FIFTH INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
DECEMBER 15-18, 1997
ADELAIDE, SOUTH AUSTRALIA
Invited Paper

MEASUREMENT OF FRAME MOTION IN HIGH INTENSITY SOUND PROPAGATION THROUGH FLEXIBLE POROUS MATERIALS

K. Khirnykh
School of Engineering Systems and Design, South Bank University, London SE1 0AA, U.K. E-mail: khirnyk@vax.sbu.ac.uk

A. Cummings
Department of Engineering Design and Manufacture, University of Hull, Hull HU6 7RX, U.K. E-mail: a.cummings@engineering.hull.ac.uk

ABSTRACT

In this paper, a method for measuring the vibrational velocity of the solid skeleton of a flexible, porous, sound-absorbing material is described. This is based on a simple electromagnetic principle, involving a thin conductor that is structurally connected to the frame of the absorbent and placed in a magnetic field. The method appears to yield acceptably accurate data. The sample test results that are presented here demonstrate that useful comparisons can be made between acoustic data and frame velocity measurements, especially where high amplitude, non-linear, effects are present.

I. INTRODUCTION

Porous media have many applications in acoustics, mainly as sound absorbents. One such use is in dissipative automobile muffles, where extremely high sound pressure levels - up to about 180 dB - can exist. At very high sound levels - in excess of about 150 dB - non-linear hydrodynamic effects begin to occur in the coupling between the fluid contained in the material, and the solid skeleton (see Nelson [1], Kuntz [2], Kuntz & Blackstock [3], Lambert [4], Khirnykh *et al.* [5, 6]) Moreover, the solid frame of the material itself is flexible and so coupling will exist between a fluid wave and a structural wave in the frame (Zwicker and Kosten [7], Sides *et al* [8]). The bulk mechanical properties of porous media are not straightforward [9] and - particularly in the case of fibrous media - tend to be non-linear (see, for example, Hilyard [10], Pritz [11] and Khirnykh *et al.* [5, 6]). As a result, at high acoustic levels, the physics of the fluid/structural wave interaction is highly complex, involving as it does the non-linear hydrodynamic coupling between a fluid-borne wave and a non-linear structural wave.

As a part of a theoretical, numerical and experimental study of the interaction between high-intensity sound and lightweight flexible porous media, it was required to carry out measurements of the structural motion of the frame of the material as well as of sound pressure and acoustic particle velocity, up to frequencies of several hundred Hertz. Clearly, even small accelerometers cannot be used to measure frame motion in lightweight media such as glass fibre or plastic foams because of the mass-loading effect, and some alternative method must be employed. Laser methods might seem attractive, but they could only be used to measure the vibrational motion of the surface of the material and would also require the use of transparent walls in a duct containing the porous material. Furthermore, the motion could only be measured at discrete points by laser techniques, and these localised data would quite likely not be representative of the motion of the frame, space-averaged over a volume or area large compared to the characteristic pore dimensions. A much simpler method was devised in the present investigation, involving the use of a thin metallic wire passing through the porous material and placed normal to a magnetic field; the electro-motive force between the ends of the wire then gave a measure of the average vibrational velocity of the material along the length of the wire, normal to the axis of the wire and to the direction of the magnetic field.

In this paper, the above experimental technique for the measurement of frame vibration is outlined, the experimental apparatus is described and some experimental results are presented and discussed.

II. A NEW METHOD OF MEASUREMENT OF THE FRAME VELOCITY

A. Principles of the Method and Sources of Error in the Measurements

For the sake of simplicity it will be assumed that a one-dimensional sound wave passes through a flexible porous medium and that the structural motion is also one-dimensional, in the x direction as illustrated in Figure 1.

