above need that pressure and velocity sensors placed inside the p-v tympanometric probe have been previously well calibrated, for instance using the PPW methodology.

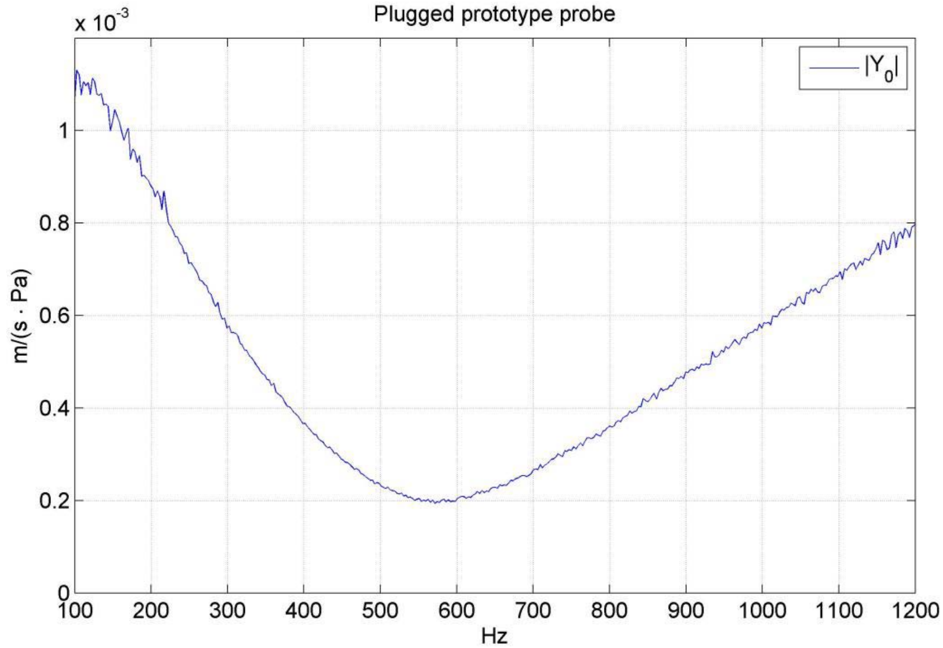

Figure 8. Specific acoustic admittance measured when the p-v prototype tympanometric probe is plugged up. The frequency dependent value of $|Y_0| \equiv |Y(\omega)|_{Plugged}$ is used as a running reference value for defining the $|Y|$ dB scale.

