



“Aircraft Noise Reduction by Flow Control and Active / Adaptive Techniques”

EXPERIENCE OF THE NATIONAL AVIATION UNIVERSITY IN APPLICATIONS OF ACTIVE NOISE CONTROL IN AN AIRCRAFT CABIN

Tokarev V.I., Makarenko V.N., Zaporozhets O.I.

23-26 September, 2014, Vilnius, Lithuania

Active Noise Control (ANC)

The concept of ANC was first described in a patent by P. Lueg N 655508.

ANC basic idea: the electro-acoustic generation of a sound field to cancel an unwanted existing sound field

The basic elements: sensors, control algorithm, actuators.

Over last 40 years the huge amount of literature was published on ANC systems. The number of publication on ANC systems is **doubling every 5 years**.

2 types of Active Noise Control

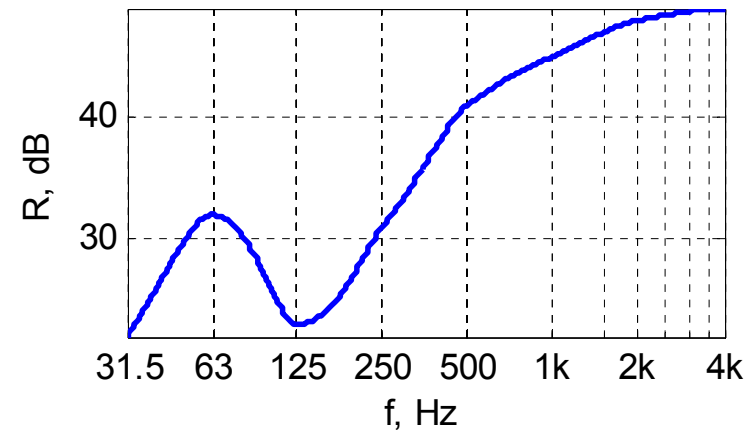
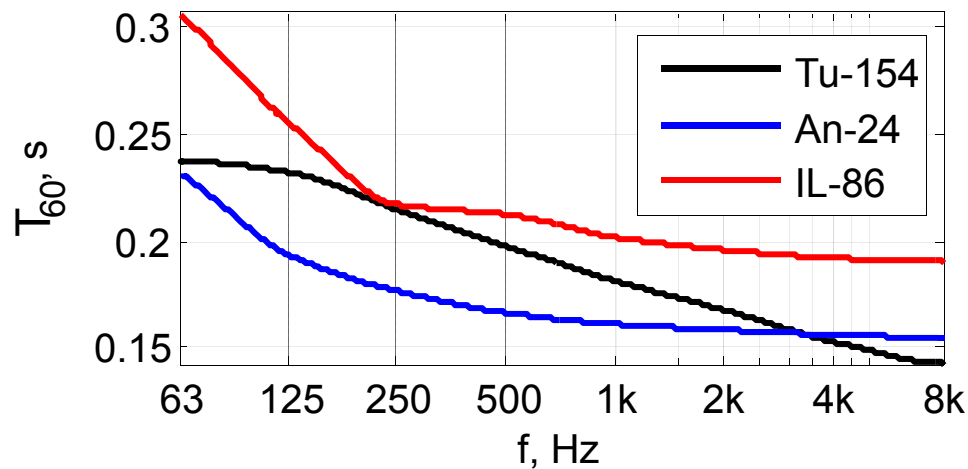
Feedforward and **feedback** control are the two main methods that have been used for ANC systems.

A **feedforward** controller requires a measure of the incoming disturbance to generate the required control signal for the control source.

A **feedback** controller requires no knowledge of the incoming disturbance and acts to change the system response by changing the system resonance frequencies and damping.

Specific features of the application of ANC system in aircraft cabins

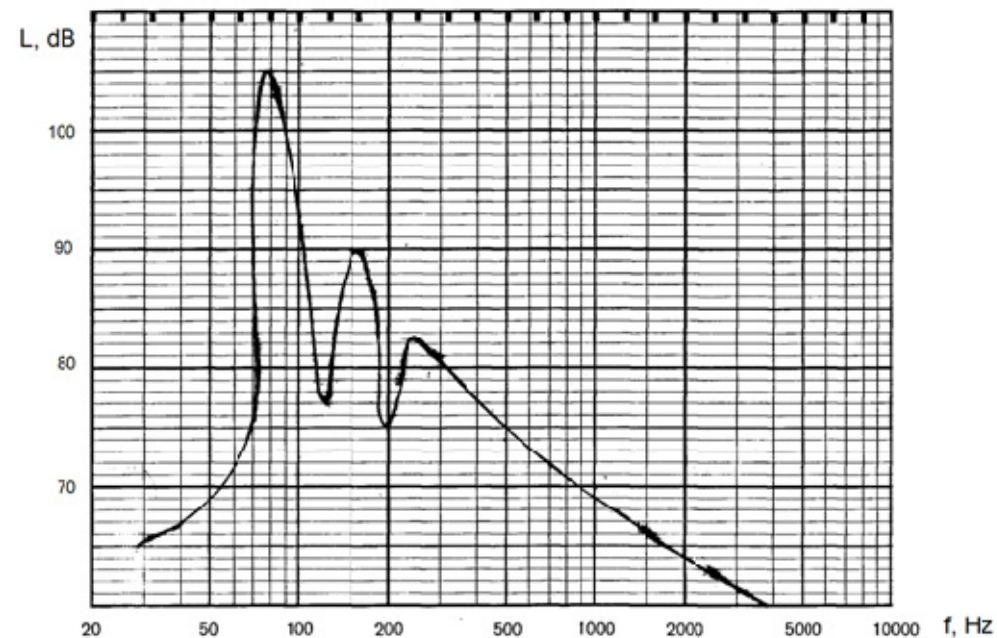
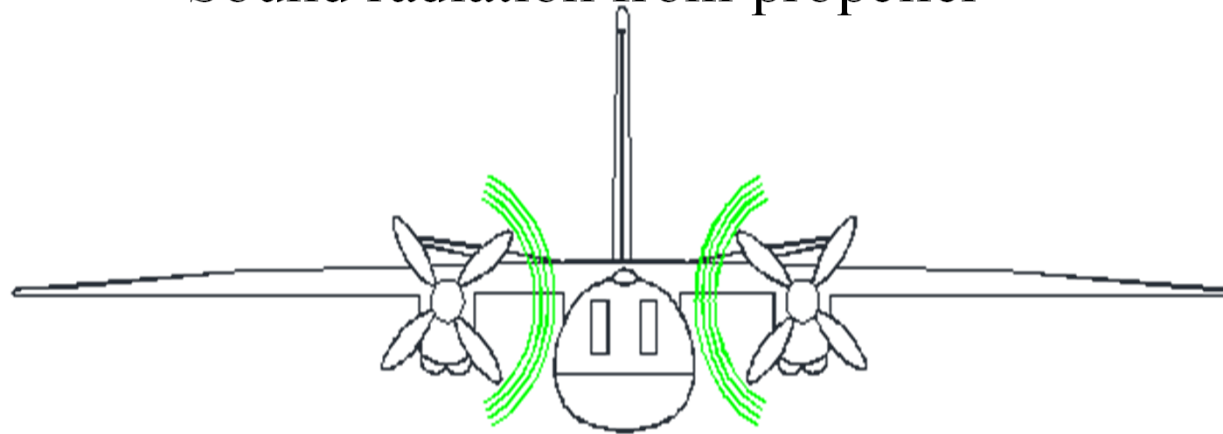
1. Small crew cabin volume.
2. Small time of reverberation and noise transmission loss of the fuselage in the low frequency range.
3. Aircraft cabin noise from external sources (propellers, engines) is determined by performances of near acoustical field.



4. Low frequency noise less than Schroder frequency ($f_{sch} < 300 \text{ Hz}$): $f_{sch} = 2000 \sqrt{\frac{T_{60}}{V}}$
5. The non-stationary acoustic field inside the crew cabin: the noise from aircraft engines, airframe noise, the noise from air conditioning systems (ACS), and the structure-born noise.

