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UDC: 534.6 Acoustic measurements

INVESTIGATION OF SOUND ABSORPTION COEFFICIENT BY DECAY OF STANDING WAVES IN THE IMPEDANCE TUBE

M.A. Chelidze.

LEPL R.dvali Institute Machines of Mechanics. Mindeli 10, Tbilisi 0186, Georgia

Abstract: *Determination of absorption coefficient in materials, in a condition of wide consumption, is a very difficult problem and in majority cases may be said it is impossible because of requirements of special laboratory, apparatuses and measured devices. Moreover, by the existing methods, the accuracy of measured coefficient depends on a method of measuring and fixing of a sample. The wide spreading of modern digital technique and software give the ability that the material acoustical features, in particular the sound absorption coefficient were determined in a wide consumption. According to the presented method, the sound absorption coefficient is measured directly i.e. by the relation of reflected and incident waves but not by bypass ways as it is done in the present, so the presented method ensures more exactness and stability of measuring.*

Keywords: *Sound absorption coefficient, decay, measurement, standing wave, plain wave, amplitude, impedance tube.*

1. Introduction:

The pollution of the modern big cities and autobahn nearby environments with a noise is a great problem. Generally, noise reduction in buildings may be achieved by isolating them from noisy radiated sources; Rooms can be protected from excessive reverberant sound pressure by covering walls with sound absorbing materials; The noise radiation from the noisy machines may be reduced by replacing the noisy mechanism with a less noisy mechanism that requires a big capital investment and in majority cases it is impossible [1].

The materials with a high density i.e. materials of high reflection ability are used for insulation buildings from noise but the materials with a big absorption coefficient are used for reduction sound reverberation in rooms. The absorption coefficients in materials are determined within 0÷1 interval i.e. the materials acoustically are able to absorb sound within 0÷100% per cent.

The sound is very complex phenomena, so to carry out measurements of the materials acoustical characteristics are very difficult and obtained results depend on the measurement methods. Commonly, two techniques used to perform such measurements: methods of sound decay in reverberation room and standing waves in an impedance tube by using transfer function. The determinations of a sound absorption coefficient, by all the known methods, are carried out by bypass ways [2,3]. For instance: by Sabine method, the absorption coefficient approximately is determined by time decay of sound reverberation $T = 0.161V / A$, where V- is room volume, A=αS, S- is equivalent absorption surface or area in m^2, α = absorbent coefficient or attenuation coefficient [3,4]. The Sabin Absorption is $A = 0.921Vd / c$ where c- is speed of sound. By the method of two microphones, where sound waves are sent down in a long tube, which by reflection at the stopped end forms nodes and loops in the tube where is to be determined maximal and minimal amplitudes with the using of a transfer function $\alpha = 1 - \lfloor r^{\wedge} \rfloor^2 = 1 - r^2$ or $A = 1 - R = 4MN / (M - N)^2$ [3,4].

The absorption coefficient is defined as the ratio of absorbed energy to incident energy i.e. by a relation of an incident and reflected wave amplitudes as it is shown by the formula (1) [2,3,5].

$$\alpha = \frac{E_{abs}}{E_{inc}} \qquad (1)$$

Though at some cases α is defined as the ratio of all energy not reflected to incident energy Fig.1.

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$$\alpha = 1 - \frac{E_{ref}}{E_{inc}} = \frac{E_{abs} + E_{tran}}{E_{inc}} \qquad (2)$$

By conservation energy $E_{inc}=E_{ref}+E_{abs}+E_{tran}$

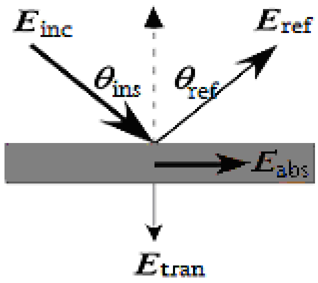

Fig. 1 Incident, reflected, absorbed and transferred energies

It must be noted that the measurement of sound absorption coefficient when used the impedance tube, the upper frequency f are limited for which only plane waves may be circulated f<0.586c / d, where d - is tube diameter. Low frequencies are limited by a length of the tube. So in the impedance tube with a diameter of 10 cm are propagated plane waves of 150÷1200 Hz, and in 3 cm diameter tube are propagated plane waves of 1200÷8000 Hz.

In a sufficiently great distance from the sound sources the front the waves become plain i.e. the solution depends only on one coordinate x along propagation of the wave [6].

$$\frac{\partial^2 p}{\partial x^2} = -\frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \qquad (3)$$

where p – is sound amplitude pressure, x –longitudinal coordinate, t -time.

The solution of the equation of (3) may be presented as two propagating waves [6,7].

$$p = f_1(ct - x) + f_2(ct + x). \qquad (4)$$

For periodic oscillations (4) takes view

$$p = f_1[\frac{c}{\omega}(\omega t - kx) + f_2[\frac{c}{\omega}(\omega t + kx)], \qquad (5)$$

where $k = \frac{w}{c} = \frac{2\pi f}{c} = \frac{2\pi}{\lambda}$ waves oscillations, λ=c/f – is length of waves.

