EFFICIENCY OF EJECTOR DEVICES AND SOUNDABSORBING STRUCTURES FOR JET NOISE REDUCTION

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Abstract

The experimental investigation results related to noise of model jets issuing from ejector noise-suppressing devices of rectangular and axisymmetrical shape and containing multi-element nozzle and ejector are presented. The acoustical efficiency of noise-suppressing devices relative to axisymmetrical profiled nozzle with identical critical section areas and pressure ratios at the nozzles is determined. The results of theoretical and experimental research of high frequency noise reduction in the ejector duct with the use of soundabsorbing treatments are presented. The optimum treatment impedance dependency on aeroacoustical and geometrical parameters of the duct providing the most effective attenuation for the definite duct model is determined. Parameters of real structures, the impedance of which is the closest to the optimum values obtained on condition of the treatment impedance optimization are found. The experimental investigation data on noise reduction at the ejector exit due to locating multi-layered soundabsorbing structures in the duct are given. Comparison between the prediction and experimental investigation results is made.

1. Introduction

The provision of ecological requirements, including those on noise exposure, is the key condition for permission of the second generation supersonic passenger transport (SST) service. This means that SST must produce the community noise levels acceptable from the standpoint of environment protection and this, as a rule, is rather difficult to realize near airports. The supersonic transport of the second generation being under development must comply with the current requirements of ICAO for the community noise of the subsonic passenger aircrafts [l-2].At the same time SST must be designed on the basis of achieving the optimum economic characteristics for different variants of its application.

To reduce jet noise of high intensity at the second generation supersonic aircraft take-off, ejector suppressors with minimum thrust losses are developed in different countries. In developing such suppressors a complex approach is used, which consists in low-frequency noise reduction at the expense of using special construction elements which intensify mixing between hot jet and ejected cold air. Thus, mechanical multi-element suppressors break the jet into a number of smaller jets and this leads to more intensive mixing and reducing the radiated acoustic energy in the low-frequency region. As a result, the noise spectrum is shifted into the region of higher frequencies. To decrease the high-frequency noise, soundabsorbing structures of the resonance type are used. Attenuation frequency band broadening .in the ejector duct is achieved with the use of multi-layered structures (double- and triple-layered) of different shape and combined structures and at the expense of non-symmetrical location of treatments on the opposite ejector walls, soundabsorbing treatments with non-identical impedances, multi-parametric soundabsorbing treatments, f. i. such as double -and triple-layered ones. Controlling the additional freedom degrees in such structures, one can broaden the attenuation frequency spectrum without increasing the overall treatment area. The structures with small non-linear effects of the absorbing layer, the impedance of which slightly depends on sound pressure level and flow velocity and the attached mass is minimum, are of special interest since all these permit significant broadening of the soundabsorption coefficient frequency characteristic.

This work presents the results of investigations related to efficiency of applying ejector noise-suppressing devices including multi-element nozzle and ejector and efficiency of applying soundabsorbing structures of different types.

2. Efficiency of ejector noise-suppressing nozzles

First we describe the results of investigations concerning the application of ejector noise-suppressing devices consisting of multi-element nozzles and ejector, in comparison with the reference axisymmetrical profiled nozzle on condition that jet issue from them occurs at identical pressure ratio and critical cross-section areas. Ejector noise-suppressing nozzles including multi-element corrugated sets and an ejector of rectangular or axisymmetrical shape were studied.

The acoustic characteristics of jets issuing from the model noise-suppressing nozzles were investigated in the anechoic chamber which allowed testing under conditions corresponding to static ones and to aircraft flight at take-off Mach number M = U/c =0.2-0.3, where U is the cocurrent flow velocity, c is the ambient sound speed. The sound pressure level measurements were carried out simultaneously at several points with the use of B&K microphones. Condenser microphones were placed on an arc with the radius of 2.5 m and with the center at the nozzle exit section in the range of angles to the jet axis from 30° to 105° (Fig. 1). The signals from the microphones after amplification were recorded with the use of a multi-channel cassette recorder "SONY KS616U". The duration of recording the acoustic signal was 60 sec. The recorded signals

