inter.noise 2000
The 29th International Congress and Exhibition on Noise Control Engineering
27-30 August 2000, Nice, FRANCE

I-INCE Classification: 2.1

EVALUATION OF VARIATIONS OF THE TURBULENT BOUNDARY LAYER NOISE INSIDE AIRPLANE CAUSED BY ITS MODIFICATION

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Keywords:
PRESSURE FLUCTUATIONS, AIRCRAFT NOISE, TURBULENT BOUNDARY LAYER

ABSTRACT
Possible variations of the wall pressure fluctuation field characteristics produced by the turbulent boundary layer on the external airplane surface, to which the airplane modification can lead, are analyzed and possible variations of elasto-inertial properties of the fuselage skin as well as of vibro-acoustic characteristics of sound-insulation, sound-absorption and vibro-absorption structures are discussed. Asymptomatic relations which describe the effect of these factors on the internal airplane noise produced by the turbulent boundary layer are presented. It is noted that these relations can be used for evaluating the internal noise not only for modified airplane versions but also for new airplanes which have prototypes.

1 - INTRODUCTION
In recent years the manufacturing firms have been modifying with increasing frequency the airplane being under production instead of developing the new ones. This is determined by their efforts to response timely to varying requests and requirements of air companies providing transportation. In this connection the operative evaluation of the anticipated variation of sound pressure levels inside airplane after its modification becomes rather actual. For modern high-speed civil airplane first of all the sound pressure levels produced by the turbulent boundary layer which is the main source of internal airplane noise are to be evaluated.

The task of the present work was to obtain relations that help to predict easily the expected noise variations in the cabin from the turbulent boundary layer of the passenger airplane external surface after its modification. These relations were obtained on the basis of information on the wall turbulent pressure fluctuation field characteristics [1], [2] and also on the basis of the asymptomatic relations obtained in works [3], [4] describing the main regularities in vibrations and acoustic radiation of thin-walled structures excited by the field, random in space and time. Moreover, the peculiarities of the thin-walled structure sound radiation connected with their resonance and inertial behavior were taken into account.

2 - GENERAL ANALYSIS
On the airplane external surface with turbulent flow in the boundary layer the field, random in space and time, of aerodynamic pressure fluctuations of sound frequency range (of pseudo-sonic pressure fluctuations) is observed. Pseudo-sonic pressure fluctuations exactly causing vibrations and the following acoustic radiation of modern high-speed airplane fuselage skin determine noise inside airplane from the turbulent boundary layer. In essence, airplane fuselage skin plays the role of transformer of pseudo-sonic pressure fluctuation energy into sound energy. Besides, the transformation process itself is determined not only by skin properties but also by space-time structure of pseudo-sonic field.

While operating any modern passenger airplane for a long time, a whole series of its modification is realized. Many structural variations of different levels are carried out. Not all modifications and especially airplane structural variations however are accompanied by airplane interior noise variations from the turbulent boundary layer on its external surface. In particular, power unit modification or its substitution

for a new one will not influence considerably the airplane interior noise determined by the turbulent boundary layer, if the main flight parameters (Mach number and altitude) remain the same.
At flight Mach number variations and at the same altitude a significant variation of noise inside airplane from the turbulent boundary layer on its external surface is observed. It is obvious that it is stipulated not only by intensity variations of wall turbulent pressure fluctuations but also by Mach number influence over their space correlation and convective properties. Space correlation and convective properties of the wall turbulent pressure fluctuation field affect significantly the fuselage skin acoustic radiation associated with both its resonance and inertial behavior.
Flight altitude variations at fixed Mach number value is also accompanied by considerable noise variations in the airplane cabin from the turbulent boundary layer due to wall turbulent fluctuation intensity variations. On the whole, it is connected with air density variations the influence of which on wall pressure fluctuations is expressed directly through wall shear stress and Reynolds number effect.
One of the most common modifications, which can significantly influence the noise inside passenger airplane produced by the turbulent boundary layer, is connected with fuselage length variations. In particular, the fuselage length increase at the expense of additional intermediate section is accompanied by a considerable increase of interior noise from the turbulent boundary layer especially in the low-frequency region. It is associated with an increase of wall turbulent pressure fluctuation intensity and fuselage skin acoustic radiation amplification caused by their space correlation increase. At such a type of modification it is possible to use another type of fuselage skin in the additional intermediate section or skin reinforcement in all the sections. This point should also be taken into account at evaluating the noise inside the airplane after its modification.
At modifications and structural variations of modern passenger airplane much attention is paid to passenger cabin trimming which apart from its main function essentially determines sound-insulation inside the airplane. Besides, side trimming panels playing the role of the second wall of airplane double-walled sound-insulating structures significantly influence sound energy transmission in the cabin from external sources.
Airplane modifications and its structural variations often include special measures for noise reduction in the cabin. Moreover, it is possible to substitute trimming panels, to install additional heat-sound-insulating layers and vibro-absorbing treatments and to use new, more effective materials from the standpoint of sound-insulation, sound-absorption and vibro-absorption. In this case, as a rule, there is the information available on characteristics of the new materials. Besides, before making decision about variations of structural elements affecting the sound energy transmission into the cabin there are experimental data available on sound-insulation, sound-absorption, vibro-insulation and vibro-absorption variations obtained in acoustic chambers. The task is to be correct in accounting for the peculiarities of fluctuations and structural radiation excited by the wall pressure fluctuation field of the turbulent boundary layer.

