VIBROACOUSTIC RESPONSE DUE TO TURBULENT FLOW EXCITATION

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1. ABSTRACT

A wind tunnel study has been performed providing detailed information on the structural excitation and related noise radiation due to turbulent flows, particularly turbulent boundary layers. The results include data on

– the hydrodynamic wall pressure fluctuations,
– the vibroacoustic response of defined panels,
– the sound radiated by the panels.

An experimental set-up has been successfully designed in keeping the background noise sufficiently low. The results show that hydrodynamic coincidence plays a key role in the excitation and transfer mechanisms for flow induced noise. A controlled mismatch of the excitation characteristic and the panel behaviour may lead to a significantly reduced power input.

The ability to determine the vibroacoustic response due to turbulent flow excitation within a large wind tunnel has been proven. A very valuable database has been generated improving the understanding of turbulent boundary layer noise excitation mechanisms. However, still a number of open questions exist in this field. The authors intend to apply the gained know-how and to extend the gained experience within future studies to further elaborate strategies for aircraft structures aiming at low interior noise levels.

2. INTRODUCTION

Turbulent boundary layer noise is an important contribution to the interior noise of aircraft. The source mechanisms of this noise excitation are yet not fully understood. To implement optimised strategies for the design of future aircraft structures detailed know-how of source properties and transfer characteristics are urgently required. For this purpose an unique experimental study on the structural excitation and associated noise radiation due to turbulent flows has been recently performed.

Hereby, the vibroacoustic response due to turbulent flow excitation has been parametrically investigated for

– a set of panels with different thickness and stiffness
– different flow velocities and
– different turbulence intensities

The present paper provides an overview on the test set-up and instrumentation, the basic findings as well as the basic conclusions for future activities. The next paragraph, however, shall try to give an overview on the entire problem.

3. OVERVIEW ON THE PROBLEM

The entire problem is discussed on basis of a simplifying scheme below. This scheme shall subdivide the problem into three, subsequent steps.

The first step is meant to provide the relevant hydrodynamic wall pressure fluctuations. The excitation of the wall pressure fluctuations is given by the flow characteristics, such as the flow velocity, the boundary layer thickness, possible static pressure gradients, temperature or humidity. In addition the problem is influenced by additional parameters such as the surface roughness or any upstream flow disturbances. Now, the excitation field of a turbulent flow is particular because of its random but also convected character. The wall pressure fluctuations are not fully described just by autospectra, since the spatial and convective distribution of the spectral turbulent energies is an important feature. Considering a frozen turbulence field moving along a surface, a fixed observer would get an image strongly influenced by the convection velocity. An e.g. increase in the convection velocity would simply result in a shift to higher frequencies. In contrast one could consider an observer travelling with mean velocity. This observer would image a time changing turbulence flow field without any influence of the convection speed and the spatial distribution of the turbulence patterns. In reality, the turbulence flow pattern is changing with time while convecting along the observed section which emphasizes the importance of the correlation of space and time.

Assuming that the wall pressure fluctuations are fully described and thus also the overall excitation mechanism one has to face the second step: The determination of the structural response. Together with the excitation parameters such as e.g. the panel geometry and thickness, the elastic modulus and the mass density are influencing the structural response. In principle the hydrodynamic pressure fluctuations generate response in each panel mode, but a panel does not respond similarly for all frequencies and wavenumbers. For the case that the hydrodynamic pressure fluctuations match the wavenumber and the frequency of a particular panel mode, hydrodynamic coincidence occurs. At hydrodynamic coincidence the bending wave speeds of the panel coincide with the convective speed of the pressure fluctuation field and the mean power input from the pressure field to the structure is maximised.