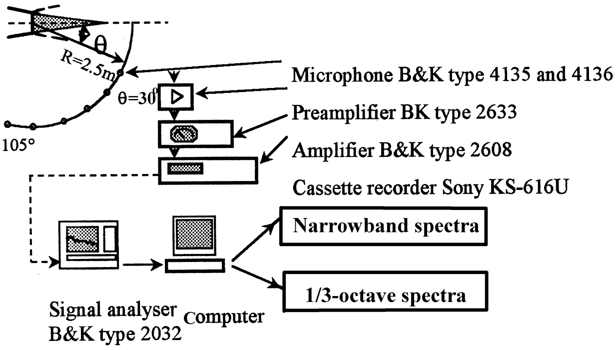

Fig.1. Scheme of measurement and data processing

of acoustic pressure fluctuations gave as the result of processing by an analyzer B&K type 2032 the narrow-band spectra with the band width Δf=32 Hz and with the upper limit of the frequency range equal to 25 kHz. In the course of the subsequent analysis these spectra were transformed into 1/3-octave bands. The signal recordings were also processed with the use of a specially developed analog-digital signal processing system which permits obtaining the narrow-band spectra of sound pressure levels with the upper limit of the frequency range up to 45 kHz.

The flow visualization at the multi-element ejector nozzle exit was realized in the anechoic chamber with the use of direct shadowgraphing. The flow under consideration was illuminated by a pulsing light source located at a distance of 2 m from the nozzle axis. The shadowgraph was recorded directly on the wide-format aerophotography film of high sensitivity and with high contrast coefficient. The exposure time determined by the light impulse duration was fractions of a microsecond.

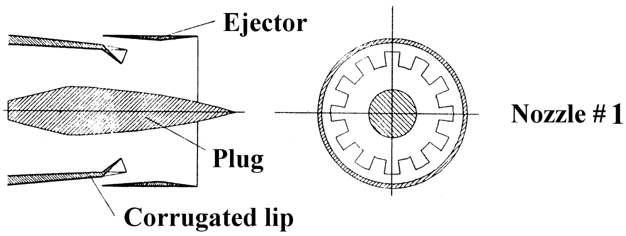

Fig.2. Scheme of axisymmetrical ejector nozzle

The detailed description of ejector noise-suppressing nozzles is presented in [3,4]. Axisymmetrical nozzle consists of a corrugated lip, a movable ejector and a central plug (Fig.2). The take-off noise reduction is provided at the expense of accelerated mixing between the jet issuing from the engine and the ejected air inside the ejector duct. At supersonic cruise flight the corrugation is removed from the jet and forms a supersonic part of the nozzle and the ejector is advanced to the nozzle and shuts down the external air flow. The multi-element noise-suppressing nozzle of rectangular shape consists of a lip, two interchangable corrugations, a central plug, side walls and ejector flaps (Fig.3).

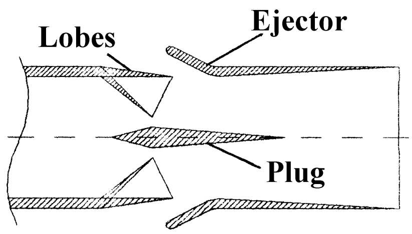

Fig.3. Scheme of the multi-element ejector nozzle of rectangular shape

The interchangable corrugations have 3 or 4 lobes with different edge shapes. The side walls and flaps are made interchangable to provide the possibility of investigating the noise of jets issuing from different elements of the multi-lobe nozzle. The ejector flaps are realized in versions – with solid walls and with windows which provide an additional air supply into the mixing zone. Noise-suppressing nozzles were designed and manufactured in propulsion division.