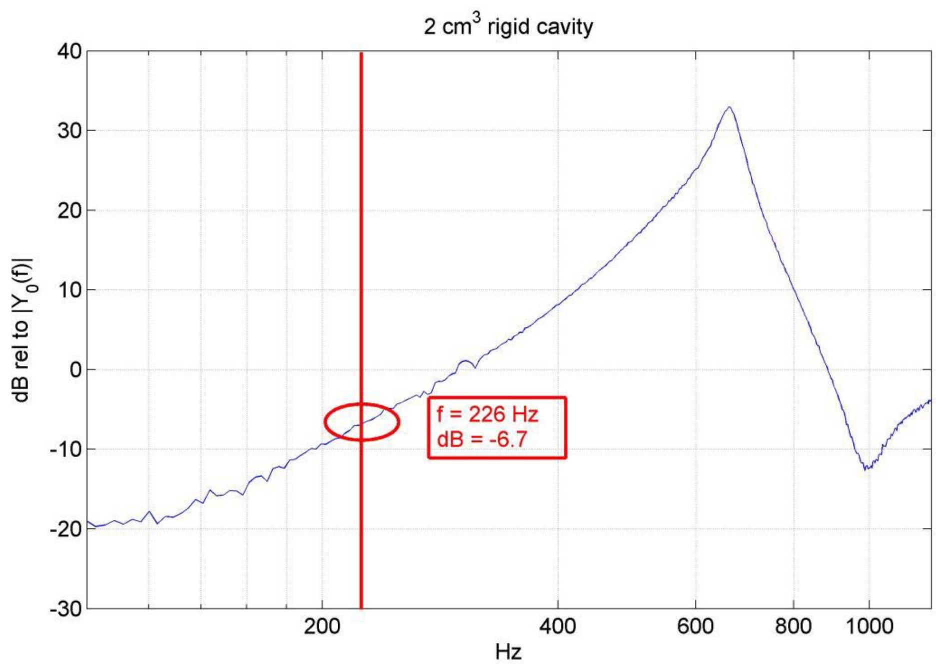

Figure 9. Admittance magnitude in dB rel. to $|Y(\omega)|_{Plugged}$ of a 2 cc rigid cavity filled with air in standard conditions.

D. Immittance measurement of normal ears with the p-v tympanometer

The operation of the p-v tympanometer prototype described in the former section has been checked over a population of 13 voluntary subjects, between 20 and 30 years old, with no certified pathologies of the hearing apparatus. All volunteers have been submitted to an otoscopic examination before the standard and p-v tympanometric tests were performed in battery. The Amplaid model 728 Tympanometer shown in figure 10 was used for the standard test, while figure 12 shows how the p-v prototype probe was fitted to the entrance of volunteers' ear canal for the p-v tympanometric test.

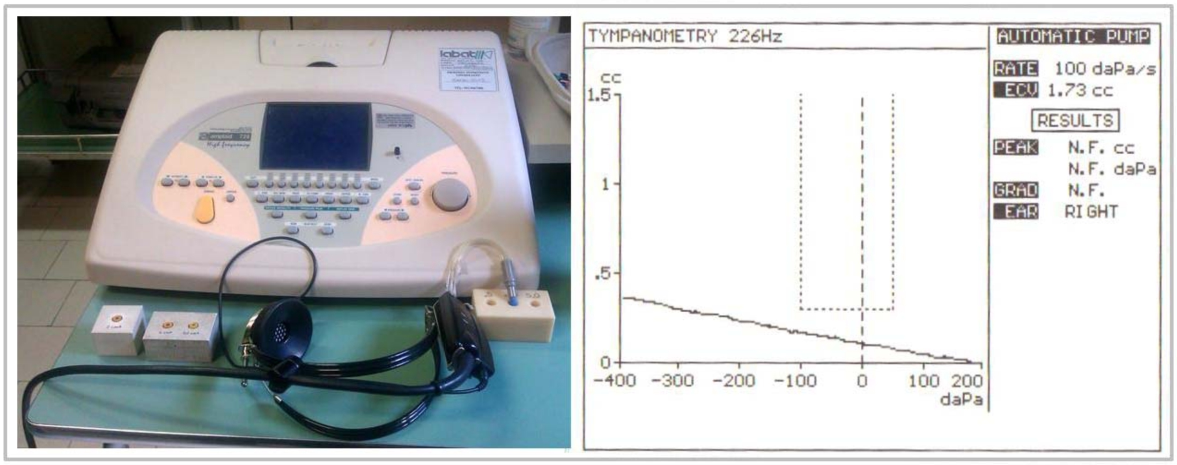

Figure 10. A standard tympanometer and its "type B" tympanogram measured on a 2 cc rigid cavity.