For harmonic waves of (5) equation takes the following view

$$p = A\cos\frac{\omega}{c}(ct - x) + B\cos\frac{\omega}{c}(ct + x) = A\cos(\omega t - kx) + B\cos(\omega t + kx), \qquad (6)$$

For simplifying calculate the summing operations of different frequency waves the (6) equation frequently is presented in a complex form

$$p = (\bar{A}e^{-jkx} + \bar{B}e^{-jkx})e^{-jkx} = \bar{A}e^{jkx-jkx} + \bar{B}e^{jkx-jkx} \qquad (7)$$

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In accordance with equations of (6) and (7) the incident and reflected flat waves are summed i.e. depending on their phase they are increased and decreased. In accordance with equations of (4) $p = X(x).T(t)$ if there will be taken two private solutions and they will be supplied in equation (3) then will be obtained equations which left and right parts will equal. There may be such solution where they will equal to -k².

$$\frac{1}{c^2}\frac{\partial^2 T}{\partial t^2} = \frac{\partial^2 p}{\partial t^2} + \frac{1}{X}\frac{\partial^2 X}{\partial x^2} = -k^2 \qquad (8)$$

From equation (8) are obtained two equation with following solutions, which are analogous of oscillation of material point [6].

$$\begin{aligned} &\frac{\partial^2 X}{\partial x^2} = -k^2 X, && X = A\cos(kx + \varphi_x) \\ &\frac{\partial^2 T}{\partial t^2} = -k^2 c^2 T = -\omega^2 T && T = B\cos(\omega t + \varphi_t) \end{aligned} \qquad (9)$$

where $\omega^2 = k^2 c^2$

The solution of wave equations is equal

$$p = XT = C\cos(kx + \varphi_x)\cos(\omega t + \varphi_t) \qquad (11)$$

The obtained equation describes free oscillation of standing waves. So private solution of the equation $p = X(x).T(t)$ gives us possibility from endless solutions were searched the standing waves equation. The solution of plane waves can be represented as standing waves so mobile waves. Moving plain waves are characteristic for unstable processes and standing waves for periodic and stable processes [6, 7].

The simple waves of the frequency f radiated from the sound source create plain waves oscillating with f frequency in the tube. The plain waves circulating in the closed impedance tube are reflected many times at the stopped ends (from the lateral covers of the tube). The obtained reverberating waves are acted on each other, summed and in the tube are created also the stable standing waves of frequency f fig.2 [3,6,8,9]. From Fig.2 is seen that the absorbing material which is fixed at the stopped end causes variation of the value of amplitudes standing waves.

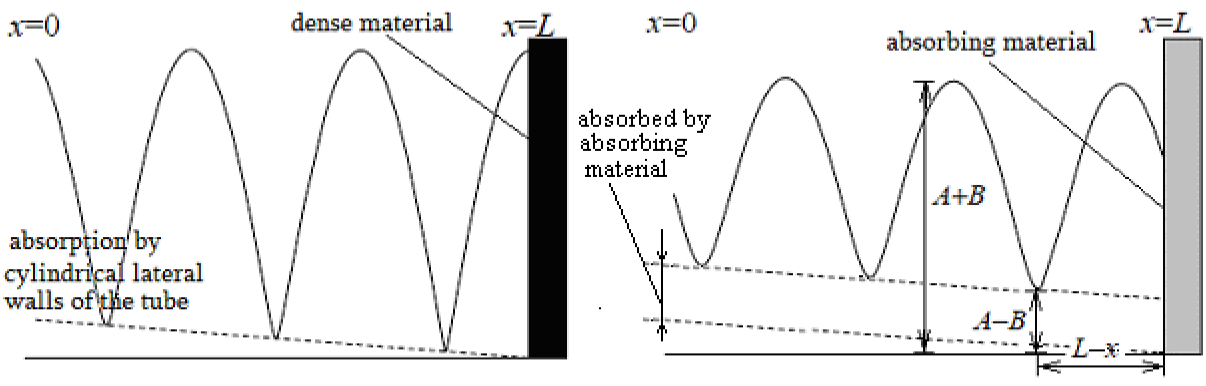

Fig.2. Standing waves in the impedance tube.

The full period of propagation plane waves from one stopped end of the tube to another and back, i.e. one full cycle, is a ratio of the double length of the tube to the speed of sound propagation

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in air. The speed of sound in air equal 331 m/c at sea level. So in the tube longitudinally are generated stable plane and standing waves. At the time of switching off the noise source, in the tube, the amplitudes of plane and standing waves fall at the same pace. In accordance with formula (1), the value of decay of sound amplitudes in each cycle is equal of the transmitted and absorbed sound energy in the material being at the stopped end of the tube.

2. Experimental Study:

To improve the accuracy of measurement, sound reflection coefficient of the tube wall should be close to 1, i.e. material for the tube should be bronze, with a minimum wall thickness of 5 mm, although the tube material may be steel [8]. Especially it should be noted that with any waveforms of decaying waves of the frequency f radiated from the sound source is seen longitudinal waves of f_{lon} frequencies that are created in the tube Fig. 3, 4.

