# Experimental investigation of sound transmission through thin-walled structures due to non-uniform pressure-fluctuation fields
# Part 1: subsonic flow

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## ABSTRACT

Theoretical models of the sound-energy transmission through thin-walled structures from non-uniform, convecting pressure-fluctuation fields were validated through experiments. The fields were created with separated flows at forward-facing and backward-facing steps and vibrations and acoustic radiation of the structures were investigated. Thin plates and model fuselage panels were used.

The data permit direct comparison with predicted results as well as evaluation of the validity of the prediction-model assumptions. In particular the elastic and inertial properties of the skin but not of the stiffeners need to be taken into account. The experiments support the validity of previously reported theoretical predictions.

## INTRODUCTION

Non-uniform aerodynamic pressure-fluctuation fields in the sound-frequency range on surfaces exposed to flow are the main sources of noise in the cabin of modern high-speed vehicles. The wall pressure fluctuations stem from turbulent-boundary-layer flow (1) on smooth surfaces with pressure gradients, (2) over forward-facing and backward-facing steps, and (3) from shocks interacting with the boundary layer.

Theoretical studies were made of the sound-energy transmission through thin-walled structures from substantially non-uniform, convecting pressure-fluctuation fields, random in space and time. These studies led to prediction models for the sound-energy transmission through the structure, determined both by its resonant [1] and purely inertial behavior [2]. It was shown that the resonant behavior of the structure played the dominant role in sound transmission due to non-uniform pressure-fluctuation fields.

The main purpose of this work was to evaluate the reliability of the prediction models through experiments. Vibrations and acoustic radiation of structures, excited by non-uniform pressure-fluctuation fields of subsonic flow, were investigated in the sound frequency range. The present paper completes work related to a contract between TsAGI and Boeing. The results of the experimental investigation for supersonic flow are presented in [3].

## FACILITIES, MODELS, METHODS, AND TECHNIQUES OF MEASUREMENT

The facility [4] was updated and used for experimental investigations of acoustic radiation of panels excited by the non-uniform pressure fluctuation field at subsonic flow velocity. The test section of this facility is a duct of about 3-m length with a cross-sectional area of 21.4 mm x 221mm. The essential facility update was the addition of a second centrifugal fan and a settling chamber of about 2 $m^3$ volume at the inlet. The inlet collector in the settling chamber leading to the test section is a smooth transition from circular to rectangular cross section with an area ratio of about 12. The external part of the inlet collector and the internal surface of the settling chamber are treated with sound-absorbing material. A separation-free diffuser, a noise suppressor and a settling chamber of about 1 $m^3$ volume, treated with sound-absorbing material, follow the test section. Internal surfaces of collector, test section and diffuser are carefully polished.

Fans at the inlet and the exit, operating either simultaneously or individually, create the flow in the test section. The maximum velocity on the duct axis with two fans operating is about 38.6 m/s, with the exit fan alone about 30.5 m/s and with the inlet fan alone about 23.9 m/s. At each operating regime there is a possibility of reducing the flow velocity by choking, both at the inlet and at the exit. All the elements of the facility, except for the fans, are located in a large (about 120 $m^3$) room, with ceiling and walls treated with structures of high sound-absorbing efficiency in the region $f \geq 1$ kHz. The fans are located outside this room behind a brick-wall foundation. The wide wall of the test section is oriented toward the ceiling. It has an aperture, in which either a rigid plate with pressure-fluctuation transducers or a test panel can be mounted. Either plate is mounted strictly flush with the smooth internal wall of the duct.

Three panels with dimensions 322 mm x 130 mm were used for the experimental research of vibrations and acoustical radiation. Panel 1 is a thin (about 0.3 mm) plate in a rectangular frame, fixed to a rigid frame. The other two panels are flat one-fifth scale models of fuselage panels, fixed in rectangular frames, similar to that used for panel 1. Panel 2 models the skin and stiffeners of fuselage panels of medium-range aircraft and panel 3 those of long-range aircraft. These panels are also fixed in rigid frames set in the aperture of the facility test section.