Application of the ejector nozzle causes the discrete noise component disappearance in comparison with the noise spectra of jet issuing from the reference axisymmetrical nozzle at the same issue regime; the jet noise level reduction takes place over a wide frequency range in comparison with the case of jet issue from the circular nozzle. The greatest noise level reduction of issuing jets, both under static conditions and under coccurrent flow conditions, in the case of applying noise-suppressing devices is observed in the direction of the most intensive radiation ($\theta=30^0$) and in the frequency region corresponding to the acoustic radiation spectrum maximum. For example, the greatest noise level reduction at static conditions for an axisymmetrical noise-suppressing nozzle is the value of 10 dB order and it is observed in the frequency range f=1.6-3.0 kHz, for a noise-suppressing nozzle of rectangular shape the largest noise level reduction is about 14 dB in the frequency range f=1.0-2.0 kHz (Fig.4).

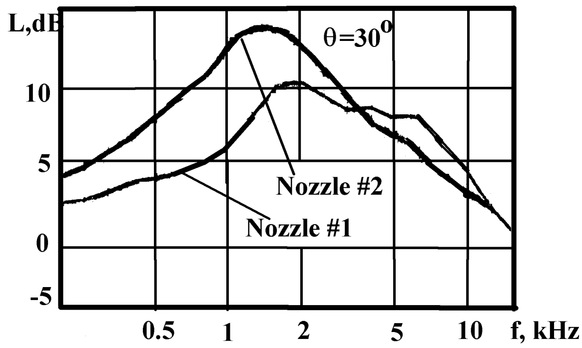

Fig.4 Efficiency of axisymmetrical ejector nozzle

In the regimes corresponding to aircraft take-off the effective thrust losses for an axisymmetrical noise-suppressing nozzle are 5.5 percent of the ideal nozzle thrust and less than 2 percent in cruise supersonic flight, thrust losses for a noise-suppressing nozzle of rectangular shape exceed these values insignificantly [4,5].

The nature of spectral characteristic transform of issuing jet noise is explained by processes of the ambient air ejection, its mixing with the main flow and respective transform of turbulent flow structure. Thus, the results of flow visualization at the ejector exit with the use of direct shadow photography show that there is a certain connection with the research data on the acoustic field of jets issuing from noise-suppressing devices. The more effective mixing between the main flow and the ejected air takes place in the mixer, the greatest reduction of acoustic radiation intensity is observed. The nature of spectral noise characteristics of jets issuing from the noise-suppressing devices is explained by considering two regions of turbulent flow mixing. In the first region which is inside the ejector, mixing of the jets issuing from the nozzle elements with the ejected air occurs. Due to high velocity of jets and their small characteristic size the noise radiated from this region is of higher frequency in comparison with the noise of the reference jet. As a rule, this noise is called “lobe noise”. In the second region mixing of the flow issuing from the ejector with the ambient air occurs. Since the characteristic flow velocity is less than the reference jet outflow velocity because of preliminary mixing in the ejector duct and the ejector exit diameter is larger, the noise radiated is more low-frequency. This noise is called “mixing noise”. The greatest noise level reduction due to applying ejector noise-suppressing nozzles is the value of 10-14 dB and is observed in the frequency region corresponding to “mixing noise” of flow at the ejector exit.

3. Investigations of soundabsorbing structure efficiency

Evaluation of efficiency of applying soundabsorbing structures (SAS) inside the ejector duct was made with using two models of flow: two-phased flow consisting of high-velocity core and cocurrent flow and of uniform flow with the boundary layer. The first model is realized in the initial part of the ejector and the second one in its succeeding parts. In developing the theory the primary emphasis is placed on accounting for the effects connected with sound refraction and reflection from the boundaries of flow layers and in the boundary layer which influence the modal field structure in the duct and, finally, the optimum SAS parameters [6].