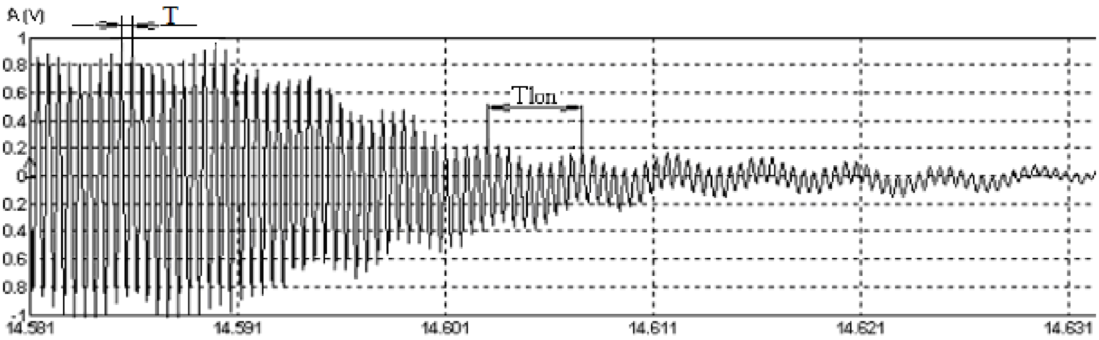

Fig.3. Sound decay, exited frequency f=2000 Hz, decay frequency f_{lon}=250 Hz.

So in the impendence tube, simultaneously are generated two type of waves: plain waves with frequency f radiated from the sound source and the reverberating plain waves of frequency f_{lon} created by means of the process of reflection plain waves at the stopped ends of the tube Fig.3,4,5.

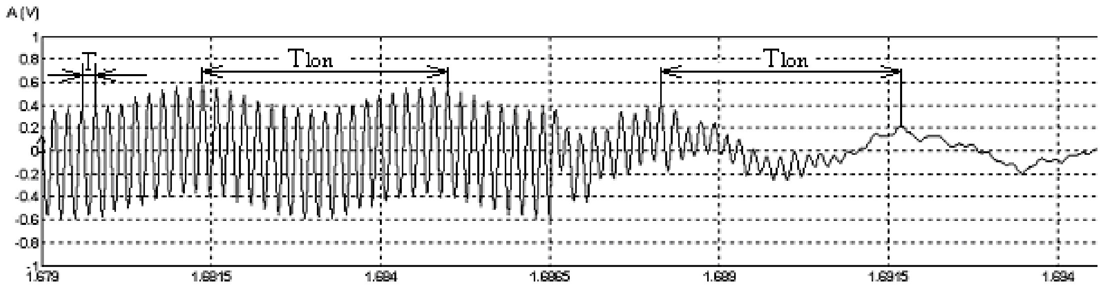

Fig.4. Sound decay, exited frequency f=5000 Hz, decay frequency f_{lon}=310 Hz, l=30 cm.

On the base of aforesaid from the moment of switching off the sound source, in the tube are generated decaying standing waves which represent combinations of sum f and f_{lon} frequencies and they are damped with appropriate frequencies (fig.3,4,5). In accordance with formula (1), the absorption coefficient α can be calculated by the relation of T_{lon}-periodic standing waves amplitudes Fig. 3, 4 and may be said that is the novelty.

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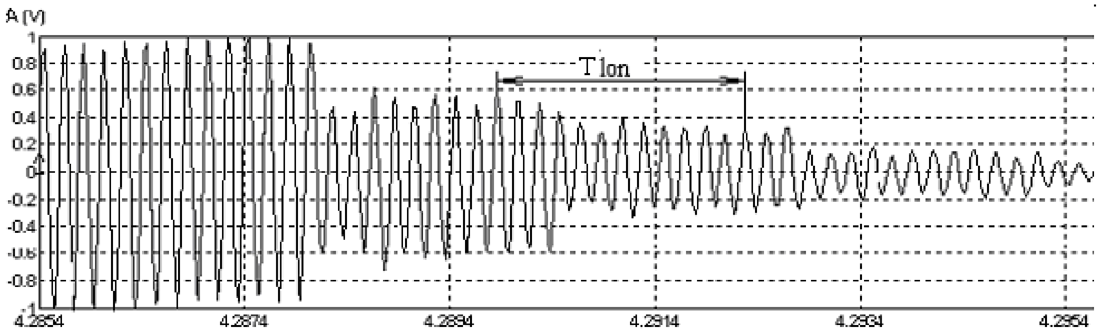

Fig.5. Sound decay, exited frequency f=5000 Hz, decay frequency f_{lon}=415 Hz, l=40 cm.

When waves of f and f_{lon} frequencies are attenuated simultaneously then to simplify the visual fixing of T_{lon} period on the waveform, the program VT RTA-168 gives the possibility to search such scale of unrolling that T_{lon} was fixed visually in one fictitious period Fig.6.

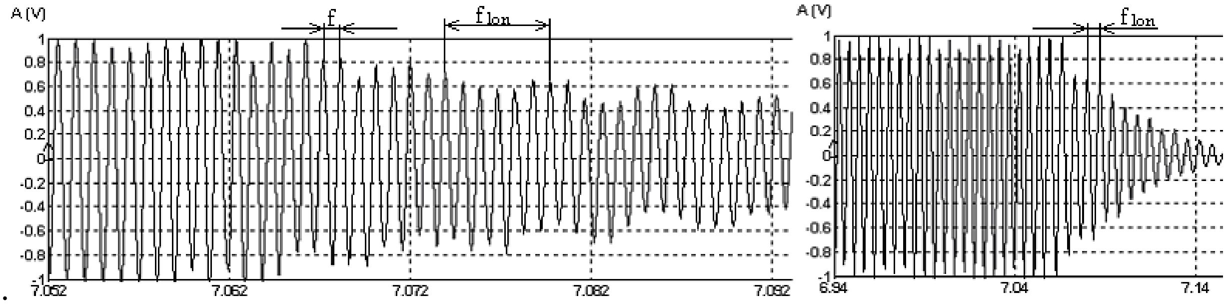

Fig.6. Sound decay, exited f=1000 Hz, decay f_{lon}=150 Hz. Waveform is compressed.