Vibro-acoustic characteristics of these panels, in particular the loss coefficients, were also found from the experiment. The mechanical loss coefficient determines the energy share dissipated in vibrations and the radiation loss coefficient the share of vibration energy transformed into acoustical energy.

In order to investigate acoustic radiation of panels excited by non-uniform pressure-fluctuation fields at subsonic flow velocities, separated flows were created before forward-facing steps and behind backward-facing steps. For this purpose, plates of 15 mm width were used. This plate size approximately corresponds to the duct width of the test section. The space-time structure of these fields was studied in some detail. Data were obtained experimentally on both spatial variation and correlation of pressure-fluctuations over the whole separation region at different frequencies.

The 15 mm-wide plates were fixed to the test panels with glue. They were light and flexible enough that their effect on the vibro-acoustical characteristics of the panels was small and unnoticeable in the measurements of the sound power radiated by the panels. This was found by comparing results of measurements of radiated power with and without this plate glued on the opposite sides of the panel (on the flow side and on the free space side). Evaluation of mean vibration velocity and radiated power was made with three independent measurement systems. Panel vibrations were determined from measurements at 20 points uniformly distributed over the panel surface with “Endevco” charge-amplifier vibration transducers of 0.6-gram mass. Sound power radiated by the panels was determined with a “Metravib” intensity probe, which was moved over the measurement zone with a three-axis traversing device. This intensity probe has three microphones and this offers the opportunity of using two microphone bases in the course of one measurement – 120 mm for measurements in the low-frequency range and 15 mm for measurements in the high-frequency range. The measurements were made at a distance of 100 mm from the panels. The microphone base in this case ($\Delta r$) was 15 mm. The signals were converted to digital form and recorded on a hard disc, and subsequent spectral and correlation analyses were made with a specially developed program.

**RESULTS OF THE EXPERIMENTAL INVESTIGATION**

The reliability of the measurements must be ascertained before the analysis. For this purpose the background noise of the equipment as well as the facility was evaluated.

For the experiments at subsonic flow velocities there are two types of background noise, in addition to the equipment noise, which are directly caused by the facility operation. The first one is due to the finite sound-transmission loss of the wind tunnel walls. Measuring the sound power with a rigid plug placed in the test-section aperture made a total evaluation of this type of noise. The sound transmission loss of this plug was much larger than that of the surrounding walls. The sound power values recorded in this case can be considered an upper limit of the background-noise level. Comparison with measurements under the same conditions (U=const) with the test panels in place indicates that the useful signal substantially exceeds the background noise at frequencies f>400 Hz both for the case of panel excitation by the non-separated boundary layer (uniform pressure-fluctuation field) and the case of flow separation over steps (non-uniform pressure fluctuation field).

The second type of background noise is due to structural noise from the wall transmitted into the sound chamber through the connecting elements of the structure and also by the fan-generated noise transmitted into the test section and affecting the test panels. Measuring the sound power radiated by the panel with the duct completely closed off allowed an integral evaluation of such background noises. When the uniform pressure-fluctuation field excites the panels, the useful signal exceeds the background noise by at least 20 dB and for the non-uniform pressure-fluctuation field by even more.

An evaluation of background vibrations was made from measurements of the lateral vibrations of the panels with the air supply in the test section completely closed off. They appeared negligibly small in comparison with vibrations at frequencies above 400 Hz of panels excited by uniform and non-uniform pressure-fluctuation fields.

It should be noted here that the panel in the test section is subjected to static pressures up to 880 Pa at the main operational range of the facility. Such static loading of the panel can lead to a change in its acoustical radiation. But the experiment showed that for frequencies above 1000 Hz a static-pressure increase up to 800 Pa hardly affected the power radiated by the panel.

Figure1 presents measurements for sound radiation of panels 2 and 3 excited by pressure fluctuations from steps of 3 mm height at flow velocity U~23.9 m/s. It is apparent that the sound power radiated by panels 2 and 3 differ little over the whole spectrum. The same results are observed at flow velocities of U=30.5 m/s and 38.6 m/s. The effect of flow velocity on the sound power radiated by the panels can be judged from the measurements presented in figure 2 for panel 2.