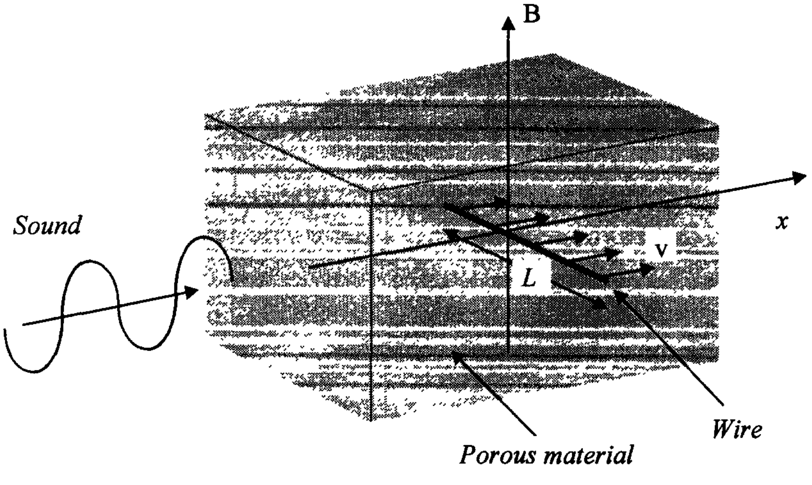

Figure 1. Orientation of sound propagation, wire and magnetic field

The motion of the frame of the porous medium will be driven by the oscillatory fluid motion *via* the fluid/structural coupling mechanism involving both viscous and (at high acoustic levels) inertial forces. A magnetic field is applied to the porous medium and is assumed to be uniform and directed normally to the x axis. A thin, flexible, metallic wire having a thin surface layer of adhesive is threaded through the pores of the material (which is assumed to of a sufficiently open structure so as to permit this without any significant distortion of its structure), and runs normal to the x axis and to the direction of the magnetic field.

In general, the electro-motive force (e.m.f.) over a length L of the wire will be given by

$$E = \int_L (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{L}\,, \tag{1}$$

where **v** is the velocity vector of the wire at any point, **B** is the magnetic field vector at the same point and $d\mathbf{L}$ is the relative position vector between the ends of an element of wire having length dL. In the present case, if **v**, **B** and $d\mathbf{L}$ are assumed always to be normal to one another and $|\mathbf{B}|$ is assumed constant, we may therefore write Eq. (1) simply as

$$E = \int_L vBL\ dL = \langle v \rangle BL\,, \tag{2}$$

where $\langle v \rangle$ is the average of v along the length of the wire. Provided B - the magnitude of the magnetic field strength - is known, the e.m.f. E, developed along the length of the wire embedded in the porous medium, gives a measure of the average vibrational velocity of the wire along its length.

For Eq. (2) to give a measure of the vibrational velocity of the solid frame of the porous medium in the *absence* of the wire, it must be assumed that the wire has the same vibrational velocity as the frame and furthermore that the presence of the wire does not affect the frame motion. A detailed analysis of this problem is beyond the scope of the present investigation and would involve the solution of the equations of motion of the frame and wire in two dimensions, including both compressional and shear wave effects in the frame. Instead, we rely here on experimental data indicating that there is no significant dependence of the measured frame velocity on the diameter of the wire, for a given wire material. The experimental arrangement is described in Section III of this paper, but it is only the experimental data, taken for two differing thicknesses of wire, that are of interest at this point. The test material was “Bulpren” foam of 72 pores per inch (ppi) (see Section III for further details), and the wires used were of tinned copper, 40 μm and 140 μm diameter. These wires were threaded through the absorbent by using a fine needle. Two notionally identical, but different, samples of foam were employed in the tests and the wires were inserted at the same position in both samples. Two separate samples were used because it was assumed that the damage incurred to the sample by insertion of the wire would render the sample useless for further tests once the wire had been removed. The test frequency was 120 Hz, and - for identical incident sound fields in the two cases - the r.m.s. velocity amplitude of frame vibration was found to differ by 5% between the two tests. This small difference could have been attributable to variations in mechanical properties between the two samples of foam as much as to the effect of the mass of the wire, and in any case was taken to signify that, for the range of wire thickness and for materials similar to those used in the tests, there was no significant mass-loading effect of the wire on the absorbent.

It is almost inevitable that there would be “end effects” in this method of measurement of the frame velocity, caused by small lengths of wire moving in the magnetic field but not embedded in the porous medium, since the ends of the wire would need to bend at some point in order to accommodate the motion of the wire. These can be minimised by careful design and should in any case be small. Some idea of their magnitude is given in the following subsection on calibration.