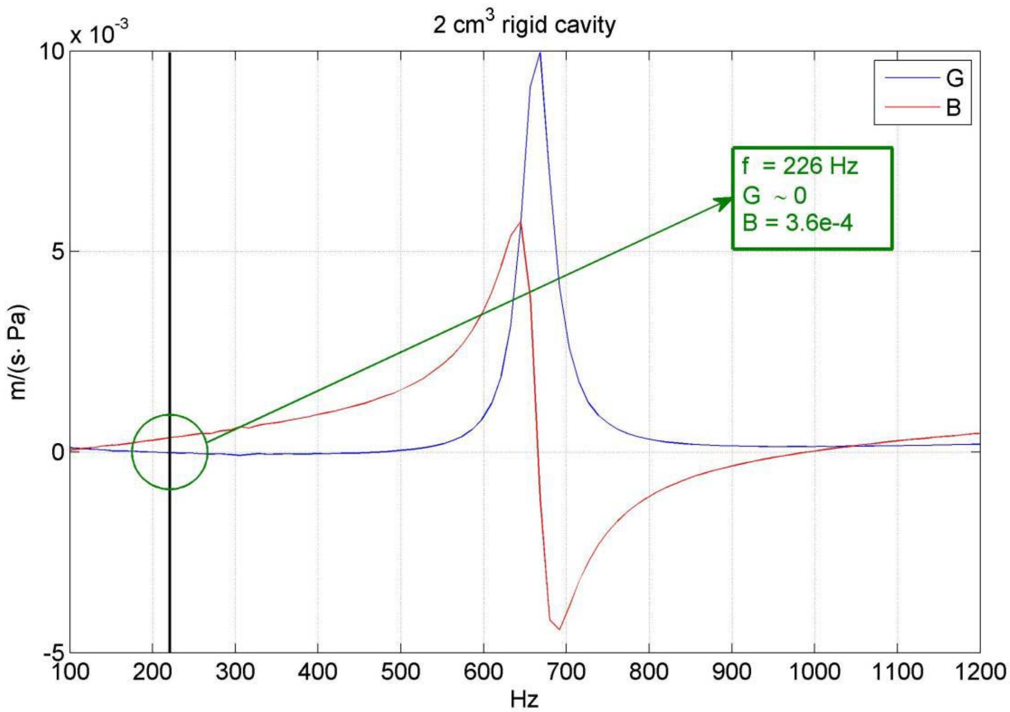

Figure 11. Real and imaginary part of the admittance $Y = G(\omega) + iB(\omega)$ measured over a 2 cc rigid cavity.

The obtained p-v tympanograms are reported in figure 13, where data relative to both right and left ears of each subject have been shuffled and displayed in only one cluster, grouping a total of 26 tympanograms. The plot clearly shows that the collected p-v tympanograms tend to converge to $L_{|Y|} \approx -12\,\text{dB}$ at 226 Hz, i.e. the preferred frequency of standard tonal tympanometry.

The detailed comparison of $L_{|Y|}\left(226\text{ Hz}\right)$ to data collected with the standard 226 Hz tympanometric test is reported in table 1. Table 1 compares values in cc of the acoustic equivalent volume (EV) and peak compensated static acoustic admittance (Y_{peak}), obtained with 226 Hz tympanometry, to the immittance levels defined in equation (11). Data in table 1 are graphically visualized in figures 14 and 15, where the regression line of the correspondences between $L_{|Y|}\left(226\text{ Hz}\right)$ and the equivalent volume EV and, respectively, Y_{peak} is plotted as well.

Figure 12. The prototype probe for p-v tympanometry is fitted to the ear canal at normal pressure conditions without sealing the external auditory meatus and having care to align the probe and canal axes.

Discussion

By looking at figure 14, where data from Table 1 have been graphically rendered and submitted to linear regression analysis, it can be safely said that the "normal" level of the ear immitance at 226 Hz can be fixed about at -12 dB rel $|Y_0| \equiv \left|Y\left(226\,\text{Hz}\right)\right|_{Plugged}$. This value corresponds to a mean EV of 0.9 cc, as measured by the Amplaid 728 at $P = +200$ daPa (see Table 1) and thus cannot be directly compared to the -6.7 dB level measured by the p-v tympanometer for a 2 cc rigid cavity in standard pressure conditions (see Fig. 9). Fortunately, as experimentally proven in figure 15, a linear relationship between the admittance levels in dB and increasing volumes at constant pressure in cc exists, and thus the gas law can be applied for extrapolating admittance levels for different static pressures. So we may extrapolate linearly the cc value corresponding to the -12 dB level at P=0, by associating the level of -6.7 dB measured by the p-v tympanometer, to the rigid cavity of 0.9 cc as measured by standard tympanometry at P=+200 daPa. In so doing we find the conversion factor $k = -6.7/0.9 = -7.45$ between the measure in dB defined by equation (11) and the cc scale defined in standard tonal tympanometry i.e. $\left|Y\left(226\,\text{Hz}\right)\right|_{\text{dB}} = k\left|Y\left(226\,\text{Hz}\right)\right|_{\text{cc}}$. Using this conversion factor we find that the equivalent volume of normal ears at normal pressure condition is 1.6 cc (see Figure 16). This value anyway is not an estimate for the air volume inside the ear canal, given that at normal pressure conditions the immitance is not purely compliant and of course energy absorptions through the tympanic membrane occur.