Typical noise spectrum of turboprop aircraft Antonov 24 in the crew cabin

Sound radiation from propeller

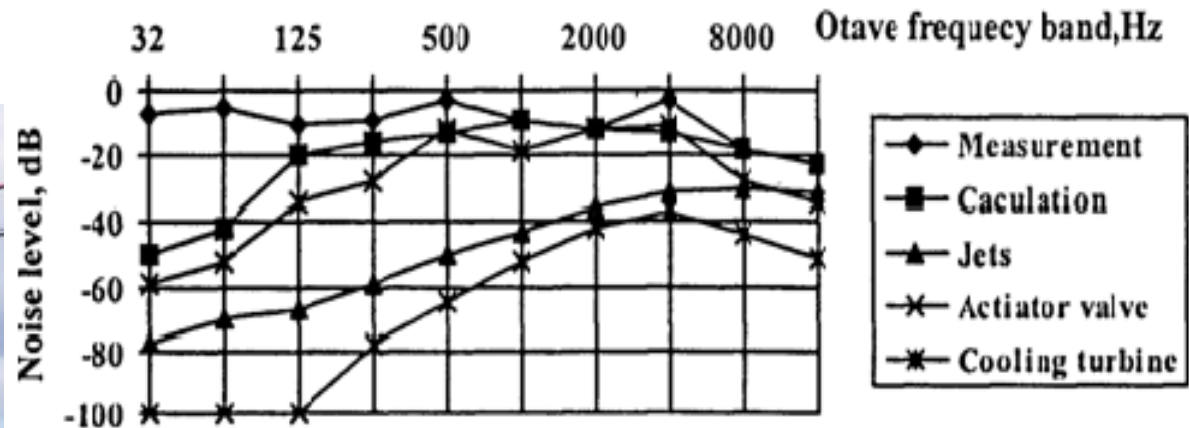


Typical sources for aircraft interior noise

Noise from air conditioning systems (ACS)

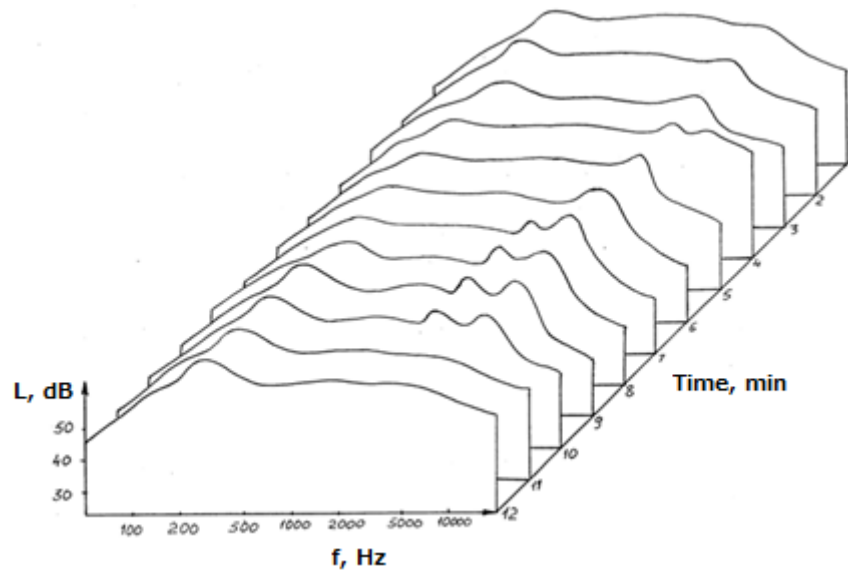
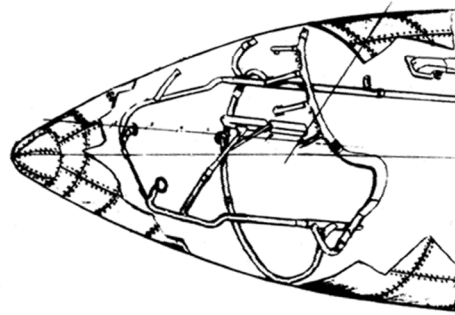


Noise spectra from ACS in the crew cabin of turbojet aircraft Antonov-72

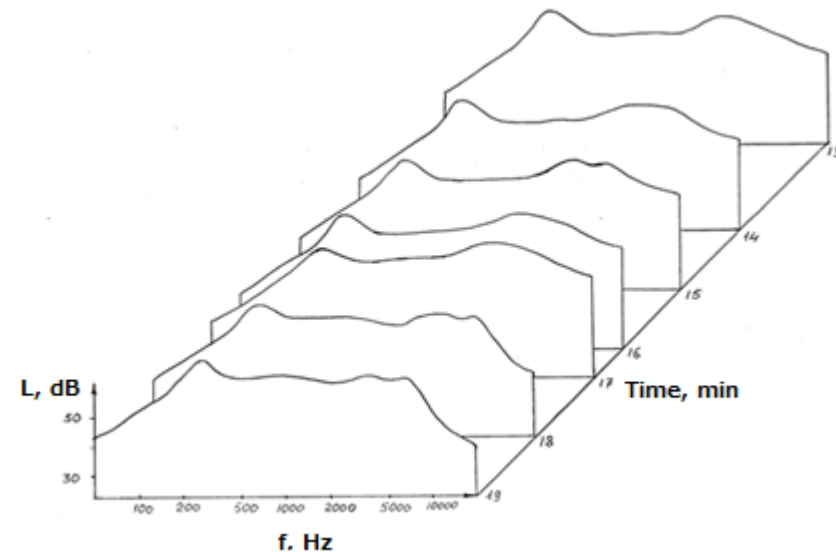


Typical measured noise spectrum of aircraft noise

Noise spectra from ACS in the crew cabin of turbojet aircraft Tupolev-154M for different phases of flight:

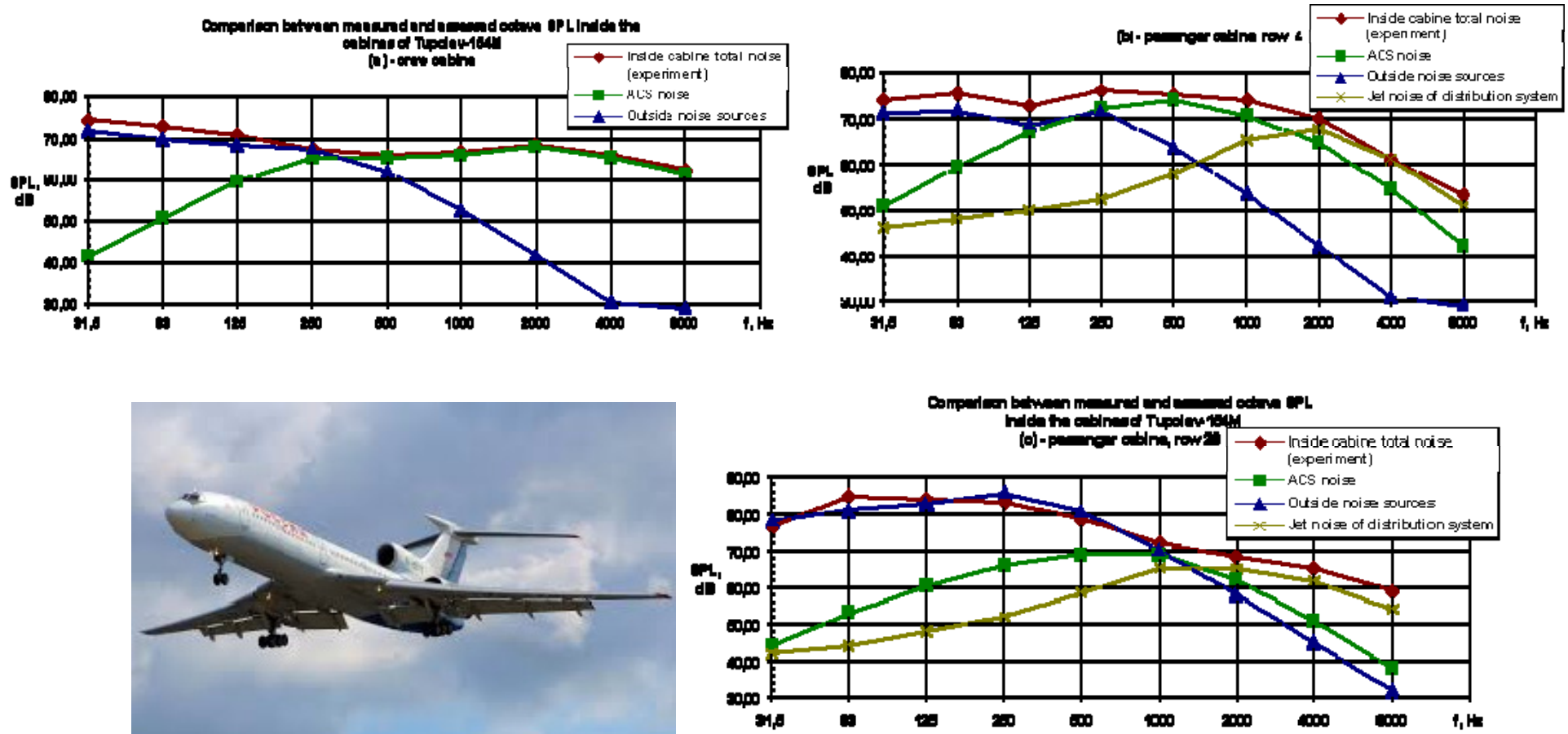


run and takeoff



approach and landing

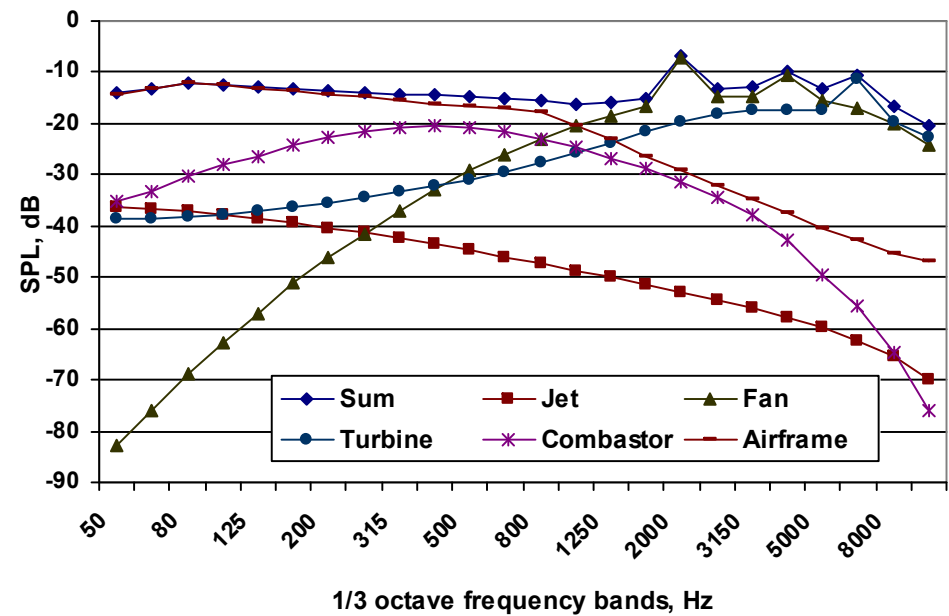
Typical calculated noise spectrum of aircraft noise



The noise spectra inside the cabins of turbojet aircraft Tupolev-154M in cruise flight at $H=11000$ m, $M=0.85$

Typical calculated noise spectrum of aircraft noise

Airframe noise



Active noise control in the crew cabin of aircraft Antonov-24

The model of polyharmonic acoustic fields control in the crew cabin of aircraft Antonov-24. Mathematical model of ANC was defined in the frequency domain in the form of a vector equation:

$$Y(j\omega) = W(j\omega)X(j\omega) + F(j\omega)$$

where $Y(j\omega), X(j\omega)$ - n -dimensional vectors of Fourier coefficients of the input and output signals; $W(j\omega)$ - matrix of the frequency characteristics of the active reduction of noise; $F(j\omega)$ - n -dimensional vector of Fourier coefficients of signals characterizing the noise in cabin. Full compensation of oscillations in the control points is defined as a vector

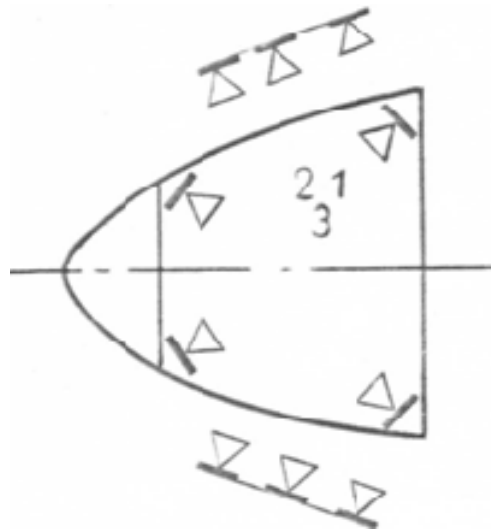
$$X(j\omega) = -W^{-1}(j\omega)F(j\omega)$$

Iterative algorithm was proposed for solving the equation to ensure cancellation of polyharmonic acoustic fields, which is implemented in the system with feedback control.



Principles of decreasing polyharmonic acoustic pressure in the crew cabin of aircraft Antonov-24

Two groups of loudspeakers were used to reduce noise in the cabin of aircraft Antonov-24. One group of loudspeakers simulates radiation of propellers, another, which is located inside the cabin, is used to compensate the sound field in the cabin of aircraft Antonov-24. Active reduction of interior noise in the cabin of aircraft Antonov-24 was carried out at three points at the head of the pilot. The table shows the results of studies on the compensation of the fundamental blade pass frequency and second harmonics of the propeller in the three control points.

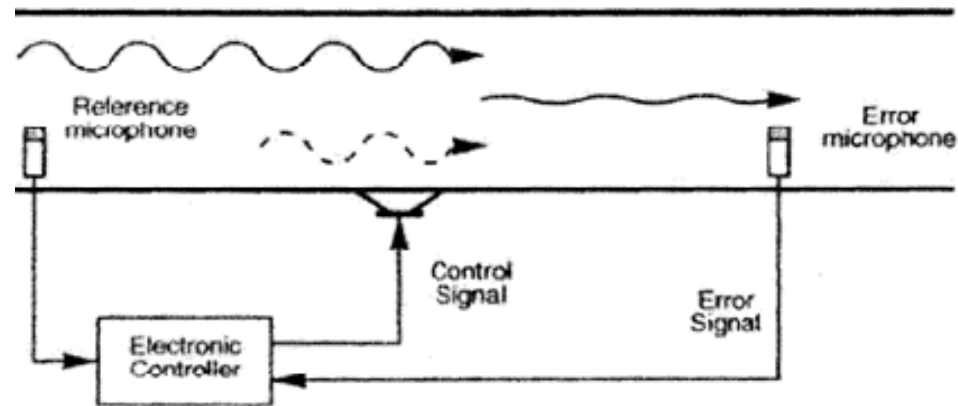


	Synphasing			Implementation feedback control and synphasing		
Decreasing of sound pressure level, dB	1	2	3	1	2	3
	2	4.7	5.6	3.5	5	10.4

Active noise control in open duct

One method of the air conditioning system noise reduction in the cabin is the use of compensating loudspeakers in air distribution nozzles.

The feed-forward control system in the infinite duct includes: reference microphone, the electronic controller, loudspeaker, and error microphone

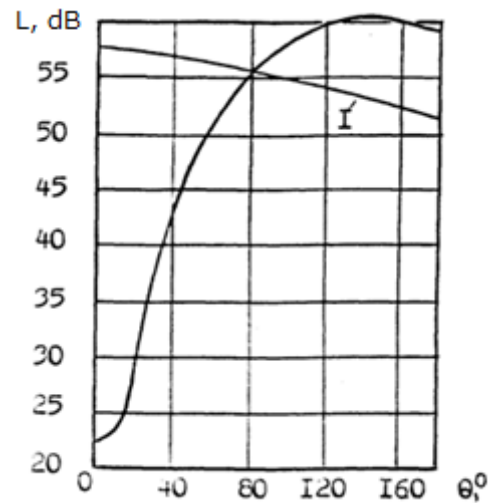
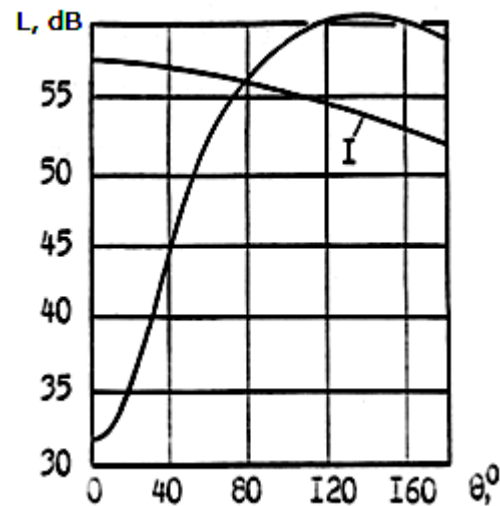


In contrast, for the simplest example of active control of a plane wave in the infinite duct near open duct sound field is represented by two acoustic waves – the direct and reflected waves.