3 - PREDICTION RELATIONS

Airplane interior noise evaluation is usually carried out in standard octave band in the middle frequency range $f_i = 31.5 - 8.0$ kHz corresponding to octave levels of sound pressure $L_p\left(f_i\right)$. In the framework of the task set it is possible to limit oneself with the simplest relation for evaluating the variations of sound pressure levels inside the airplane after its modification or its structural variations:

$$\Delta L_p\left(f_i\right) = \left[L_q^*\left(f_i\right) - L_q\left(f_i\right)\right] - \left[R^*\left(f_i\right) - R\left(f_i\right)\right] - \left[L_\alpha^*\left(f_i\right) - L_\alpha\left(f_i\right)\right] \tag{1}$$

Here $L_q^*\left(f_i\right)$ is the wall pressure fluctuation levels of the turbulent boundary layer [1]; $R\left(f_i\right)$ is the transmission loss which reflects the processes of sound energy transformation and transmission through board structure; $L_\alpha\left(f_i\right)$ is the sound pressure level correction inside the airplane considering the effect of both environment parameters under flight conditions and sound-absorption as well as sound transmission loss through sound-insulating layers and trimming panels. The asterisk indicates the belonging of corresponding values to the airplane after its modification or structural variations.
The variations of skin transmission loss connected with its resonance behavior are evaluated with the help of the relation:

$$R_r^*\left(f_i\right) - R_r\left(f_i\right) \approx 10\lg\left[\frac{\eta^* m^* \eta_r n F\left(\beta\right)}{\eta m \eta_r^* n^* F^*\left(\beta\right)}\right] \tag{2}$$

Here η is the general loss coefficient of skin; η_r is the loss coefficient of radiation; n is the eigen-frequency density; $F\left(\beta\right)$ is the function of dimensionless parameters [3]; $\beta = \left(k_q/\kappa\right)^2$, $\kappa = \left[\left(2\pi f_i\right)^2 m/D\right]^{1/4}$ is the wave number of free flexural waves; m is the surface mass; D is the cylindrical rigidity of structure; $k_q = 2\pi f/U_{ph}$ is the convective wave number; U_{ph} is the phase (convective) velocity. The function $F(\beta)$ includes, besides U_{ph}, the space correlation scales [2] of spectral components of the wall turbulent pressure fluctuation field (longitudinal Λ_1 and lateral Λ_2).

Relation (2) follows from the asymptomatic relation for acoustic radiation of thin-walled structures excited by the wall turbulent pressure fluctuations [3].

The variations of skin transmission loss are associated with its inertial behavior are evaluated by the relation:

$$R_n^*(f_i) - R_n(f_i) \approx 10\lg\frac{(m^*)^2 F(\alpha)}{(m)^2 F^*(\alpha)} \tag{3}$$

where $F(\alpha)$ is the function of dimensionless parameters obtained in work [4]; $\alpha = k_q/k_0$, $k_0 = 2\pi f/c_0$ is the wave number; c_0 is the velocity of sound wave propagation in the cabin.

For comparative evaluation of sound energy flow from the skin, connected with its resonance and purely inertial behavior, it is possible to use the relation:

$$F(\alpha,\beta) = \frac{\pi\eta_r\tilde{n}F(\beta)}{2\eta\tau^{1/2}F(\alpha)} \tag{4}$$

where $\tilde{n}$ is the ratio of the eigen-frequency density of airplane fuselage panels and the eigen-frequency density of the plate with the same geometric dimensions; $\tau = (\rho_0 c_0/\pi f m)^2$, ρ_0 is the air density in the cabin. On condition of $F(\alpha,\beta) >> 1$, the energy flow from the skin, connected with its resonance behavior, will dominate but on condition of $F(\alpha,\beta) << 1$, the energy flow from the skin, connected with its inertial behavior, will dominate.

The effects of variations of environment parameters, sound-absorption inside the airplane and also sound transmission loss variation through sound-insulating layers and trimming panel are realized in conformity with the following relation:

$$\Delta L_\alpha^*(f_i) - \Delta L_\alpha(f_i) \approx 20\lg\frac{\rho_0}{\rho_0^*} + 10\lg\frac{\bar{A}^*}{\bar{A}} + 20(\gamma^* d^* - \gamma d)\lg e + (R_{tr}^* - R_{tr}) \tag{5}$$

Here the following additional symbols are used: $\bar{A}$ is the average coefficient of sound-absorption inside the airplane; γ is the wave parameter of attenuation in heat-sound-insulating damping layer; d is the thickness of the layer; R_{tr} is the sound transmission loss through the trimming panel.

Thus, with the help of relations (1)−(5) it is possible to evaluate the noise variation inside the airplane produced by the turbulent boundary layer on the external surface of the airplane after its modification and its structural variations. The same relations can be used for estimation of the noise inside new airplanes which have prototypes.

ACKNOWLEDGEMENTS

This work supported by the Russian Foundation for Basic Research, project no. 98-02-16239.

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