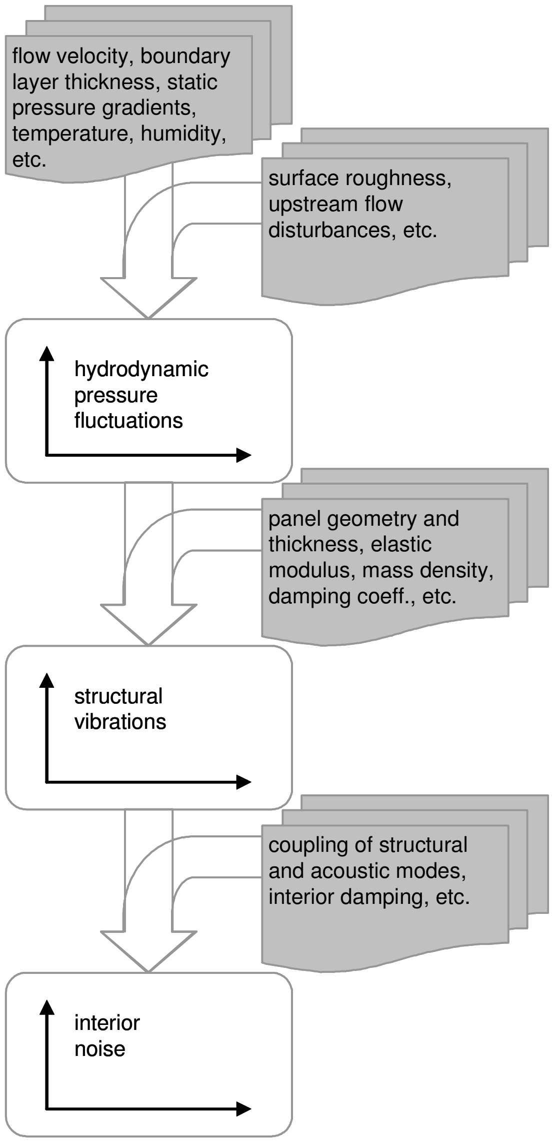

FIG. 1 Schematic differentiation into subsequent steps

The final step does provide the interior noise based on the structural response. Additional important parameters here are e.g. the coupling of the structural and acoustic modes or the interior acoustic damping characteristics. These additional parameters are strongly connected to a specific design and are thus difficult to assess within a generic study. It is therefore of lower importance for the present study in which the control of the structural response is the first priority objective. Nevertheless, the final step towards interior noise shall also be discussed.

4. TEST SET-UP

A very large test set-up of more than 9m length has been placed within a large low speed aeroacoustic wind tunnel (Fig 2.). The test set-up can be divided into three modules:

– Test section (Fig. 1, A)
– Acoustic test enclosure (Fig. 1, B)
– Streamlined cover (Fig. 1, C)

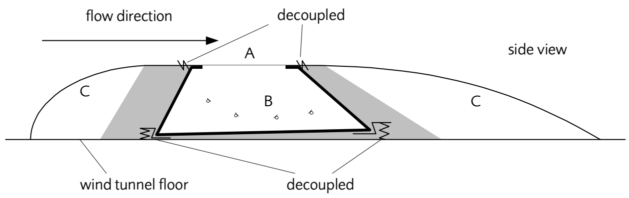

FIG. 2 Schematic view of the test set-up

With this set-up the wind tunnel was able to provide velocities up to 60m/s.

4.1. Test section

The test section mainly consists of five different test panels to be mounted in a stiff frame. The stiff frame is made from aluminium with a thickness of 25.4 mm. The frame is flat and it is adjusted parallel to the wind tunnel floor.

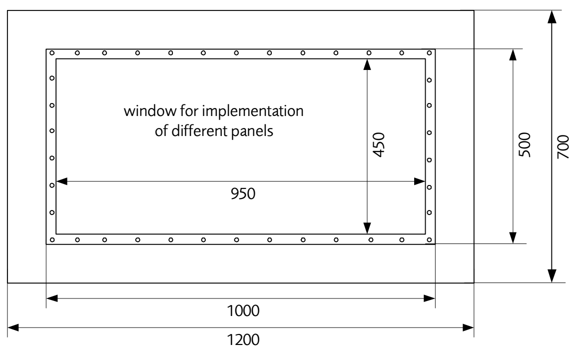

FIG. 3 Stiff frame for mounting of test panels, view from the top

The test panels are of a size of 1000 mm by 500 mm. All in all 6 panels have been manufactured and tested:

– A stiff panel of the same thickness / material as the frame (thickness 25.4 mm, material aluminium)
– A stiff panel of the same thickness / material as the frame (thickness 25.4 mm, material aluminium) with holes for the unsteady surface pressure sensors
– A simple panel which is just a flat plate (thickness 0.5 mm, material aluminium): p0.5mm
– A simple panel which is just a flat plate (thickness 0.8 mm, material aluminium): p0.8mm
– A simple panel which is just a flat plate (thickness 1.2 mm, material aluminium): p1.2mm

– An aircraft panel which is a flat plate similar to the simple panel (thickness 1.2 mm, material aluminium) and additionally stiffened by 5 stringers: p1.2mmS. The used stringers are typical aircraft stringers.

4.2. Test enclosure

The frame described above is the cover of the acoustic test enclosure. To suppress the vibroacoustic excitation of the walls of the enclosure the frame and the enclosure have been connected using several layers of thick and soft viscoelastic material in between.

The acoustic test enclosure itself is an irregular box. The test enclosure has been made of 40 mm chipboard which is coated on the inner and outer side. The irregular geometry of the inner volume allowed to use this box as a reverberation room with a volume of 2.53m³. Reverberation time measurements in the laboratory proved that this configuration is capable to measure sound power for frequencies above 600Hz. In addition the box was easily transferable into an anechoic chamber by installing pre-confectioned sound absorbing inserts.