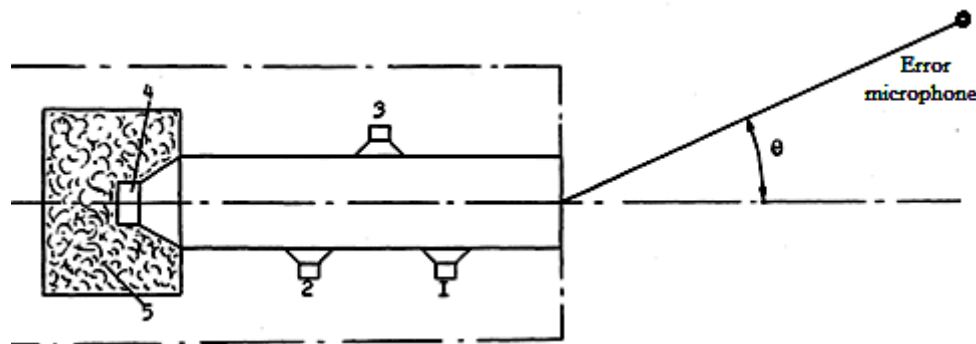
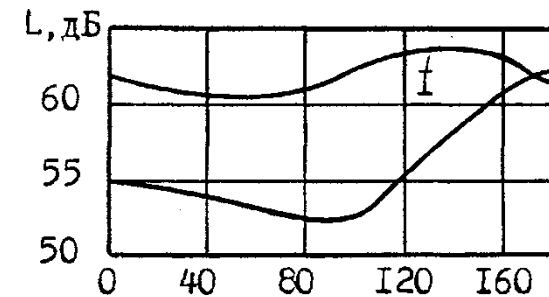
In the National Aviation University performed theoretical and experimental studies of the effectiveness of active noise reduction methods of air conditioning systems. Experimental studies were carried out in an anechoic chamber using an open duct with diameter 0.1 m.

ANC application for open duct

Directional characteristics of sound radiation from an open duct, the frequency of 100 Hz (below cut-off frequency)



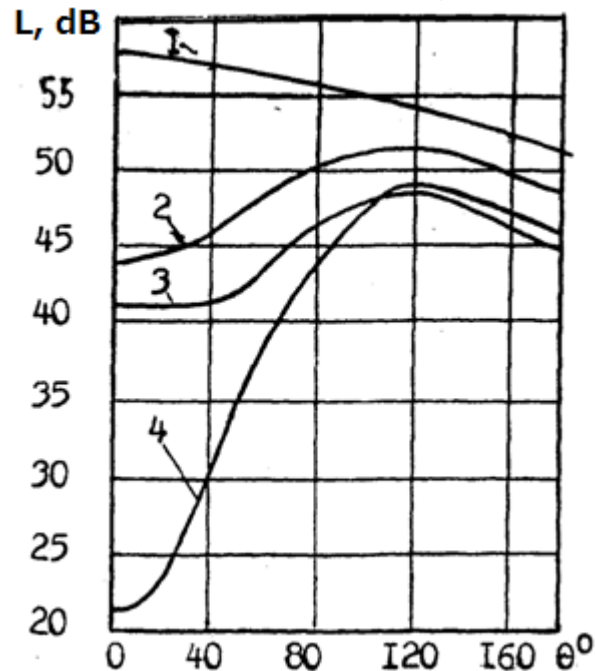
An error microphones are adjusted for next angles: 1 - 0° , 2 - 90° , 3 - 135°



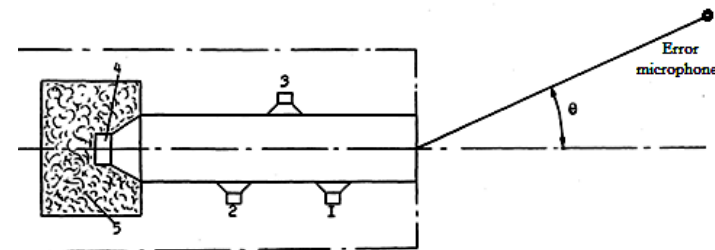
1, 2, 3 are loudspeakers;
4 is sound source (loudspeaker);
5 is soundproofing.

ANC application for open duct

Effect of the error microphone placement in open duct with active noise control system (loudspeaker N 2).

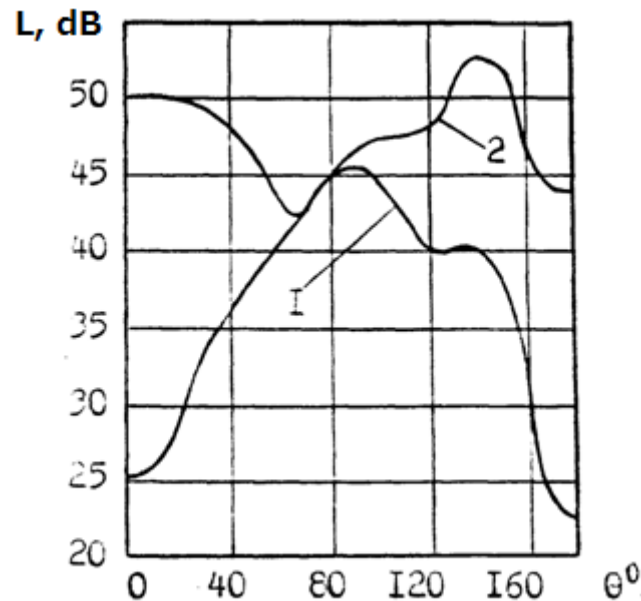


1. Without active noise control usage
2. The error microphone inside duct at distance 8 cm from the end of the duct
3. The error microphone outside duct at distance 20 cm from the duct end
4. The error microphone outside duct at distance 70 cm from the duct end

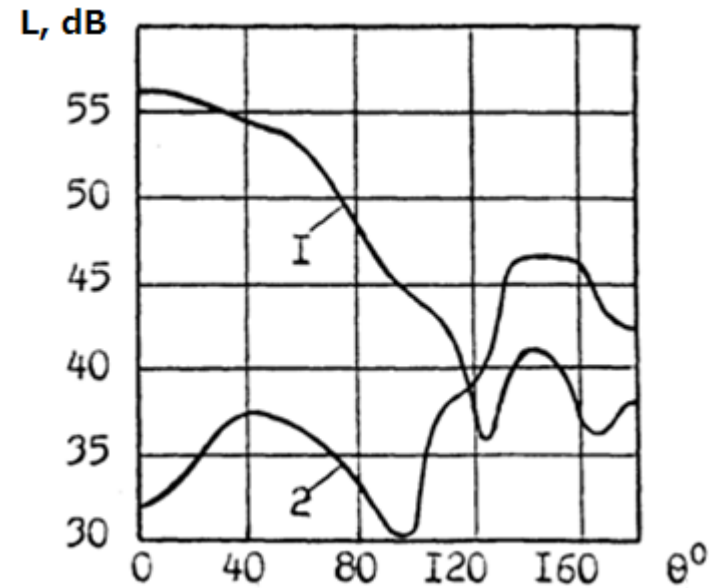


Application of active noise control system in open duct

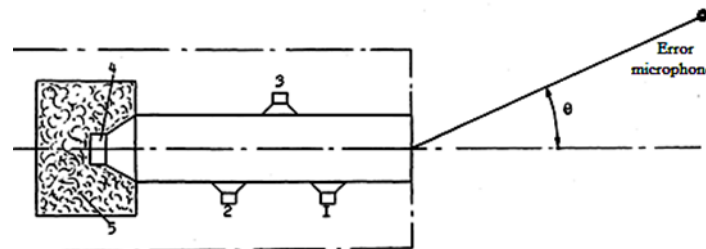
Directional characteristics of sound radiation from an open duct for the frequencies of 250 Hz and 500 Hz (curve 1 - without active noise control usage)



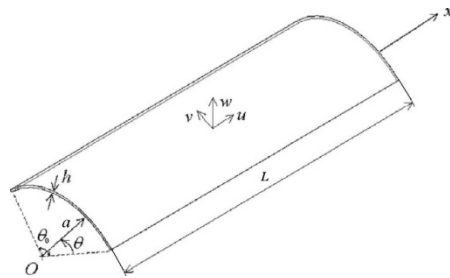
2 - frequency 250 Hz
(loudspeaker N 2).