A further possible source of error, that could in principle be of concern at higher frequencies, relates to any structural resonance effects that might occur in the unsupported lengths of wire within the absorbent, between the points at which it is in contact with the solid frame of the porous medium. Again, a detailed treatment of this effect is hardly possible unless comprehensive information is available concerning the effective boundary conditions at the contact points and the distribution of unsupported lengths of wire. We can, however, make order-of-magnitude estimates about the resonance frequencies. The 140 μm diameter wire was used in the great majority of the experimental tests in view of its relative robustness and ease of handling, so we base our estimates on this. The coarser of the two foam sound-absorbing materials used in the experiments had 42 ppi, so that a typical pore dimension was about 0.6 mm. Supposing the wire was effectively simply supported every five pore dimensions, we may now estimate the fundamental resonance of an unsupported length of wire - in isolation from the rest of the wire - as $f_1 = (\pi / 2l^2)\sqrt{EI / \rho A)}$, where l is the length of the wire between supports, E is the Young's modulus of the wire material, ρ its density, I its second moment of area about the neutral axis and A its cross-sectional area. For a copper wire as above with l = 3 mm, we find $f_1 \approx 22\,\text{kHz}$, which is well above the frequency range of interest. It is likely that l has been overestimated here, but even if the wire were supported only every ten pore dimensions, we should now have $f_1 \approx 4.5\,\text{kHz}$, which is still safely clear of the upper frequency of interest. It therefore seems unlikely that resonance effects in the wire should be of any concern.

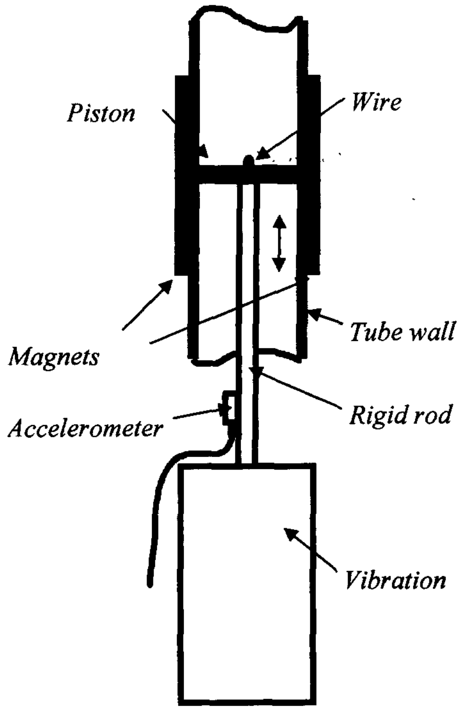

Figure 2. Calibration arrangement.

B. Calibration of the System

The magnetic field in the experimental apparatus was provided by two identical ferrite permanent magnets, measuring 100×151×25 mm. These were clamped firmly to opposite sides of a perspex tube with 19 mm walls and an internal cross-section of 60×60 mm (see Section III for details). The distance between the opposite faces of the magnets was therefore 98 mm. The magnetic field strength at the position of the wire was measured by means of a Gauss meter with a Hall probe, and was found to vary between 0.05856 and 0.0602 Tesla along the length of the wire, the average value being 0.0596 Tesla. This figure is accurate to about 1%.

Although the e.m.f. measured at the ends of the wire should be proportional to the frame velocity *via* a coefficient which can be directly calculated from a knowledge of the magnetic field strength and length of the wire (see Section IIA), a separate test was carried out in order to assess the magnitude of any extraneous effects that might cause departures from the theoretical estimates of frame velocity.

A rod of non-ferromagnetic plastic material was attached to a Brüel and Kjær (B&K) Vibration Exciter type 4809 and placed in the section of the rectangular tube in which the porous samples were tested. A conducting wire, 140 μm in diameter, was glued to a square piston of side 55 mm, which was attached to upper end of the rod as shown in Figure 2. The length of the aluminium rod was such that no axial vibrational resonance effects occurred within the frequency range of the calibration experiments.

Because the voltage to be detected was very low it was necessary to amplify the signal, and accordingly an amplifier with a gain of 1300 was built. The amplifier was battery powered and had a very high input impedance in order to reduce noise caused by possible ground loops and extraneous induction effects. The voltage signal from the wire was fed to the amplifier through conducting wires that were glued to the tube walls in order to eliminate spurious signals caused by vibration. A twisted pair of conducting wires was used away from the vicinity of the magnets in order to minimise the picking up of electrical noise.

The voltage signal from the wire was compared to the integrated signal from the accelerometer (B&K type 4332, with B&K Charge Amplifier type 2635) over a range of frequencies from 120 to 300 Hz, appropriate factors being applied to yield the inferred r.m.s. velocity signals. These velocity signals were in good agreement, the maximum discrepancies being about 2.5%, which could be accounted for by the small inaccuracy in measuring the amplifier gain, end effects leading to a small uncertainty in the length of the wire (see Section IIA) and errors in measurement of the magnetic field strength.