The data obtained in the experiments permit not only a direct comparison with predicted results, but also evaluation of the validity of assumptions made for the prediction model. In particular, function $F(\beta, \lambda)$ [1], which reflects the space-time structure of the random convecting fields of aerodynamic pressure fluctuations with essential non-uniformity in the resonant behavior of the thin-walled structure, accounts for elastic and inertial properties of the skin but not of the stiffeners. The same can be said about the analogous function $F(\beta)$ [5] obtained for the uniform boundary layer, which used the same idealized model of the thin-walled structure for its derivation. The validity of applying this prediction model for evaluating vibrations and acoustic radiation of real structures excited by the uniform field of wall turbulent pressure fluctuations within the limits of the statistical-energy method was proved not only by direct comparison of predicted and experimental data, but also by indirect comparison. It was shown that function $F(\beta)$ well reflected the characteristics of the structure of the space-time field in vibrations and acoustic radiation of real thin-walled structures.

To evaluate the validity of this prediction model in application to essentially non-uniform fields of aerodynamic pressure fluctuations exciting real thin-walled structures, it is possible to use a comparison of the sound-power measurement results for panels 2 and 3. These panels are the flat models of representative pieces of real panels with dimensions 1.66 m x 0.6 m of two different aircraft types. They have different construction and spacing of stringers and frames and similar skin thickness (skin thickness of panel 3 exceeds the skin thickness of panel 2 by about 20 percent). This difference in the skin thickness is unlikely to cause an increase of vibrations and acoustic radiation of panel 2 in comparison with panel 3 by more than 1.5 dB, when excited by the same pressure-fluctuation field. Approximately the same difference, in the average, over the spectrum can be observed in figure 1. If the stiffeners of the panels had an essential effect on the manifestation of the space-time structure of the exciting non-uniform pressure-fluctuation field of vibrations and acoustic radiation of thin-walled structures, the difference in the measured sound power radiated by panels 2 and 3 would be significantly larger. This is an indirect support of the validity of the proposed model.

The comparisons of experimental data on vibrations and acoustic power radiated by panels 1, 2 and 3 at different flow velocities also permit stating that function $F(\beta, \lambda)$ well reflects real variations of response and acoustic radiation of thin-walled structures due to variation of the structure of exciting pressure-fluctuation fields. The experimental data shown in figure 3 on the increase of sound power radiated by three different panels, panel 1 without stiffeners and panels 2 and 3 with different stiffeners, illustrate this statement. Indeed, for panels with practically identical skin thickness, made of the same material but with and without stiffeners of different rigidity, the increase in radiation is practically equal. Similar results supporting the validity of the prediction model are obtained for an increase of the vibration velocity averaged over the surface of panels, excited by non-uniform pressure-fluctuation fields, as the flow velocity is increased. Moreover, the increase of sound power radiated by these panels observed in the experiment and of vibration intensity of these panels (with practical differences) is almost undistinguishable (figure 4). This was indeed the expected result according to the proposed prediction model.

The experimental and predicted data [1] shown in figure 6 lend direct support to the application of the prediction model to determination of the effect of a step on the increase of the sound power radiated by panels with stiffeners. The data apply to panel 3 excited by pressure fluctuations on a smooth surface (uniform field) and with steps of 3 mm height, which model the non-uniform field at flow velocity 38.6 m/s. Note that information obtained from the experiment on all characteristics of these two pressure-fluctuation fields was used in the predictions.

The degree of agreement between the prediction results according to [1] and the experimental data on the sound power radiated by a panel, excited by a non-uniform pressure-fluctuation field, can be judged from figures 6 and 7, where results for U=38.6 m/s and h=3.0 mm are presented.

In conclusion, experiments support the validity of predictions [1] of acoustic radiation of panels excited by aerodynamic pressure-fluctuation fields of substantial non-uniformity. This is true for supersonic flow [3] as well as for subsonic flow, reported here, where the pressure-fluctuation fields were realized by flow over forward-facing and backward-facing steps.