From the above discussion one may infer that the mean peak compensated static acoustic admittance Y_{peak}, obtained with 226 Hz tympanometry (usually measured in mmhos), can be obtained simply by subtracting the admittance of the normal ear rigid cavity (i.e. 0.9 cc, as measured in the average by the Amplaid 728) from the normalized EV (i.e. 1.6 cc as extrapolated from p-v tympanometric data). In our case one finds a mean $Y_{peak} = 0.7$ mmhos, in perfect agreement with data collected for peak compensated static acoustic admittance by Margolis and Heller (1987) as reported in the literature [1].

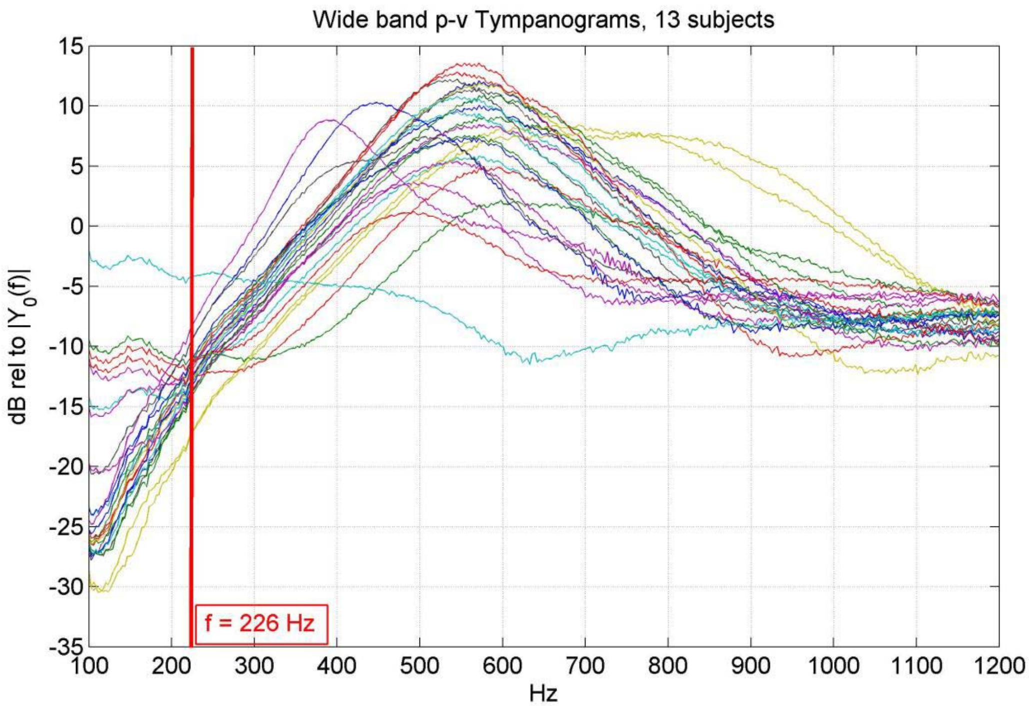

Figure 13. Specific admittance measured with p-v technique in the frequency range of standard multi-frequency tonal tympanometry. Results are reported for left and right ears of 13 different subjects for a total of 26 tympanograms. The standard 226 Hz frequency where almost all data collapse is highlighted by the vertical red line.