III. THE EXPERIMENTAL APPARATUS

In Figure 3 is shown a test apparatus consisting of a JBL 2206H 300 mm diameter cone loudspeaker, mounted in an enclosure and coupled by means of a square-section conical horn to a perspex tube of 60 mm × 60 mm internal cross-section.

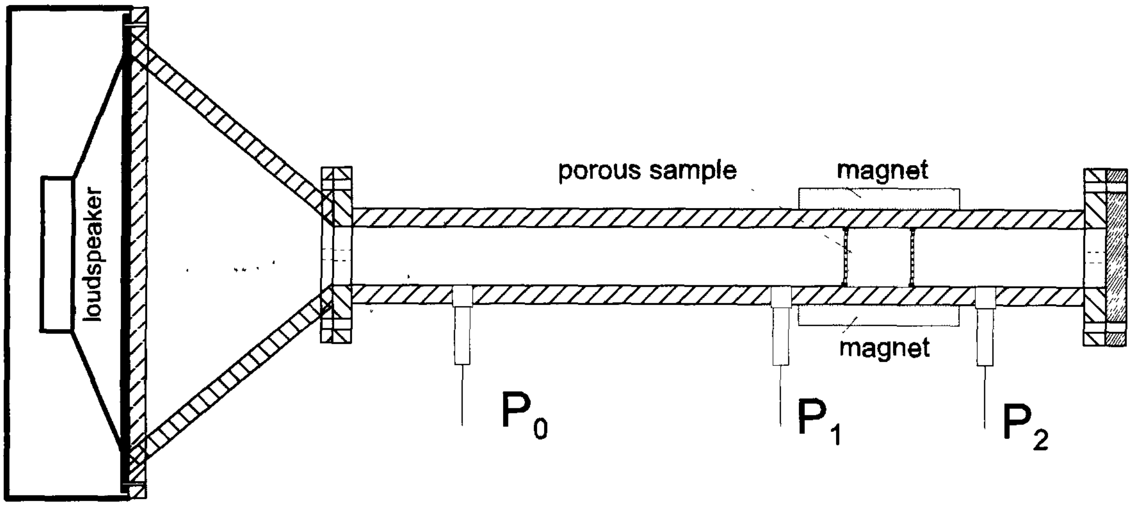

Figure 3. Experimental Apparatus.

Two identical magnets of dimensions 100×151×25 mm were secured by a G-clamp to the Perspex tube. To reduce possible distortion of the magnetic field only non-magnetic nylon bolts were used. All the three microphones were B&K ¼ in. condenser microphones. Microphones P_1 and P_2, positioned in the side walls approximately 15 mm away from the sample, were used to measure sound pressure level (SPL) in front of and behind the sample. Microphones P_0 and P_1 were used to measure the impedance of the sample and the cavity or termination behind the sample by using the two microphone technique [12].

All the experiments were carried out with two types of porous materials: "Bulpren" S75 5734 foam with 72 ppi and "Filtren" 2145 foam with 42 ppi. The foam samples had dimensions of 60 mm × 61 mm × 61 mm. Both these materials were fully reticulated polyurethane foams.

A series of tests was carried out with the two types of sample: i) with a cavity, ii) with a rigid termination and iii) with an anechoic termination behind the sample. The arrangement shown in Figure 3 shows an experiment with a cavity behind the sample. To test the consistency of the results three wires were incorporated inside each sample: one centrally positioned and two displaced 10 mm to the right and left respectively in the *x* direction (see Figure 1). The frame velocity data presented later in this paper were taken from the centrally-place wire; the two adjacent wires had given almost the same signal, indicating that the frame velocity was not sensitive to *x*.

IV. SOME EXPERIMENTAL RESULTS

The main aim of the experiments was to test the method and study the patterns of frame movement at different frequencies and sound pressure levels. During the experiment the following quantities were measured: velocity of the frame, sound pressure signal in front of and behind the porous sample (the latter in cases where there was a cavity behind the sample).