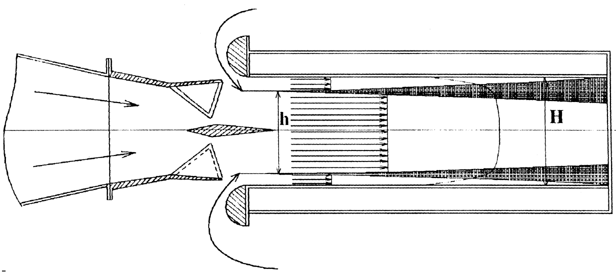

Fig.5. Scheme of flow in ejector duct

The assumed simplified model of flow inside the ejector duct is schematically shown in Fig.5. In the initial part the flow consists of a high-velocity hot core and a relatively low-velocity and colder cocurrent flow. Further an averaged flow is formed due to intensive mixing, and the averaged flow is approximated to a uniform flow with the boundary layer. It is assumed that the acoustic field in such a duct is generated by a harmonic point source located in the zone of maximum intensity of noise generation. Convenience of considering the point source field consists in possibility of its extension to the case of the complex source field by integrating this field over the volume occupied by this source. The duct walls are treated by the soundabsorbing material, which is described by complex admittance β. In a general case the admittances of the opposite walls are not similar. In the case of two-phased flow its parameters are as follows: h is the potential core height, V_2 is the flow velocity in the core; ρ_2 is the medium density in the core; c_2 is the sound speed in the core. In the cocurrent flow (boundary layer) the respective parameters have index I, the duct height is H.

It is supposed that the boundary between the flows in the duct is sufficiently marked and is the shear layer on which the acoustic displacement continuity is fulfilled. In the averaged flow the velocity profiles in the boundary layer on the upper and lower walls are expressed as follows:

$$M(y) = M_o \Phi\left(\frac{H-y}{\delta_1}\right);$$

$$M(y) = M_o \Phi\left(\frac{H}{\delta_2}\right);$$

$$\Phi(0) = 0; \quad \Phi(1) = 1$$

where Φ is the arbitrary function, M=V/c.

The acoustic field in the duct satisfies the convective wave equation in the shear flow with the right-hand side:

$$\nabla^2 p - \frac{1}{c^2}\frac{D^2 p}{Dt^2} + 2\rho \frac{dV}{dy}\frac{\partial u_y}{\partial x} = = -A_0 \delta(x - x_0)\delta(y - y_0)\exp(-i\omega t), \quad (1)$$

where p is the acoustic pressure, A_o is the source amplitude, (x, y) are the coordinates of the observation point, (x_o, y_o) are the source coordinates, ω is the circular frequency, $\frac{D}{Dt} = -i\omega + V\frac{\partial}{\partial x}$; u_y is the acoustic velocity in y-direction. Boundary conditions on the lower and upper duct walls are respectively as follows:

$$i\omega\frac{\partial p_1}{\partial y} = -\frac{\beta_0}{c_1}\frac{D^2 p_1}{Dt^2}; \quad y = 0; \tag{2}$$

$$i\omega\frac{\partial p_1}{\partial y} = \frac{\beta_1}{c}\frac{D^2 p_1}{Dt^2}; \quad y = H; \tag{3}$$

Besides, in the shear layer region the conditions of acoustic displacement continuity are to be fulfilled:

$$\eta_{1,2} = \eta_{2,1} \qquad \eta_{2,3} = \eta_{3,2} \tag{4}$$

The condition of momentum conservation in the axis "y" direction is the following:

$$\frac{Du_y}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{5}$$

Apply Fourier transform simultaneously to Equation (1), boundary conditions (2)-(4) and Equation (5):

$$P = \int_{-\infty}^{\infty} p\exp(-i\alpha x)dx, \quad \eta = \int_{-\infty}^{\infty} \eta e^{-i\alpha x}dx \tag{6}$$

Note that at Fourier transform operator $\frac{D}{Dt}$ is replaced by $-i\omega + iV\alpha$, and the displacement image is connected with the pressure image by the following relation:

$$(-i\omega + iV\alpha)^2\eta = -\frac{1}{\rho}\frac{\partial P}{\partial y},$$

and Fourier transform from $\frac{\partial u_y}{\partial x}$ is as follows:

$$F\left(\frac{\partial u_y}{\partial x}\right) = \frac{\alpha}{\rho ck}\frac{dP/dy}{(1 - M\alpha/k)}$$

After Fourier transform, accounting for the singularity presence at the source, the respective algebraic transformations and reverse Fourier transform the expressions for the acoustic field in the ejector duct were obtained which correspond to the first flow model in the ejector duct. In solving the similar task with the use of the second flow model in the ejector the method of matched asymptotic expansions was used according to which a sufficient smallness of the boundary layer thickness was supposed. After realizing the respective computation procedure the expressions for the acoustic field were also obtained, which corresponded to the second flow model.