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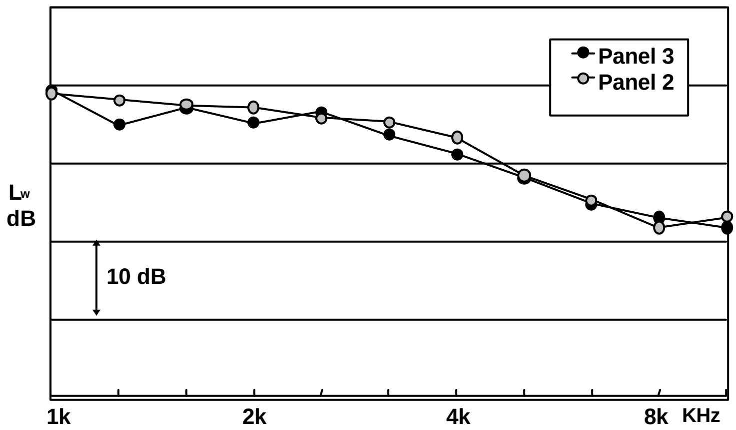


Figure 1.
Sound power radiated by different panels excited by pressure fluctuations from 3 mm-high steps at U=23.9 m/s.

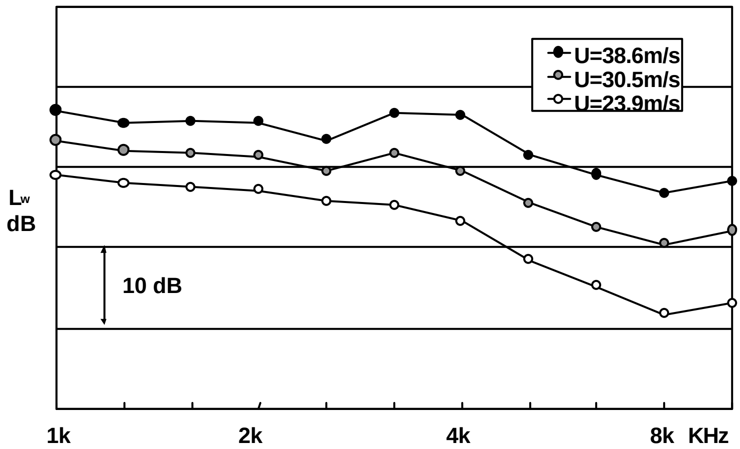


Figure 2.
Effect of flow velocity on sound power radiated by panel 2.

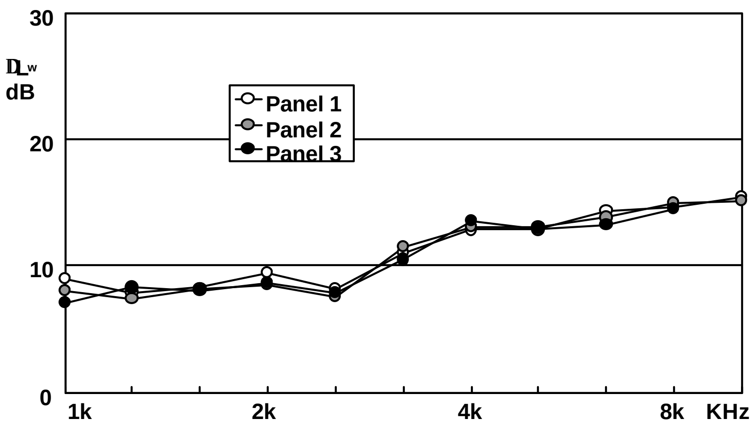


Figure 3.
Variation of sound power radiated by different panels excited by the pressure-fluctuation field from steps when flow velocity is increased.