The r.m.s. value of the frame velocity was measured for sound pressure levels in front of the sample (P_1) equal to 140 dB and 130 dB and in the frequency range from 150 to 1100 Hz. Additional data included values of impedance at the surface of the sample measured by the two-microphone method mentioned above. These data helped to establish the existence of resonances and explain maximum values of the frame velocity. In some cases a maximum in the frame velocity occurred at a different frequency from that of the acoustical resonance. For example, Figures 4 and 5 show r.m.s. values of the frame velocity together with impedances of the Filtren and Bulpren samples correspondingly. The imaginary part of the impedance of porous samples with a 40 mm cavity is equal to zero at 650 Hz in the case of Bulpren and at 700 Hz in the case of Filtren, indicating acoustical resonance and maximum absorption. The

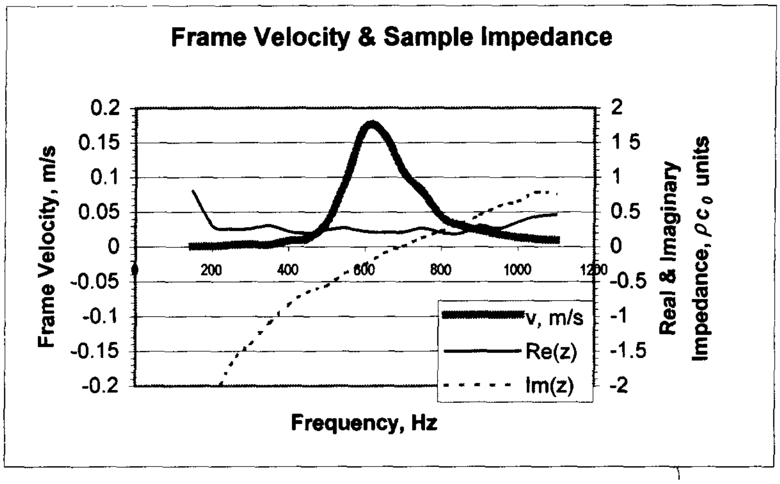

Figure 4. Frame displacement and impedance of Filtren foam; p_1 =140 dB, cavity depth = 40 mm.

fact that maxima in the frame velocity occurs at a different frequency for both samples (500 Hz for Bulpren and 600 Hz for Filtren) possibly indicates a structural resonance of the material which is coupled to an acoustic resonance of the cavity (assuming that Filtren and Bulpren are rather different in their elastic properties). This may take place for a number of reasons, discussion of which lies beyond the scope of this paper.

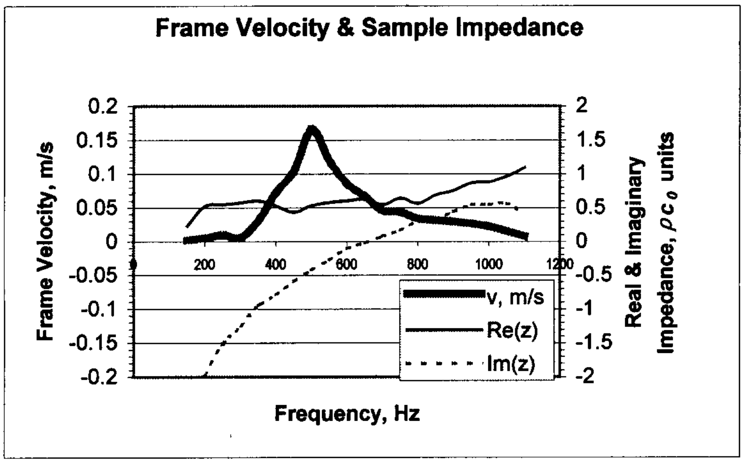

Figure 5. Frame displacement and impedance of foam plus cavity for Bulpren foam; p_1=140 dB, cavity depth = 40 mm.

Some of the measurements were carried out at sound pressure levels of P_1=165 dB. During the measurements at this higher SPL it was found at some frequencies that the frame movement exhibited distinctly non-linear features. For, example in Figure 6 is shown the time history of the frame velocity of the Filtren sample at P_1 =155 dB and f = 220 Hz. The coefficients of the first harmonics of P_1 and P_2 were equal to 2.1% and 1.7% respectively. At the same time the coefficient of the third harmonic of the frame velocity in this case exceeded 58%, indicating a highly non-linear frame motion.