2 - frequency 500 Hz
(loudspeaker N 2).

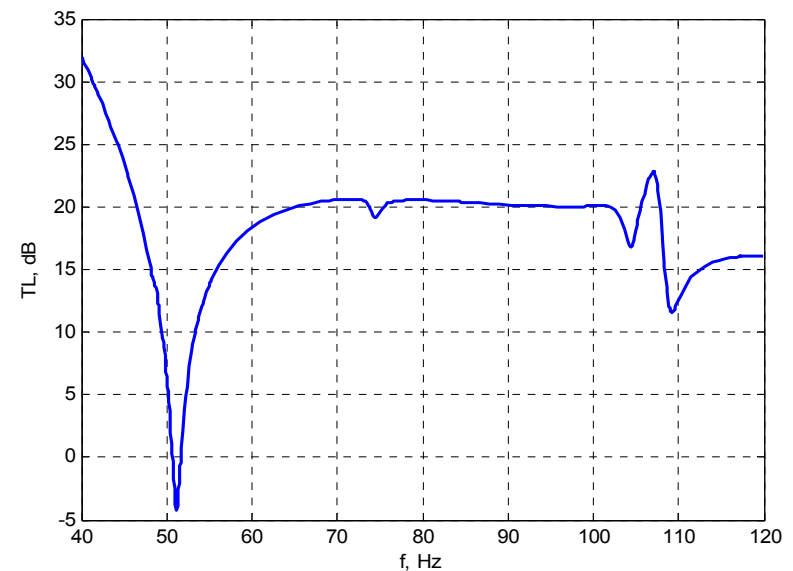
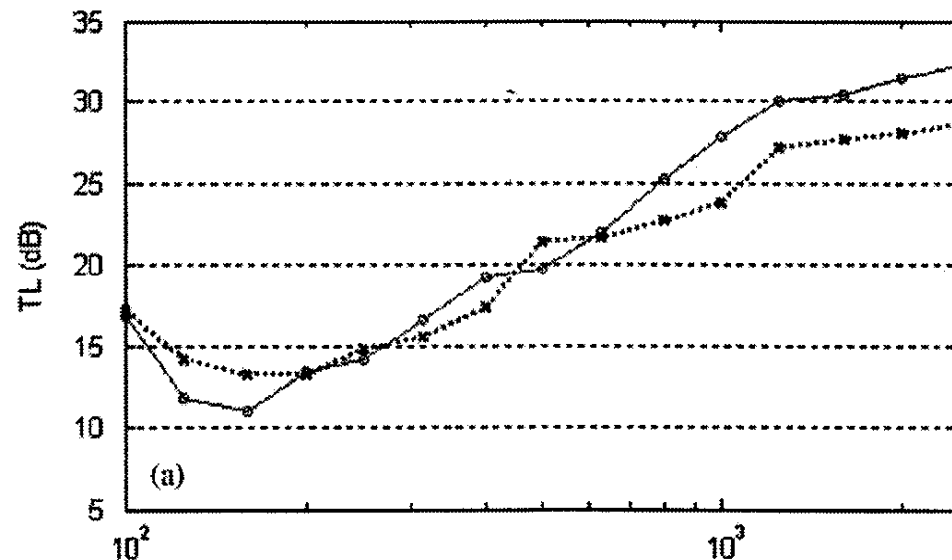


Sound transmission control through the cylindrical panel



Property	Value
Youngs modulus	$6.85 \cdot 10^{10}$ Pa
Poisson's ratio	0.3
Density	2770 kg/m ³
Dimensions	$2.2 \times 1.67 \times 1,2 \cdot 10^{-3}$ m ³
Radius	2 m

Property		Value
Youngs modulus in longitudinal direction, E_L		$15.7 \cdot 10^9$ Pa
Youngs modulus in transversal direction, E_T		$6.3 \cdot 10^9$ Pa
Shear modulus, G_{LT}		$2.1 \cdot 10^9$ Pa
Poisson's ratio ν_{12}		0.204
Damping loss factors	η_L	$1.005 \cdot 10^{-2}$
	η_T	$1.699 \cdot 10^{-2}$
	η_{LT}	$1.807 \cdot 10^{-2}$
Density		1430 kg/m ³
Dimensions $L \times h \times b$		$0.560 \times 3 \cdot 10^{-3} \times 0.860$ m ³
Radius, a		2m



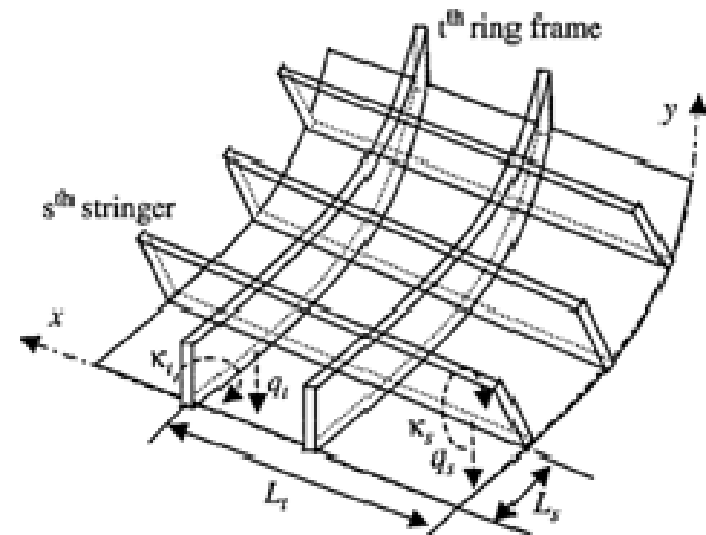
Sound transmission control through curved aircraft panel with stringers and ring frames

Differential equations of vibration of the curved panel with stringers, frames and masses (the form of Donnell-Mushtari-Vlasov equations):

$$\left\{ \begin{aligned} D \left(\frac{\partial^4 w}{\partial x^4} + \frac{2}{r^2} \frac{\partial^4 w}{\partial x^2 \partial \theta^2} + \frac{1}{r^2} \frac{\partial^4 w}{\partial \theta^4} \right) + \frac{1}{r} \frac{\partial^2 \varphi}{\partial x^2} + \rho h \frac{\partial^2 w}{\partial t^2} = \\ = 2(p_i - p_r)_{z=0} - \sum_{k=1}^K f_k \delta(x - x_k) \delta(y - y_k) - \\ - \sum_{l=1}^L q_l \delta(y - L_l) - \sum_{m=1}^M q_m \delta(x - L_m) - \sum_{n=1}^N \kappa_n \delta'(y - L_n) - \sum_{p=1}^P \kappa_p \delta'(x - L_p), \\ \frac{Eh}{r} \frac{\partial^2 w}{\partial x^2} - \left(\frac{\partial^2 \varphi}{\partial x^2} + \frac{2}{r^2} \frac{\partial^2 \varphi}{\partial x^2 \partial \theta^2} + \frac{1}{r^2} \frac{\partial^2 \varphi}{\partial \theta^2} \right) = 0, \end{aligned} \right.$$

Basic equations of bending and torsional displacements w_s , of stringers, frames w_r , φ_r and mass displacements w_k , θ_k written as:

$$\begin{aligned} D_1 \frac{d^4 w_1}{dx^4} - m_1 \omega^2 w_1 = q_1, \quad T_1 \frac{d^2 \theta_1}{dx^2} - E_1 C_{11} \frac{d^4 \theta_1}{dx^4} + \rho_1 I_{p1} \omega^2 \theta_1 = \kappa_1, \quad -m_2 \omega^2 w_2 = f_2 \\ D_r \left(\frac{d^4 w_r}{dy^4} + \frac{2}{r^2} \frac{d^2 w_r}{dy^2} + \frac{w_r}{r^4} \right) - m_r \omega^2 w_r = q_r, \quad T_r \frac{d^2 \theta_r}{dy^2} - E_r \frac{I_{pr}}{r^2} \theta_r + \rho_r I_{pr} \omega^2 \theta_r = \kappa_r \end{aligned}$$



Sound transmission control through curved aircraft panel with distributed point masses

The optimization task is formulated to design such **control parameters**, which maximize transmission loss of the panel. The objective criteria is an integral assessment of sound insulation in the frequency range f_{min}, f_{max} :

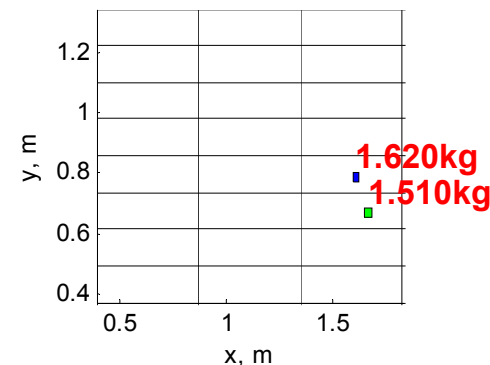
$$\min F_{\omega} = 10 \lg \frac{1}{f_{max} - f_{min}} \int_{f_{min}}^{f_{max}} \tau_d df,$$

under constraints imposed on location and weight of masses, τ_d is transmission coefficient.