Attenuation in the duct with the treatment length equal to I can be found with the use of the formula

$$\Delta SPL = 10\lg\frac{N(0)}{N(1)},$$

where N(0) is the energy flow close to the source and N(l) is the energy flow at a distance of I from it. The latter maximum depends on impedance (admittance) of upper and lower treatments. For the case of a point source in the duct and a uniform flow the first reverse task is solved-evaluation of the optimum impedance of walls according to aeroacoustical and geometrical parameters of the duct providing the best attenuation for the model selected.

We have developed a new, more rapid, approach to the optimum impedance determination on condition of providing the minimum energy at the exit of the treated duct part. This approach foundation is a simplex method of minimizing the function of many variables. The optimum impedance of the duct walls is determined according to the following block-scheme:

$$W(\bar{f}, M, Z_1, Z_2, l) \longrightarrow \Delta SPL = $$
$$= \max 20\lg \frac{W_{x=0}}{W_{x=1}} \longrightarrow Z_j^{opt}(\bar{f}, M, l), \qquad j=1,2.$$

The following symbols are used in this scheme: W is the total flow of acoustic energy, $\bar{f}$ -*fH/c* is the dimensionless frequency, SPL is the attenuation, Zj is the impedance of the j[th] wall, Z_j^{opt} is the optimum impedance of the j[th] wall, *l* is the treatment length, M is Mach number.

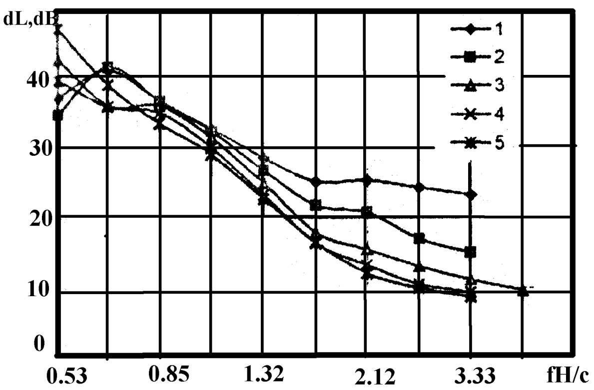

Fig.6. Frequency dependence of optimum attenuation at different source positions and at unequal opposite wall impedance of plane ejector

Below, some numerical results of the first reverse task solution are presented. Fig.6 shows the attenuation frequency characteristics at different source positions at flow velocity M=0.5. In the whole region of middle and high frequencies the optimum attenuation increases as the source drifts to one of walls and at high frequencies this effect is more essential than at middle ones. Application of treatments with unequal impedances on the opposite walls is beneficial in this frequency region, in comparison with those possessing the similar impedances and this benefit is the more, the closer is the source to one of the walls.

At present the character of broadband noise sources generated in the ejector is not studied profoundly. For noise reduction the treatments much more broadband will be required than the well-known honeycomb SAS. One of the possible ways of widening the frequency band of soundabsorption consists in increasing the number of geometric parameters of treatments affecting their impedance, i.e. in increasing the number of freedom degrees which can be regulated at our discretion. It is desirable in this case that such an increase would not lead to substantial complications of the structure itself. Double-layered combined structures [7,8] can serve as an example. These structures have additional layers or cells of different volume and resistance.