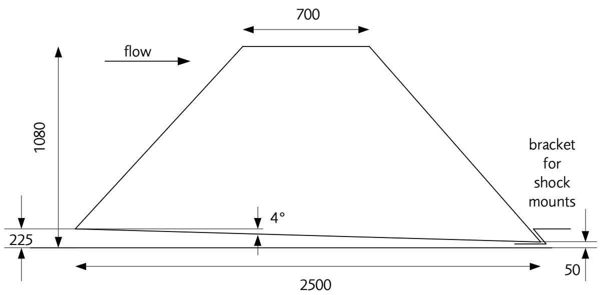

FIG. 4 Side view on test enclosure

4.3. Streamlined cover

The streamlined contour is covering the acoustic test enclosure and has an opening of the same size as the test section. The streamlined body ensured the attached flow over the test panel.

4.4. Turbulence devices

Basic configuration for the excitation of the panels was the turbulent boundary layer generated without any upstream disturbance of the flow. An artificial increase of the “turbulence intensity” has been implemented into the test matrix by mounting two different additional flow devices upstream of the panel. The devices are specified as TA (turbulence amplifier) within the results. Besides the configuration “tbl” (turbulent boundary layer = without any device) devices named as “low TA” and “med TA” have been realised. “low TA” was a wire (6mm diameter) glued directly on the streamlined body 300mm upstream of the panel. “med TA” was made of equilateral vertical triangles (height 30mm), positioned 600mm upstream of the panel.

In addition, the turbulence amplification generated a significantly better signal to noise ratio which was beneficial for the validity of the results.

5. INSTRUMENTATION

To specify the excitation mechanism the flow turbulence above the test panel has been determined applying 2-dimensional hot wire anemometry. In addition, the unsteady pressure distribution on the test panel surface has been measured using flush mounted pressure sensors. Following sensors have been applied:

– 2 miniatur pressure sensors with a diameter of 1.6 mm (Kulite XCQ-062-350mBAR VG)
– 7 microphones (B&K 4135 1/4"), without grid.

mic	Type	x-pos [mm]	y-pos [mm]
1	XCQ-062-350mBAR VG	231	500
2	XCQ-062-350mBAR VG	234	500
3	B&K 4135 1/4"	240	500
4	B&K 4135 1/4"	250	500
5	B&K 4135 1/4"	250	510
6	B&K 4135 1/4"	250	530
7	B&K 4135 1/4"	270	500
8	B&K 4135 1/4"	310	500
9	B&K 4135 1/4"	390	500

TAB. 1: Wall pressure fluctuation measurement positions in test panel coordinates

As also specified in the table above the sensors have been arranged in flow direction and in crosswise direction so that different distances among the different sensors have been realised, particularly for correlation analysis.

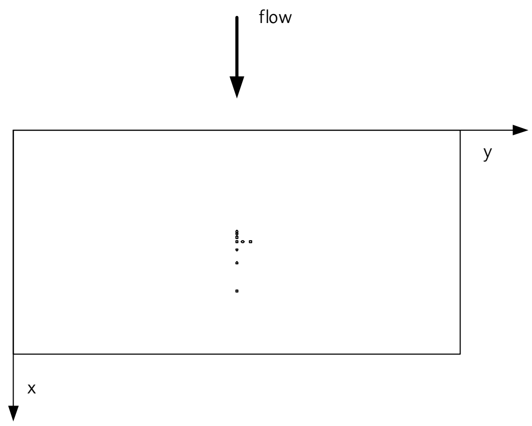

FIG. 5 Definition of the test panel coordinate system

The response of the panels has been determined in terms of vibration and noise emission. For the panel vibration particularly lightweight accelerometers (PCB Piezotronics 352C22) have been mounted backwards of the panel in an arbitrary arrangement. However, the positions of the sensors were the same for all panels and are shown in the figure below.

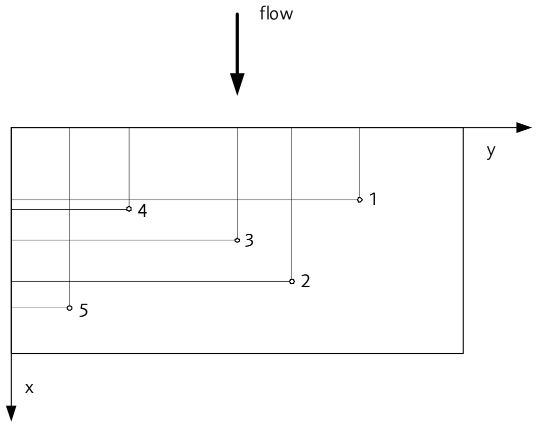

FIG. 6 Position of accelerometers

The panel noise emission has been measured within the acoustic test enclosure on the back side of the test panels. As described above this enclosure has been alternatively configured as an anechoic as well as reverberating environment. For both configurations six B&K 4166 ½" microphones have been well distributed within the enclosure. For the reverberating environment a sufficient diffusion of the sound field within the enclosure has been proved by laboratory experiments.