Under certain ratio of tube length and diameter with excited frequency f, the frequencies f and f_{lon} may coincide with each other Fig.7.

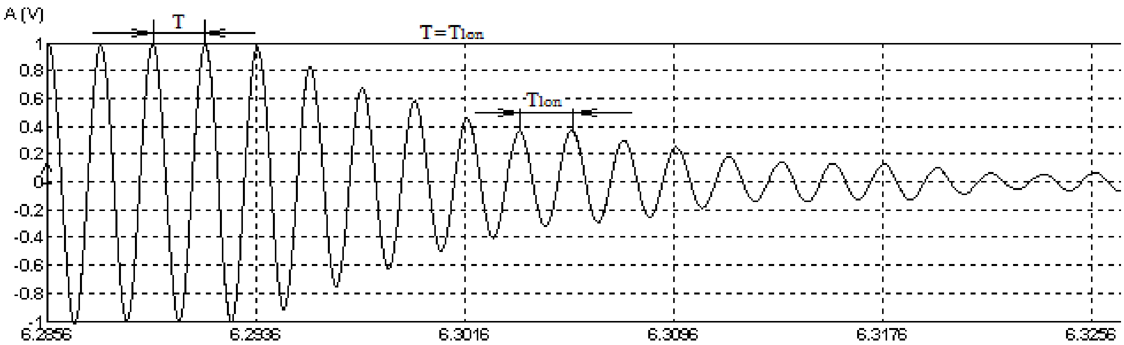

Fig.7. Sound decay, exited frequency f=500 Hz, decay frequency f_{lon}=500 Hz.

Based on theoretical investigation it can be said that the tempo of decay plain waves in impedance tube is determined: by the imperfect reflection of sound at the both stopped ends, sound propagation in air and by the resistance of side walls with sound waves spreading along the length of the tube that is proved by the experimental research. If one lateral cover of the tube will be replaced by sample material which has different absorption ability then accordingly will be replaced rate of sound decay in the tube Fig.8. So by this way become possible to determine how much bigger the searched sample absorption coefficient to the etalon. Moreover, if subtracted from the absorption coefficient calculated for a material with a high absorption capacity with the low capacity absorption coefficient of etalon material (bronze) we will obtain the searched value of the absorption coefficient of the material.

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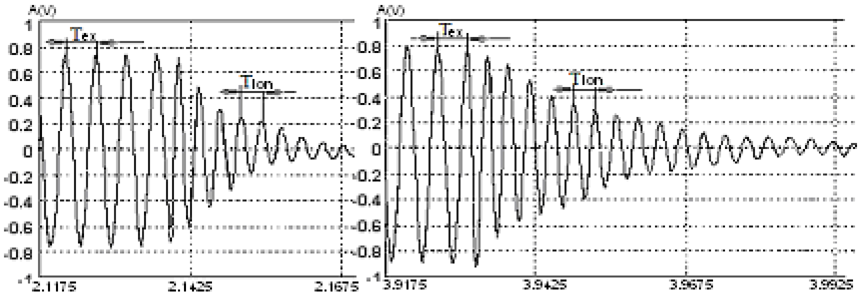

Fig.8. Sound decay of concrete and marble, exited f=200 Hz, decay f_{lon}=250 Hz. l=65 cm.

The material absorbing ability depends on the sound frequency that is clearly seen in Fig 4 and Fig.9, where radiated f high-frequency waves from the sound source for given material decays more quickly than low frequency excited by reverberating sound waves in the tube of impedance.

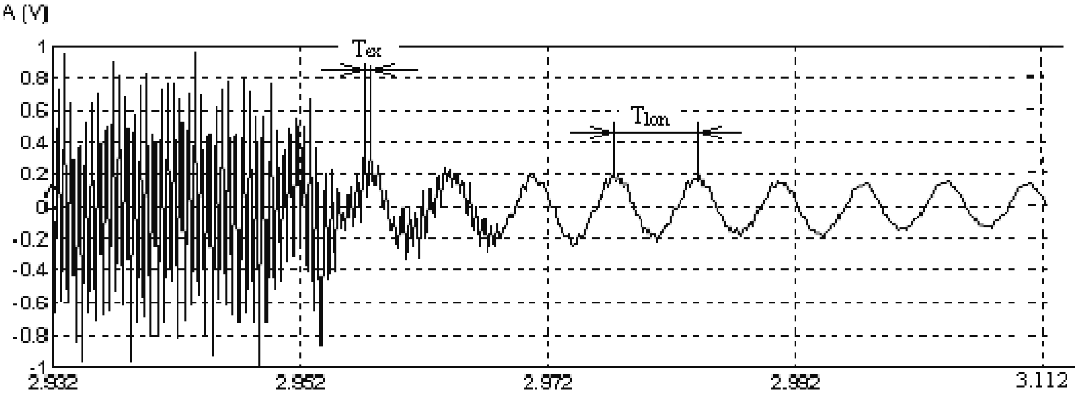

Fig.9. Sound decay, exited frequency f=10000 Hz, decay frequency f_{lon}=150 Hz.