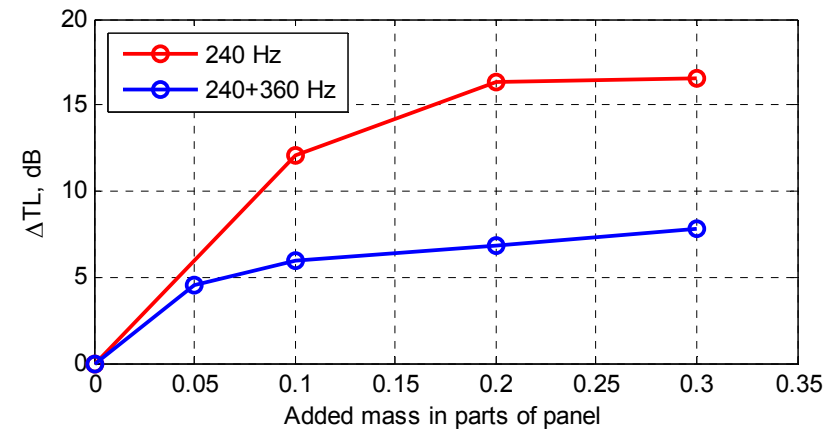
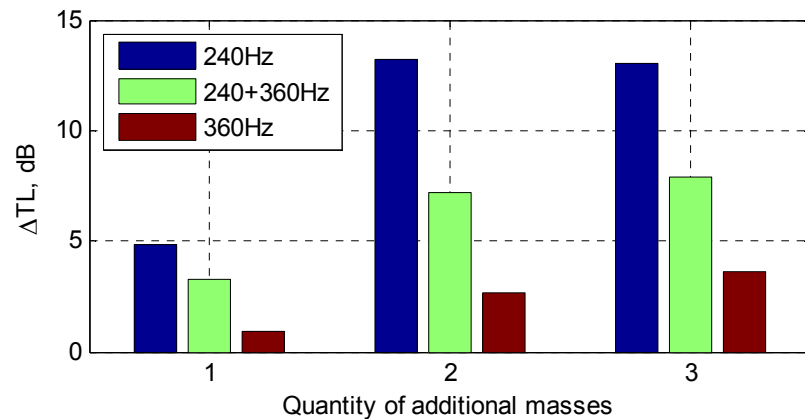
The logarithmic form of transmission coefficient is the **transmission loss** (TL) :

TL = -10lg τ_d . The **control parameters** are: $m_k, x_k, y_k, k=1,2,...,K$.

The genetic algorithm with penalty functions for the constraints has been used to solve this task. Theoretical and experimental investigation showed TL increase of the panel (aircraft Antonov-72) at the frequency of 374 Hz to 6.9 dB. The panel is made of duraluminium with dimensions 2.22m x 1.6m, thickness is 1.2 mm, mass is 23.6 kg.



Sound transmission control through curved aircraft panel



The effect of a number of distributed masses on TL increase in case of optimal location of the masses on investigated panel (total weight of distributed point masses is equal to 13.3% of the total panel mass).



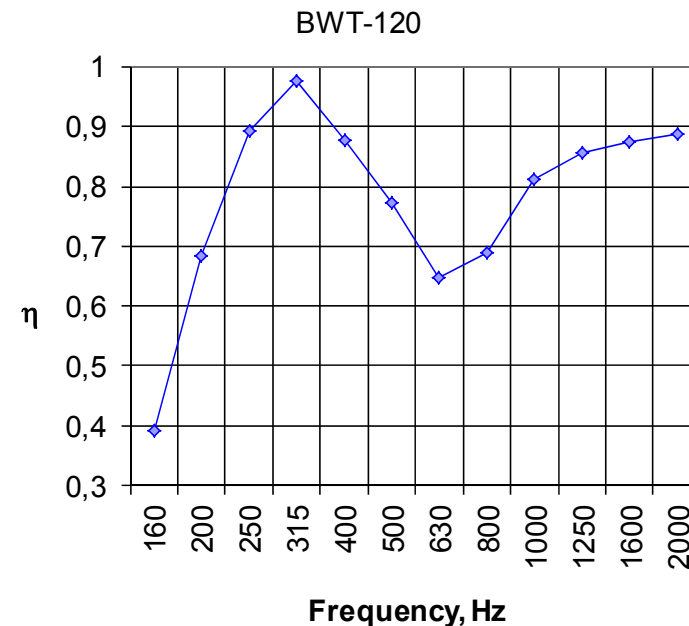
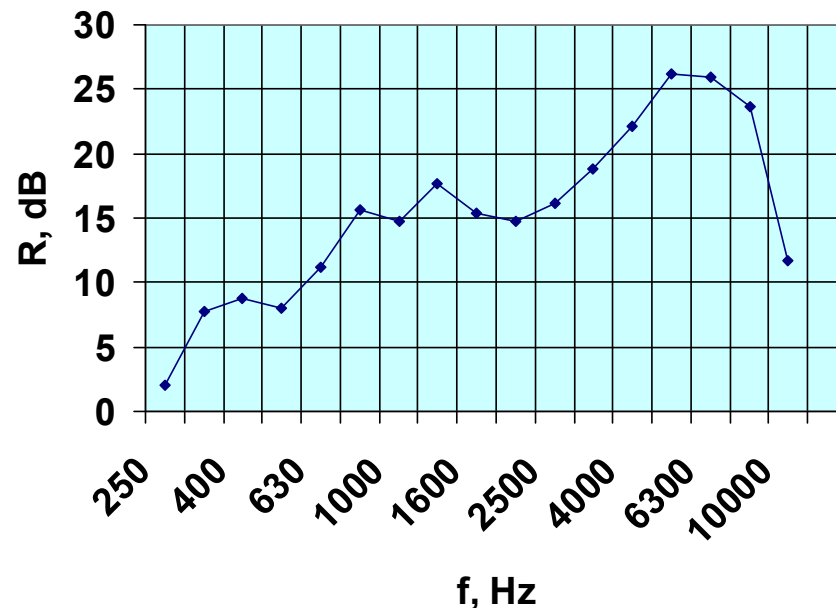
Application of sound insulation designs and damping layers for increasing fuselage TL

Principle of impedance mismatch is used in optimal sound insulation designs. It provides a sound insulation of a multilayered structure due to two effects: the absorption of sound energy in the material and the reflection of sound waves from the interface between materials.

Sound energy absorption is small in solid materials, so the sound insulation of such materials is determined by effect of sound reflection.

On the other hand, effect of reflected sound is relatively small for porous materials comparing to the irreversible loss of sound energy in the material layer, so soundproofing is completely determined by absorption in this case.

In real structures both effects determine the actual sound insulation of the panels.