Provision of the most uniform frequency characteristics of absorption in a wide frequency range requires a special selection of geometrical parameters of layers and cells of the complicated structures with account for mutual influence of the layers and cells on each other. In this connection the reverse task solution - evaluation of geometrical parameters of double-layered or combined structures which provide the maximum attenuation value in the duct or the maximum soundabsorption coefficient in a given frequency range $\bar{f}_1 < \bar{f} < \bar{f}_2$ - is of great interest. The problem in this case consists in evaluating the minimum of aim-function of the following kind:

$$\Psi = \sum \left| Z(\bar{f}_n) - Z_{opt}(\bar{f}_n) \right|,$$

where $\bar{f}_1 < \bar{f} < \bar{f}_2$; $Z(\bar{f}_n)$ is the impedance of double-layered or combined SAS, $Z_{opt}(\bar{f}_n)$ is the optimum impedance. The optimum impedance was determined according to the method described above. To find the best characteristic of the sound-absorption coefficient, it is assumed that Z^{opt}=l. The task of determining the minimum of ψ-function has not a unique solution and the result depends, to a considerable extent, on the way of ψ minimization. At high sound pressure levels the principle parameters determining the impedance of double-layered and combined structures are the perforation percent F and the air cavity depth h. Thus, in the case of double-layered treatment the aim-function depends on four variables and in the case of combined treatment consisting of N cells the aim-function depends on 2N variables. One can expect that if K=N (in the case of double-layered treatment N=2), i.e. if the number of frequencies f_n from a given frequency range $f_1<f_n<f_2$ is equal to the number of cells (or 2 in the case of double-layered treatment), minψ=0 and at these frequencies the soundabsorption coefficient or attenuation will be the maximum possible. If K>N, minψ>0 and possible gaps in frequency characteristics will be smoothed out, but at none of frequencies the soundabsorption coefficient value or attenuation in the duct will achieve the maximum possible values.

Using a procedure of direct search for a global extremum of ψ-function, several tasks for double-layered and combined treatments in the duct of rectangular section treated on both sides with SAS of identical impedance were solved. In predictions the following conditions were assumed: air flow velocity in the duct was M=0,5; dimensionless length of treatment was l/H=3 where H was the distance between the treated sides of the duct. The sound was excited by a point source located in the middle of the inlet duct section.

Fig.7 presents as example the prediction results obtained on the basis of ψ optimization with the aim of getting the best attenuation characteristics for single-and double-layered treatments. In predictions of geometrical parameters of treatments and of their efficiency two tuning frequencies ($\overline{f_1}$ = 1,69 and $\overline{f_2}$ = 4,23) were selected of the frequency range 1,25<f< 6. This Figure also shows the efficiency of single-layered treatments tuned to frequencies $\overline{f_1}$ = 1,69 and $\overline{f_2}$ = 4,23 of double-layered treatment and the maximum possible attenuation (signs). Each of single-layered structures provides the maximum possible attenuation at its tuning frequency. The double-layered treatment provides the maximum possible attenuation simultaneously at two frequencies $\overline{f_1}$ = 1,69 and $\overline{f_2}$ = 4,23.

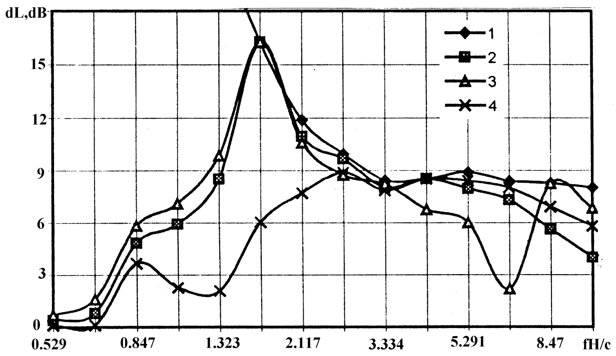

Fig.7. Comparison of attenuation frequency spectra for double-and single-layered treatments with the maximum possible one. 1 – maximum attenuation, 2 – double-layered lining, 3 – single-layered, f=1.69, 4 – single-layered, f=4.23

Thus, on the basis of the second reverse task solution it appeared possible, on the one hand, to determine the parameters of single-layered (uniform) structures of the resonant type which provided the maximum possible attenuation at the tuning frequency and, on the other hand, to provide in the best way the attenuation band widening into the high frequency range with the use of double-layered and combined treatments without extending the area of their placement.