On the basis of the experiments was proved the theoretical viewpoint that by the selection of the tube length it is possible that the wave frequency created in the tube was fitted with the frequency of the coherent wave radiated from the sound source i.e. when the length of the tube coincides with the sound wavelength. When the sound frequencies f, and f_{lon} are alike the wave attenuation is determined mainly by the absorption capacity of the materials from the lateral covers of the tube.

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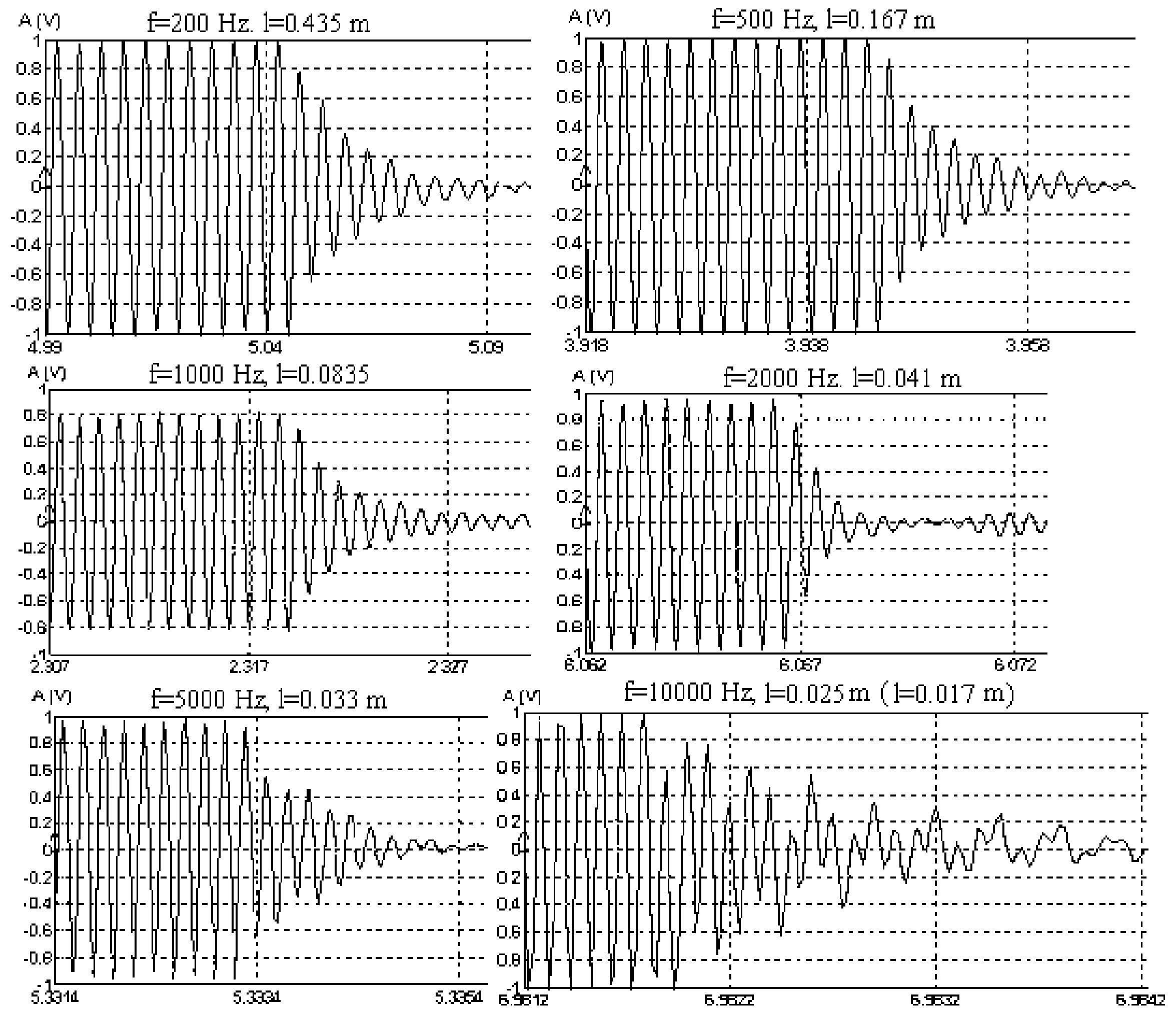

Fig.10. Achievement of equality of excitement and fading frequencies by means of regulation of the tube length. Sample material is cork.

On the Fig. 10 are fixed waveforms of decay standing waves of 200, 500, 1000, 2000, 5000 and 10000 Hz frequencies when plain waves decay amplitudes f_{lon} frequency in the tube is the same f frequency as it has radiated sound source. The equality of frequencies f_{lon} with f is reached by regulating of changing the tube length. Waveforms recorded in such manner very accurately determine the absorption coefficients for the test materials at all these spectra. The exception is 10000 Hz frequency, which decay frequency occurs at 3000 Hz. The tube length at which the sound decay will happen at 10000 Hz must be 17 mm. The length of our microphone was 20 mm. For given case, the length of the tube was 25mm. So the obtained decay frequency was 3000 Hz. The waveforms of decay shown in Fig 10 are obtained for the case when the sample (the material cork) is installed at the stopped end of the tube.