Optimal number and placement of damping material

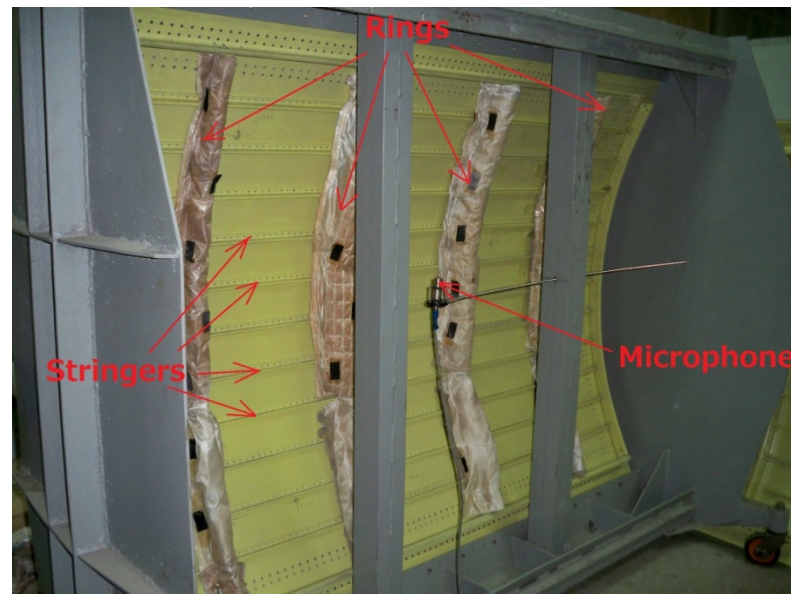
The optimization problem is formulated as the determination of the maximum of the goal function:

$$\max TL = -10 \lg \tau_d,$$

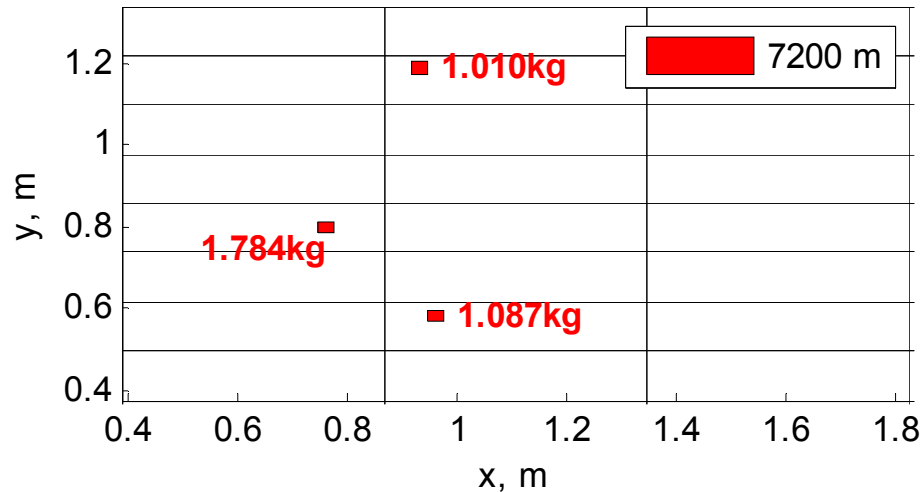
where TL is transmission loss of the panel.

In the model of panel the modulus of elasticity $E' = E(1 + i\eta)$ has been introduced, where η is a loss factor of damping materials. For determination of optimal location and size of damping material the optimization for increase of TL is done. The genetic algorithm was chosen for definition of damping material locations.

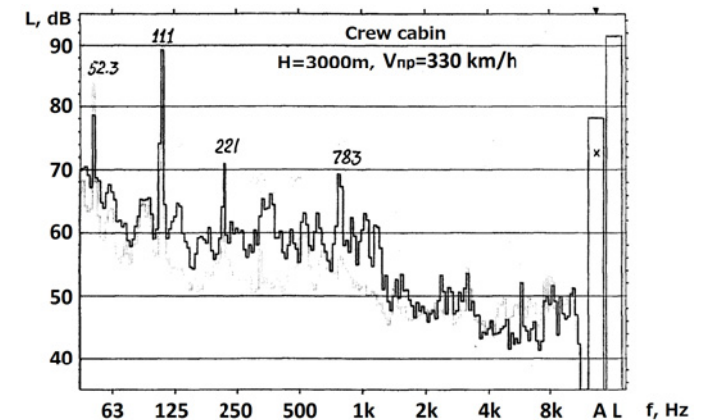
In optimal structure high loss factor viscoelastic layer is used. The employment of damping material on the ring frames cylindrical panel allowed increasing the transmission loss of panel on 10 dB in in audio frequency range from 330 Hz to 350 Hz.



Sound transmission control through curved aircraft panel



The increase of transmission loss at the fundamental propeller blade-pass frequency inside crew cabin of the Antonov-140 using three distributed masses is equal to 9.7 dB. The total weight of distributed masses is 16% of the panel weight (dimensions 2.22 m x 1.6 m).



Future developments

1. Aircraft noise reductions in cabins due to active noise control are achievable as a result of the interaction between system theory, engineering acoustics, electro-acoustics and adaptive signal processing.

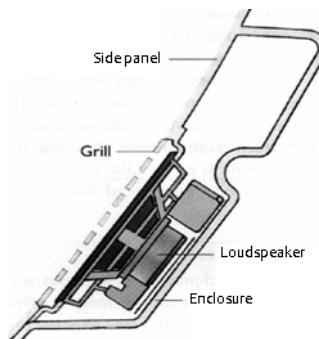
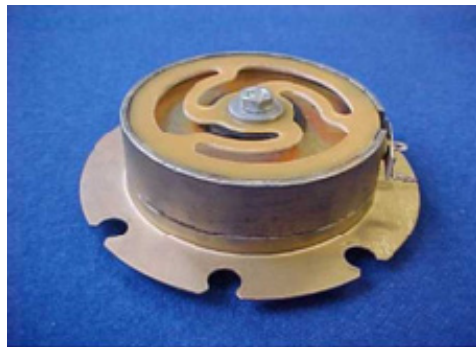
Examples of the development and installation of ANC system:

- the **reference and error sensors** are used to obtain and derive a signal that is used by the controller to generate the driving signal for the control of loudspeakers;

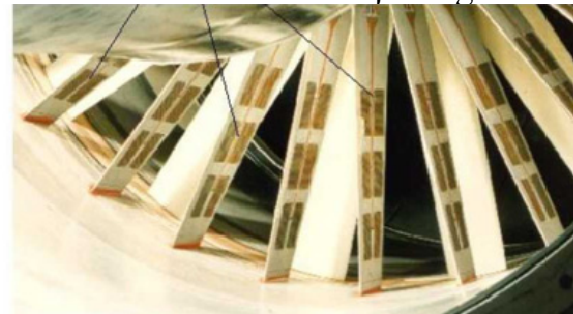


From C. H. Hansen, DOES ACTIVE NOISE CONTROL FUTURE?, Manuscript Number: 1226U

- novel **actuator systems** suited specifically to active control applications. An example is a low cost inertial actuator and/or the flat loudspeaker developed by Ultra Electronics to fit behind aircraft trim panels;



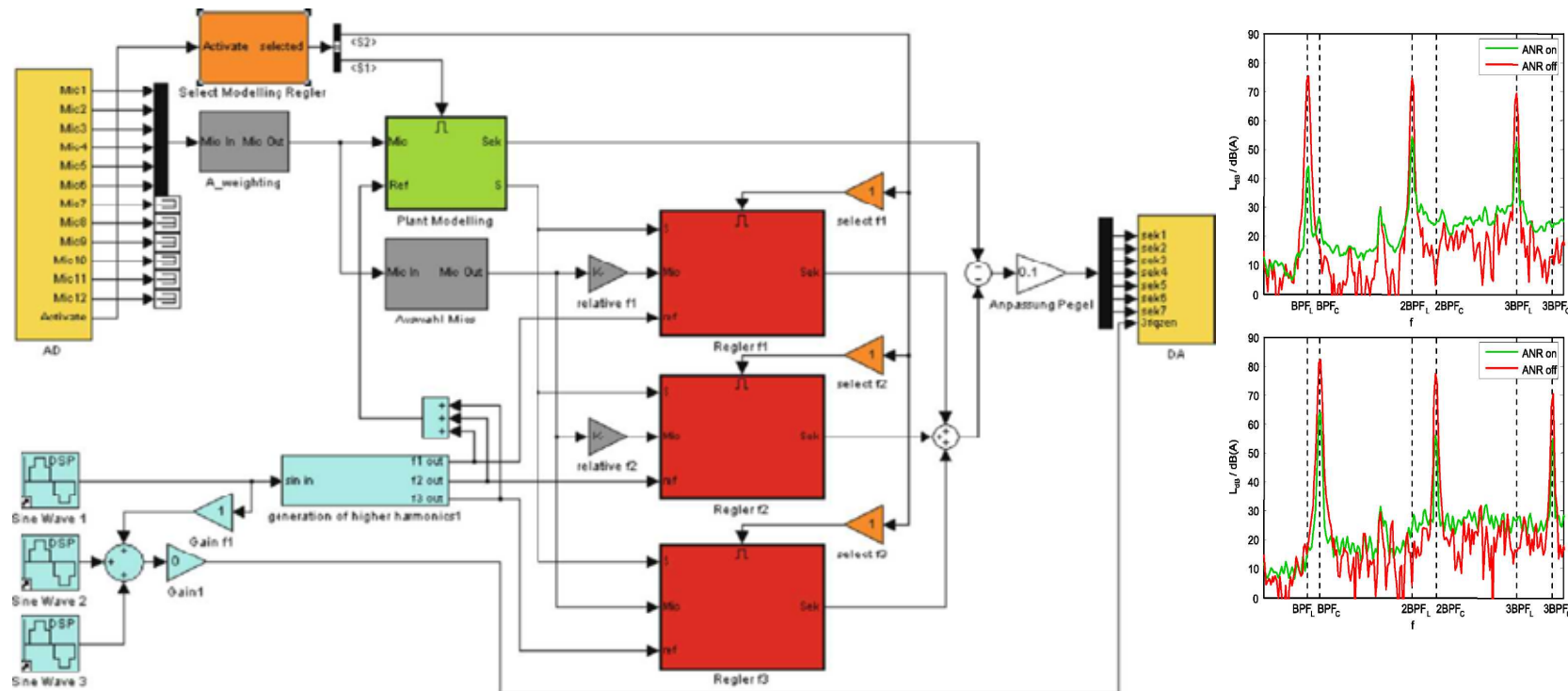
The piezoelectric actuators on jet engine fan blades