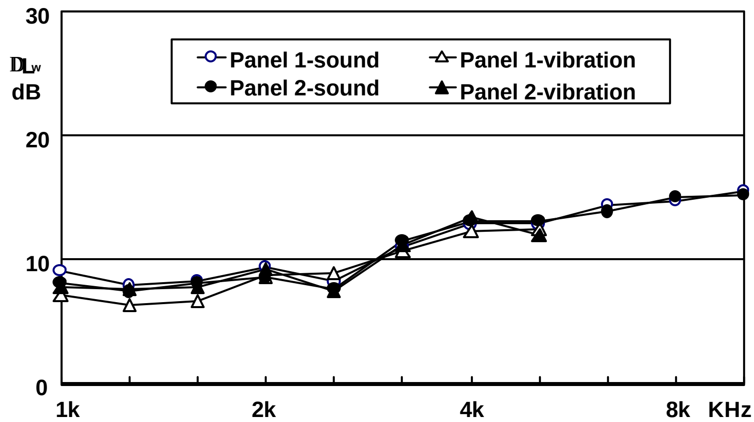


Figure 4.
The increase of vibrations and sound radiation of panels are virtually identical as flow velocity is increased.

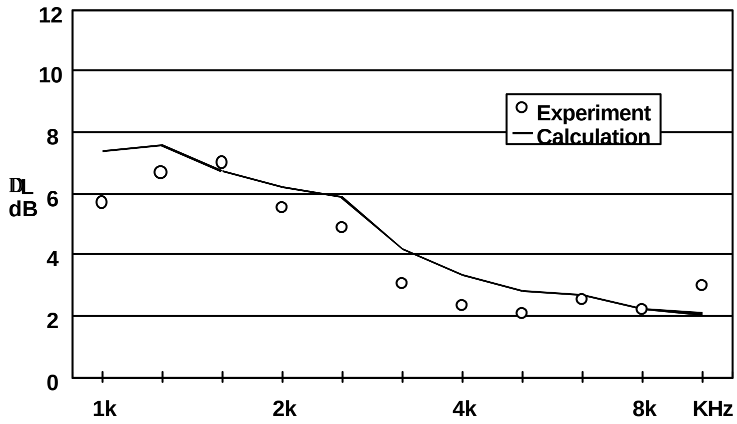


Figure 5.
Comparison of predicted and experimental increases in sound-radiation for panel 3.

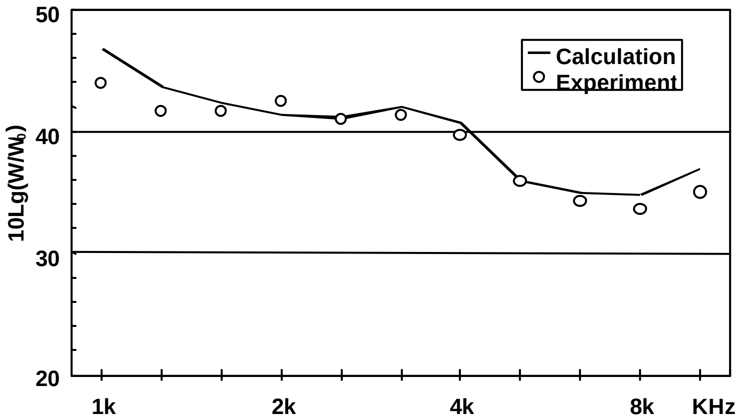


Figure 6.
Comparison of predicted and measured sound power radiated by panel 1.

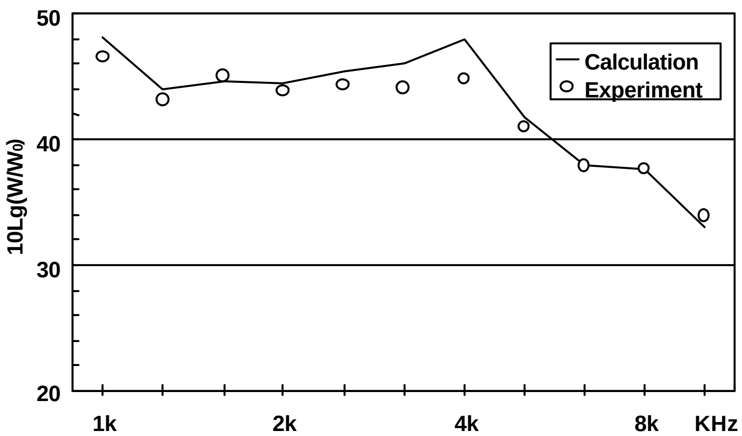


Figure 7.
Comparison of predicted and measured sound power radiated by panel 3.