Theoretically, in the closed space, in particular, in the tube the process of sound waves decay and an increase of amplitudes at the presence of low powerful source must be the events of inverse interaction that fully are proved by experimental investigations. On the Fig.11 are shown processes of increase and decrease amplitudes of standing waves in a closed space at the time of the switching and turn off the low-level power noise source. From Waveforms of Fig. 11 is seen that processes of decrease and increase standing waves obtained by summing of reverberating plain waves have mirror images.

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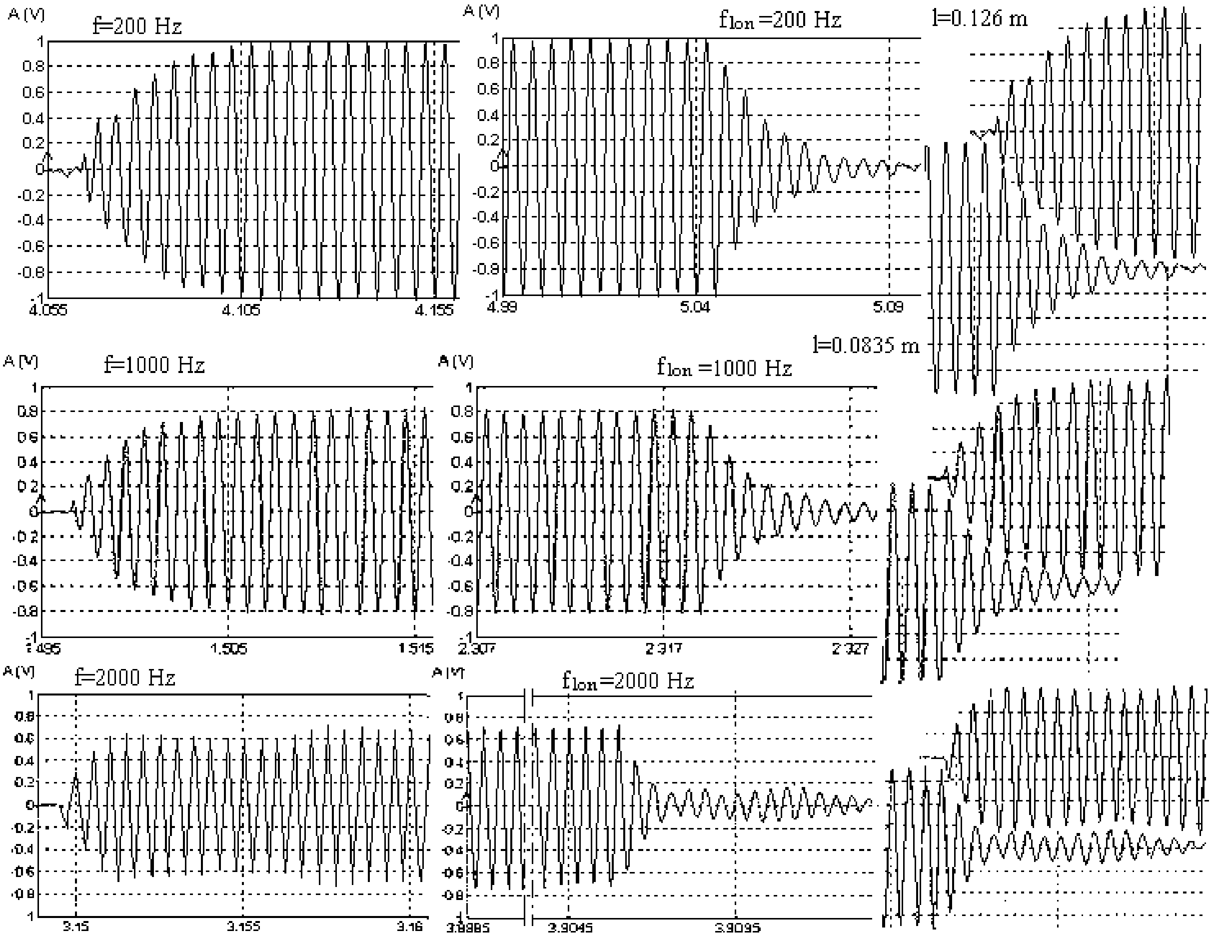

Fig.11. Mirror images of forming and decay amplitudes in a closed space at the presence of low sound energy.

The mirror images of processes of forming and attenuation of sound standing waves once more confirm that the presented method are correct, perspective and new, furthermore sound absorption coefficient can be determined also by the process of increase of reverberating sound amplitudes. So the absorption coefficient can be determined by the decay of reverberating sound amplitudes similarly as it is happened in the vibration theory by means of formula (1), Fig12, [5,9,11].