Table 1. Measured values of immittance levels $L_{|Y|}$ obtained with p-v tympanometric probe, peak compensated static acoustic admittance Y_{peak} and equivalent volume EV obtained with the standard system (13 subjects 26 ears).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Mean
Ly (dB)	-13.2	-13.8	-14.0	-9.4	-11.9	-11.3	-12.8	-12.5	-12.2	-4.2	-17.0	-8.2	-12.7	-12.7	-12.4	-9.3	-10.9	-10.9	-11.6	-13.7	-11.9	-11.3	-11.3	-13.0	-13.6	-17.1	-12.0 ±2.5
Ypeak (cc)	0,61	1,02	0,62	0,47	1.04	1.04	==	1.00	2.86	2.07	0.23	0.26	0.76	0.70	1.23	1.70	1.09	0.86	0.82	0.76	0.72	0.66	0.89	0.73	1.09	1.05	1.1±0.7
EV (cc)	1,00	1,08	0,71	0,63	1.16	1.09	==	0.85	0.75	0.62	0.36	0.39	1.13	0.94	1.23	1.70	1.09	0.86	0.82	0.76	0.72	0.66	0.89	0.73	1.09	1.05	0.9±0.3

E. Conclusions

The fundamentals of p-v tympanometry have been here laid by summarizing a complete 1-D working model of the sound energetics of ear canal so linking the specific acoustic admittance of equation (4) to the energy current admittance defined in equation (5). A general and precise definition of the Energy Absorbance (EA) introduced by Keefe has been given in equation (6) and its wide band measurement has been proved feasible thanks to the development of a p-v tympanometric probe prototype.

The operation of the p-v prototype has been checked by comparing its wide band measurement results to standard tympanograms obtained with 226 Hz tympanometry using the Amplaid 728 system. The data comparison was successful and allowed to interpret standard quantities like the Equivalent Volume (EA) and Peak compensated static acoustic admittance (Y_{peak}) in the frame of p-v tympanometry.

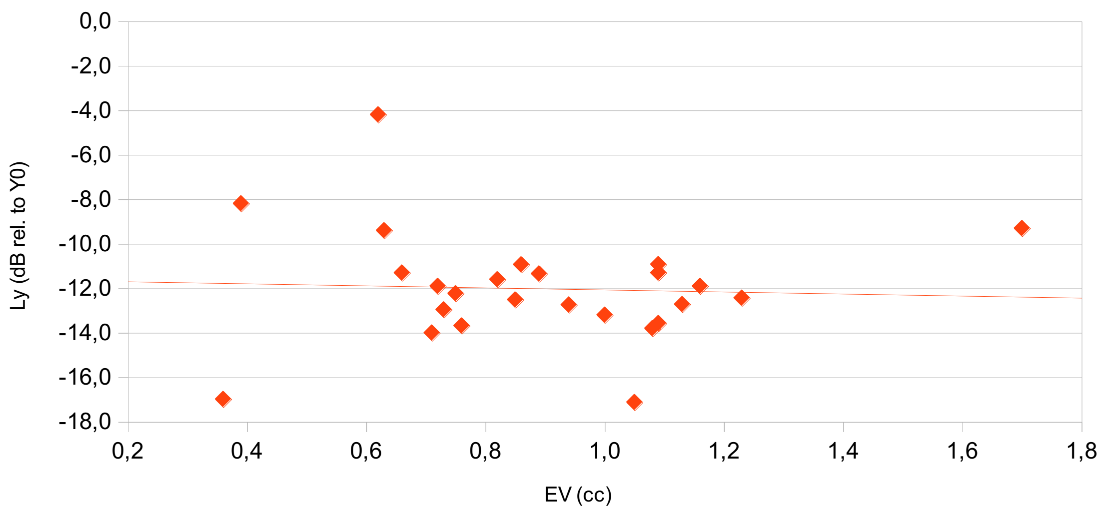

Figure 14. Graphical rendering of specific admittance levels in dB collected from 26 normal ears with p-v tympanometry at 226Hz versus equivalent volumes in cc measured with the Amplaid 728. The linear regression analysis show that -12 dB can be considered the normal level of aural immittance in standard pressure conditions.