Experimental investigations were carried out on two models of ejector suppressor simultaneously: large-scale model (approximately a one fourth (fifth) scale) and small-scale model [9]. The jet issue velocity for the first model was smaller than that of a full-scale one, but there was a possibility of varying the geometric parameters of treatments according to given aeroacoustical parameters. The second model gave a possibility of making the tests at much higher jet issue velocities but there was no possibility of using multi-layered resonant structures in view of their small thickness. Tests with the large-scale model were made with the use of “flow duct facility”. and allowed separating the noise radiated on the exit side and on the intake side. They were continued in an anechoic chamber with the aim of determining the effect of treated and untreated ejectors on the radiation directivity pattern. In determining the soundabsorbing treatment parameters the emphasis was placed on providing the maximum broadband spectrum of noise reduction with the use of multi-layered structures of resonant type. The tests were carried out with ejectors treated by both single-layered honeycomb SAS and SAS combined of two and three layers (Fig.8)

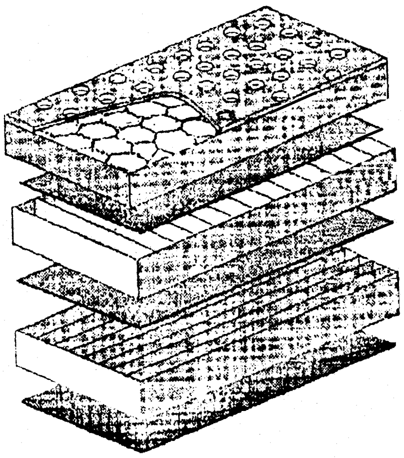

Fig.8. Scheme of soundabsorbing structure investigated

The experimental research permitted proving the main items of the theory developed on determining the optimum parameters of SAS in the ejector duct.

It was shown that a double-layered and, all the more triple-layered treatment, provides a more effective noise reduction in the frequency range of 500-5000 Hz than a single-layered one. The maximum value of noise level reduction achieves 14-15 dB.

Fig 9 presents an efficiency of applying a treated ejector relative to an untreated one obtained as a result of comparison between the sound pressure levels in the far sound field for untreated and treated ejector suppressors in the horizontal plane. A honeycomb soundabsorbing structure with the face sheet perforation percentage F=8%, air cavity depth h=2 mm, was used as the duct treatment. At the ejector exit (under angle $\varphi=60^0$) the SAS provides noise reduction in the whole frequency range under investigation. The largest value of noise reduction is observed at 1600 Hz and is dL=11 dB.

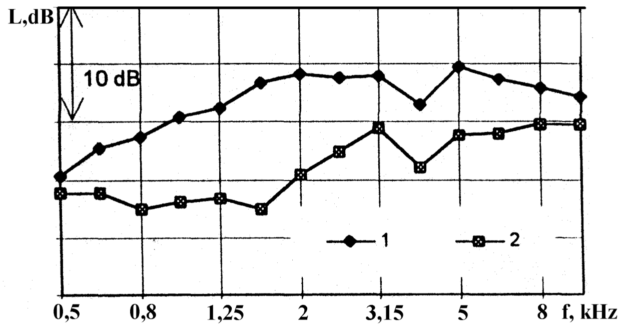

Fig.9. Comparison of sound pressure levels for treated and non-treated ejectors in the maximum radiation direction
1 – non-treated ejector, 2 – treated ejector

Conversion of the SAS acoustic efficiency from model conditions into full-scale ones is possible with the account for the equality of wave parameter $\overline{f}$ =fH/c at the similar frequencies, where c is the sound speed in the compressible flow. Predictions show that M increase in the duct up to transonic values in practice produces no effect on the maximum value of sound power level reduction at high frequencies, but requires variations of the optimum SAS parameters.

Thus, it is shown as the result of predictions and experimental research that due to applying soundabsorbing structures the ejector sound-suppressing device efficiency can be increased by the value of ~10-15 dB in the frequency range corresponding to the acoustic radiation spectrum maximum.

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