Future developments

2. The next generation of ANC systems will be powerful to allow very large numbers of channels as well as a high enough processing speed to implement feedback as well as feedforward control.

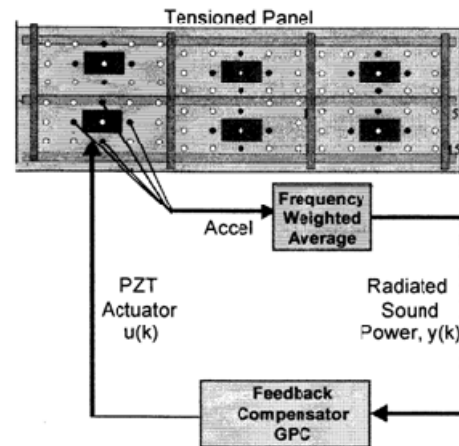
Block diagram of multichannel ANC system MIMO (multiple-input and multiple-output system).



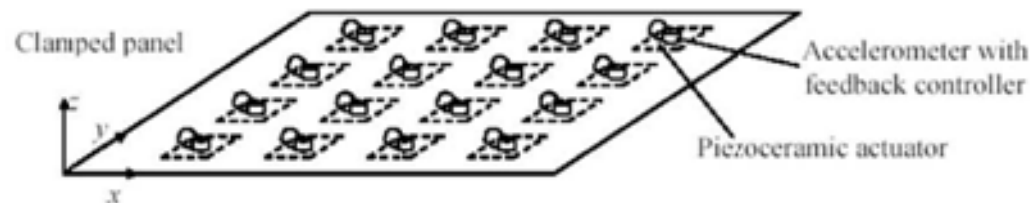
From T. Kletschkowski, Adaptive Feed-Forward Control of Low Frequency Interior Noise, Springer, 2012.

Future developments

The **airframe noise** generated by the air flow over the fuselage can be reduced using feedback active control (from Gibbs, G.P. and Cabell, R.H. , 2002. Active Control of Turbulent Boundary Layer Induced Sound Radiation from Multiple Aircraft Panels. Paper no. AIAA 2002-2496, 8th AIAA/CEAS Aeroacoustics Conference, Breckenridge, CO, June 16-18, 2002.)



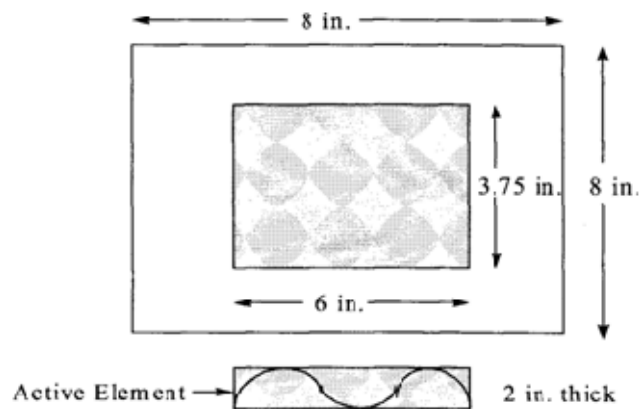
Multiple single-channel independent feedback controllers can be used to improve the low-frequency **transmission loss** of a panel (from Gardonio, P., Bianchi, E. and Elliott, S.J. 2002. Smart panel with multiple decentralized units for the control of sound transmission. Part I: Theoretical predictions, Part II: Design of the decentralized control units, Part III: Control system implementation. Proceedings of Active 2002, Southampton, UK, July 15-17.)



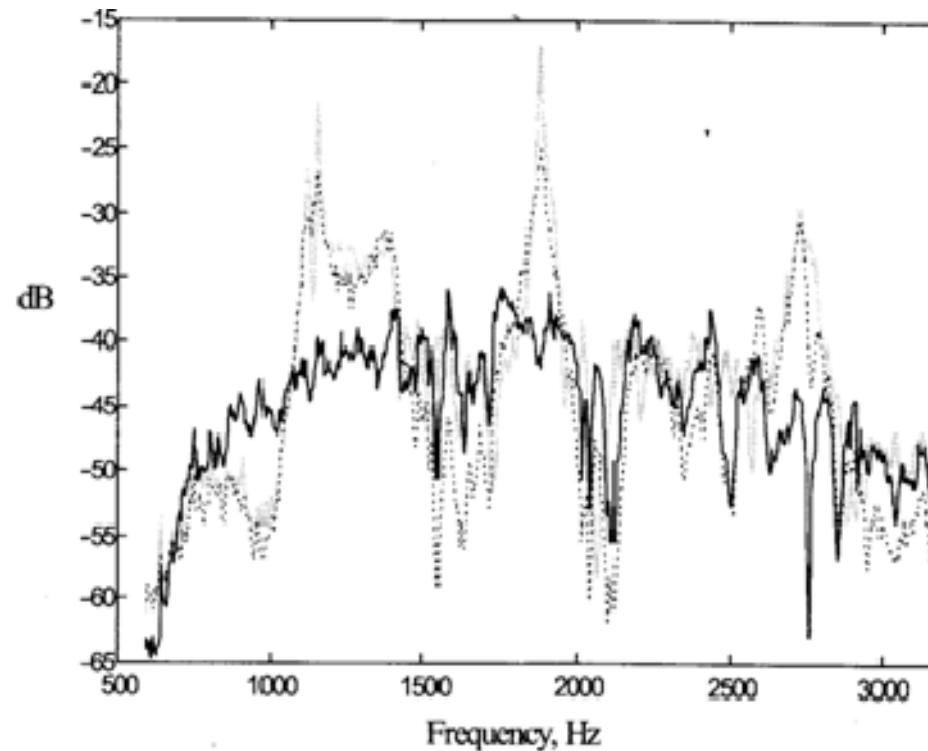
Future developments

3. Application of predictive control using active foam

Predictive control techniques can be used to provide regulation of plate vibrations over a wide bandwidth using piezoelectric actuators. The active element consists of regular foam with piezoelectric polymer polyvinylidene fluoride embedded in it and shaped similar to a sine wave. The foam is able to act as a passive absorber because the air molecules oscillate at the same frequency as the disturbance. This oscillation causes frictional losses. A control actuator adaptively modifies the acoustic impedance of the vibrating surface. The goal of the active foam is to modify the acoustic radiation impedance seen by the structure in order to yield a net decrease in the far-field sound power radiated by the vibrating surface.



From K. W. Eure, Adaptive Predictive Feedback Techniques for Vibration Control, 1998.



Future developments

- implementation of active structural acoustic control (for structure-borne sounds) includes simultaneously active control of structural vibrations and active control of sound fields;
- semi-active approaches with application of passive and active noise control;
- smart panel design.