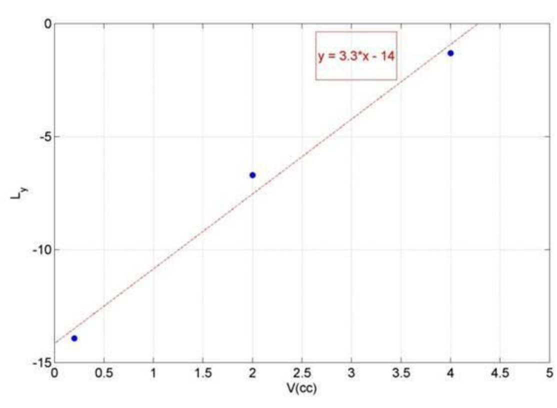

Figure 15. Admittance levels of 0.2, 2.0, 4.0 cc rigid cavities at P=0 measured with the p-v tympanometer at 226 Hz.

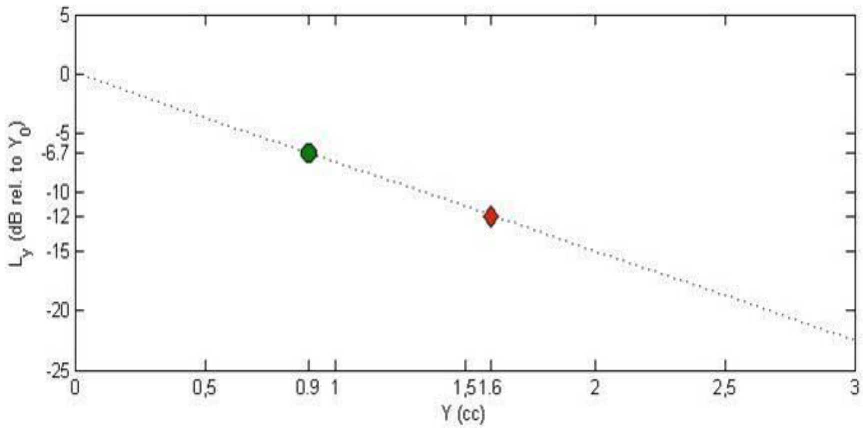

Figure 16. The orange diamond corresponding to 1.6 cc indicates the extrapolated value of the Equivalent Volume of normal ears at atmospheric pressure as obtained from p-v and standard tympanometric data measured at different static pressures. The green circle indicates the measured values.

Acknowledgments

Authors wish to thank the Labat company for allowing us to modify one of its standard tympanometric probes in order to use it with p-v micro-sensors. We also thank Prof. Silvano Prosser and its students of the University of Ferrara for collaborating to the tympanometric tests. A special thanks to Fosca Fimiani for her contribution, as a visiting student of the Physics Department of the University of Bologna, during the preliminary phase of this work.

References

1. Shanks J. E. , “Tympanometry”, in Kent R. D., The MIT Encyclopedia of communication disorders, Bradford books, 2004, part IV: Hearing, pp. 558-563
2. van Camp K.J., Margolis R.H., Wilson R.H., Greten W.L., Shanks J.E., Principles of Tympanometry, ASHA Monographs n. 24, 1986
3. Stanzial D., Sacchi G., Schiffrer G., Stanzial D., Sacchi G., Schiffrer G., Calibration of pressure-velocity probes using a progressive plane wave reference field and comparison with nominal calibration filters, J. Acoust. Soc. Am., 129 (6), 2011, pp. 3745-3755.
4. Liu Y.W., Sanford C.A., Ellison J.C., Fitzpatrick D.F., Gorga M.P., Keefe D.H., Wideband absorbance tympanometry using pressure sweeps: System development and results on adults with normal hearing, J. Acoust. Soc. Am., 124 (6), 2008, pp. 3708–3719
5. Stanzial D., Sacchi G., Schiffrer G., On the physical meaning of the power factor in acoustics, J. Acoust. Soc. Am., 131 (1), 2012, pp. 269-280.