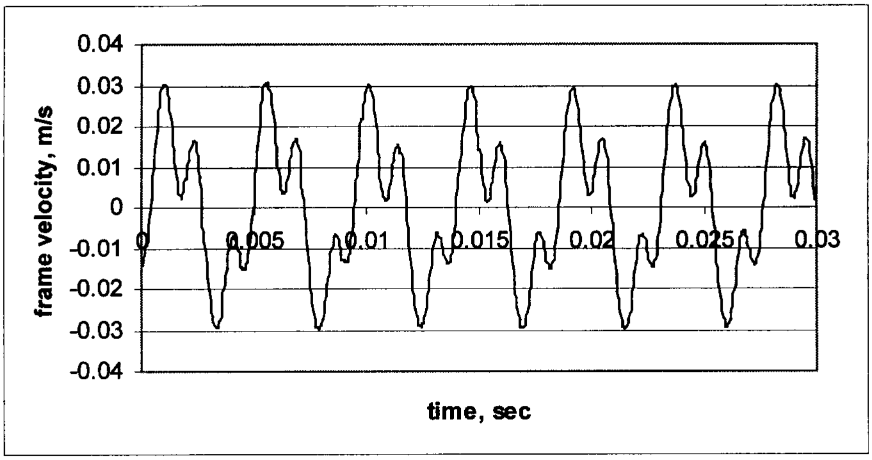

Figure 6. Non-linear behaviour of frame vibration. Time history of the frame velocity of Filtren sample at p_1 = 155 dB and f = 220 Hz.

V. CONCLUSIONS

The main point of this paper has been to describe a simple method of measuring the vibrational velocity of the solid frame of a flexible porous material. This method is quite robust, has a reasonably predictable accuracy and has several desirable features: it does not involve the use of any device (such as an accelerometer) that would mass-load the material, the velocity can be measured in regions of the material away from the surface, the method does not require penetration of laser light into the inner regions of the medium, and it yields a space-average of the vibrational velocity along the length of a wire that is embedded in the material (thereby avoiding any spurious local variations in velocity amplitude). Its main disadvantages would seem to be that magnets have to be placed on either side of the wire and that measurement of a three dimensional vibrational velocity field could involve a cumbersome arrangement of wires and magnets. While these drawbacks could create difficulty in come circumstances, skilful design of the apparatus could enable the ready measurement of two dimensional velocity fields under many circumstances.

REFERENCES

1. D.A. Nelson. 1984, University of Texas at Austin, Applied Research Laboratories, MS Thesis. Propagation of finite-amplitude sound in air-filled porous materials.
2. H.L. Kuntz. 1982, University of Texas at Austin, Applied Research Laboratories Technical Report ARL-TR-82-54. High-intensity sound in air saturated porous materials.
3. H.L. Kuntz, D.T. Blackstock. 1987, Journal of the Acoustical Society of America 81, 1723-1731. Attenuation of intense sinusoidal waves in air-saturated bulk porous materials.
4. D.K. Wilson, J.D. McIntosh, R.F. Lambert. 1988, Journal of the Acoustical Society of America 84, 350-359. Forchheimer-type nonlinearities for high-intensity propagation in air-saturated porous media.
5. K.Khirnykh, A.Cummings, B.M.Shield. Proceedings of Euronoise '95, Lyon (France), 21-23 March 1995, 3, 841 - 846. Modelling of high-amplitude sound propagation through flexible porous material.
6. K.Khirnykh, A.Cummings, B.M.Shield. Proceedings of InterNoise 1995, Newport Beach, California, USA, 1, 449-452. A non-linear model for flexible porous materials.
7. C.Zwikker, C.W.Kosten. Sound Absorbing Materials, 1949. Elsevier Publ. Co.
8. D.J.Sides, K.Attenborough, K.A.Mulholland. 1971, Journal of the Acoustical Society of America 19, 49-64. Application of a generalised acoustic propagation theory to fibrous materials.
9. R.I. Nesterov, A.I.Toropov. 1987, Soviet Machine Sciences (English Translation of "Mashinivedenie") 2, 46-53. Evaluation of the rigidity and tensile strength of highly porous fibrous materials.
10. N.C.Hilyard and A. Cunningham (eds.). Low Density Cellular Plastics - Physical Basis of Behaviour: Chapman & Hall, 1994.
11. T.Pritz. 1986, Journal of Sound and Vibration 106, 161-169. Frequency dependence of frame dynamic characteristics of mineral and glass wool materials.
12. I.V.Lebedeva, S.P.Dragan. 1988, Measurement Techniques (in Russian) No. 8, 52. Measurements of acoustical parameters in tubes using a two microphone method.