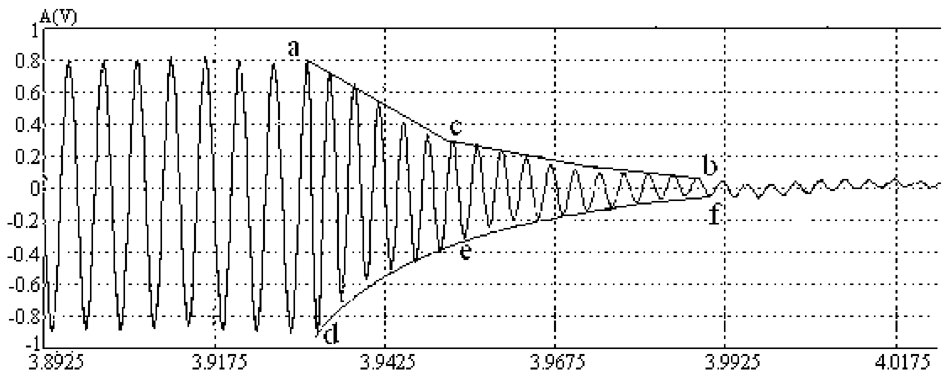

Fig.12. Determination of sound absorption coefficient by decay of reverberation amplitudes.

The experimental investigation shows [4,9] that the reverberating sound amplitudes are damped non-linearly accordingly of curve def presented by waveforms in the Fig.12. The rate of decay on the intervals de and ef is different and consequently another absorption coefficient correspond them. If we shall suggest that de and ef are linear in conformity with ac and cb linear

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intervals than for noted linear intervals the formula for calculation sound absorption coefficient will take the following view.

$$\alpha_k = \frac{A_a - A_b}{mA_a} \qquad (11)$$

where A_a- and A_b- maximal and minimal amplitudes on the calculation interval accordingly, m- the number of amplitudes of decay, or increase on the calculation interval.

Evidently that average value of absorbing coefficient, entirely for def curve, will be the average mathematical sum of separated linear intervals. At least by practical viewpoint desirable that the determined absorption coefficient was comparable to high 80÷20dB level sound pressure. In Figure 12 such interval is de interval of the curve or linear ac range.

In the theory of vibration, the absorption coefficient for ac range is calculated using ab interval by adding 2 in the formula (11).

$$\alpha_k = \frac{2}{m}\frac{A_a - A_b}{A_a} \qquad (12)$$

In such cases it is desirable that the high inclination curves ac (de) and low inclination curves cb (ef) were approximately equal.

Theoretically, when in the closed impedance tube the radiated length of the wave is bigger than the length of the tube (on account of reverberation) the period of oscillation of plane waves in the tube must be decreased i.e. the frequency of generating of plain waves become higher. In the tube are created high-frequency standing waves.

On the Fig.13 are shown processes of creation and attenuation of 2500 Hz frequency waves when in the 35mm length tube acts 200, 500, 1000 and 2000 frequency waves excited from the noise source. At the periods of the processes on and off noise source, aforesaid 2500 Hz impulses sharply stood out in the periods of unstable processes. Entirely the frequency of sound waves decay is 300 Hz and it is accompanied by 2500 Hz frequency, but at the stable regimes with the f frequencies 300 Hz frequency are stand out.

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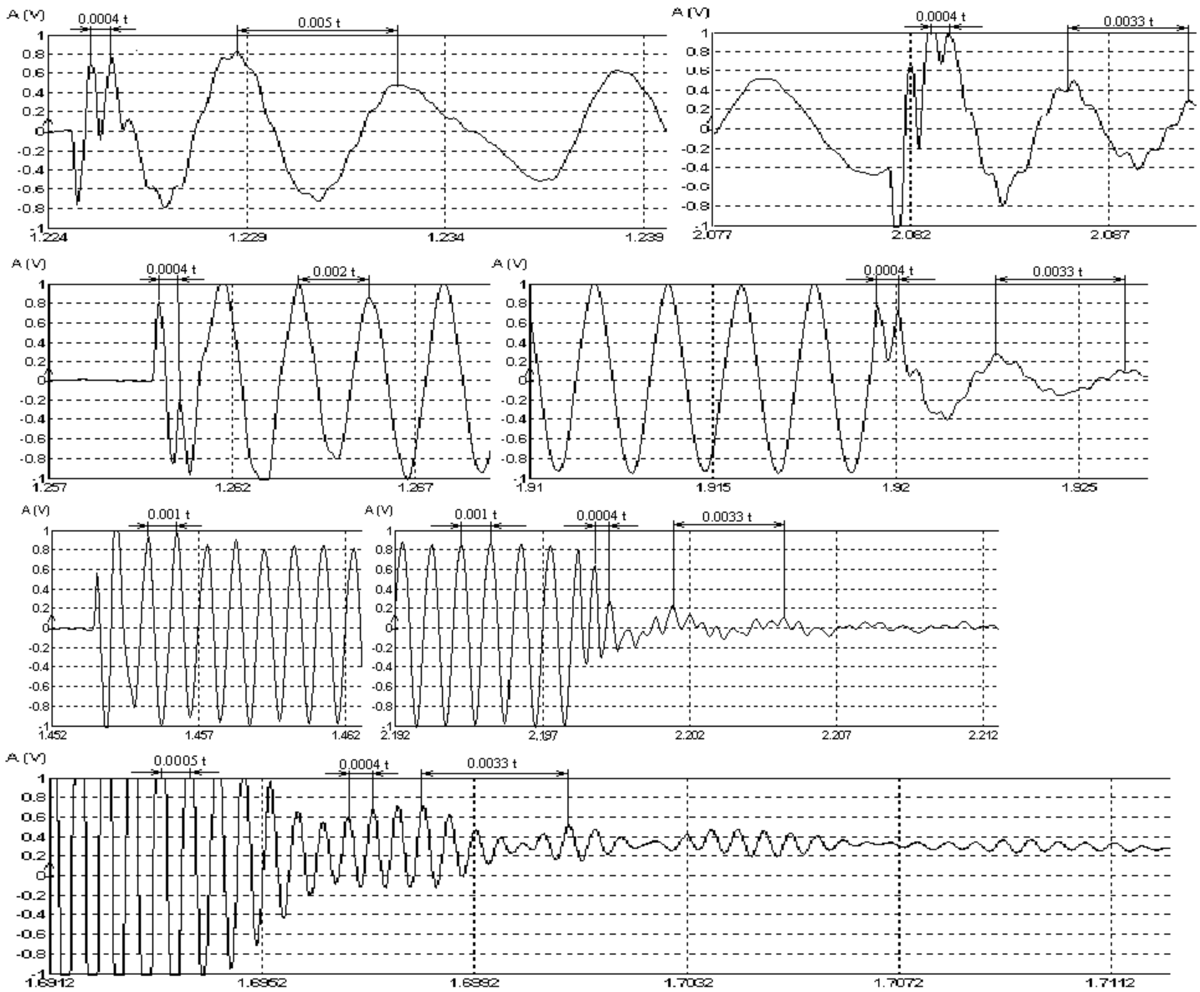

Fig.13. Dependence of frequency reverberation oscillation with the dimension parameters of closed space.

More than 200 the scientific literature, which was seen and analyzed by us, cover periods of 1927 2014 years, among them 6 fundamental monograph, are not contain calculations of absorption coefficient by presented methods and are not shown waveforms in which clearly are shown decay and tempo of reverberation amplitudes in the materials. By noted waveforms, graphically, may be determined absorption coefficient in the materials that are new method and must be perspective for further investigation by the viewpoint of elaboration and refinement.

3. Conclusion:

The method of determining absorption coefficient in the materials by decay generating of reverberation plain waves in the tube makes it possible that by using a cheap and low precision devices the measured value of the coefficient was practically acceptable and exact that will give wide possibility using it in the practice.

The method of determining of absorption coefficient by means of decay reverberating waves peaks is enough stable and shows low sensitivity on a whole admission mistakes at the process of measurements.

By the given method, the sound absorption coefficient measured directly i.e. by the relation of reflected and incident waves but not bypass ways so the presented method ensures more exactness and stability of measuring.

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The wide spreading of the modern digital techniques, PC and software give it possible that ability of sound absorption in materials and coefficient of absorption were measured in a required accuracy without of special laboratories in a wide consumption conditions.

literature.

1. Acoustics in buildings. FESI Document A4. October 2007.
2. A. A. Igolkin, L. V. Rodionov, E. V. Chess, A. I. Kox. The Sound-absorption. The Methods of the measurements. Samarskiy State Aerospace University, Name of the Academician S.P. Кoroleva 2010.
3. Sound absorption coefficient measurement: Re-examining the relationship between impedance tube and reverberant room methods. Proceedings of Acoustics 2012 – Fremantle. 21-23 November 2012, Fremantle, Australia. https://www.acoustics.asn.au/conference_ proceedings /AAS2012/papers/p55.pdf.
4. Floyd R. Watson Professor. The Absorption of Sound by Materials. University of Illinois Bulletin. vol. xxv November 29, 1927 no. 13.
5. M.A.Chelidze, D.Nizharadze, J.Javaxishvili, M.Tedoshvili. Investigation of Sound Absorption. Modern achivements of Science and Education VIII International Conference September 29 –Octoumber 06, 2016 Jerusalim (Israil) pp. 66-71. http://www.iftomm.ho.ua /docs/MASE_2016.pdf
6. Eugen Skudrzyk. The Foundation of Acoustic. Basic mathematics and basic accounts. 1971 Spribger-verlag Wien New York. V1,520p. https://www.livelib.ru/book/
7. Lawrense E. Kinsler, Austrin r. Frey, Alen B. Coppens, Jeimes V. Sanders. Fundamentals of acoustics. Fourth Editions. New York, Toronto 1982 p.550
8. I.B. Crendall Acoustics. ISB5397001325 2009 168p. www.twirpx.com/file/540138
9. M.A.Chelidze. Investigation of Sound Absorption Characteristics in Materials by Help of Subtraction Method on the Base of PC. Science and Education VIII International Conference June 27 – Jjuly 06, 2015 Bergen (Norway) pp. 24-27. http://www.iftomm.ho.ua/docs/SE-_2015.pdf
10. Andrew F. Seybert Notes on Absorption and Impedance Measurements. University of Kentucky Lexington, KY 40506-0108 859-257-6336 x 80645
11. The Vibrations in Technique. Reference book in 6 volumes. Under editing M.D. Genkina. M. "Machine building" 1981. t.1.,t .4.
12. Muehleisen plenary. Acoustic properties materials. Measurement of the Acoustic Properties of Acoustic Absorbers. Illinois institute of technology. Transporting Lives. Investing the Future. www.iit.edu

The article is presented by 13 pictures.

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