6. SELECTED RESULTS

6.1. The wall pressure fluctuations

The figure below presents an overview on the measured wall pressure fluctuations for the flow velocities 40m/s, 50m/s, 60m/s for all three turbulence intensities tbl (w/o TA), low TA, med TA. The data are provided for the panel microphone 3 (see Tab. 1) as 3rd octave band spectra in the frequency bands from 100 to 6300 Hz.

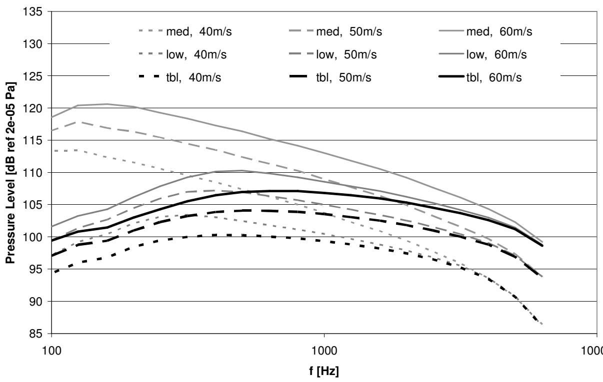

FIG. 7 wall pressure fluctuations for different flow velocities and different turbulence intensities

For the case tbl the maximum levels are reached in a broad frequency range from 500 to 1000 Hz. The low TA device shifts the maximum to lower frequencies at around 400 Hz but increases the levels only by 3-4dB. The med TA however generates significantly increase levels (+ 20dB) at 100 to 300 Hz. Common for all TA's is the influence in the low frequency range, levels at higher frequencies are nearly not influenced. In addition an expected increase of the level with the flow velocities is observed.

6.2. The panel response

Figure 8 provides a comparison of the panel response of the simple panel with 0.8mm thickness (p0.8mm) for the three different velocities 40m/s, 50m/s, 60m/s (tbl) and for three turbulence intensities tbl, low TA, med TA (60m/s). p0.8mm is taken as an example here, however, the tendencies are quite similar for the other panels. The spectra show that compared to the excitation a significant maximum for the panel response is observed. The peak frequency increases with an increased flow velocity, although no significant frequency shift is given by the excitation. For a constant flow velocity and different turbulence intensities the peak frequency keeps constant and a level increase for all frequencies is observed. This is at least surprising since the excitation shows a very significant shift to lower frequencies.

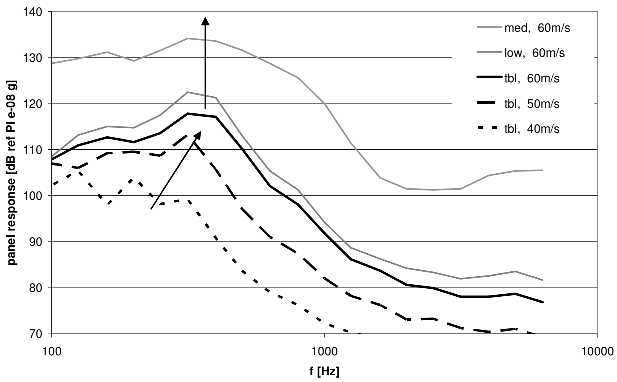

FIG. 8 panel response, P0.8mm, acc2 for different flow velocities, different turbulence intensities

This phenomenon may be explained by the aerodynamic coincidence. As described above, at hydrodynamic coincidence the bending wave speeds of the panel coincide with the convective speed of the pressure fluctuation field and the mean power input from the pressure field to the structure is maximised. For simple flat panels the peak frequency for the aerodynamic coincidence may be estimated applying

(1) $\omega_{aero} = U_c^2 \sqrt{\frac{\rho \cdot h}{B}}$ with $B = \frac{E \cdot h^3}{12 \cdot (1-\nu^2)}$ [3]

and U_c being the convection velocity, ρ being the density of the panel material, h the panel thickness, B the bending stiffness. For the present study the estimated coincidence peak frequencies are given in the table below.

Panel	0,5mm	0,8mm	1,2mm
40 m/s	209 Hz	131 Hz	87 Hz
50 m/s	327 Hz	204 Hz	136 Hz
60 m/s	471 Hz	294 Hz	196 Hz

TAB. 2: Estimated coincidence frequency f_{aero} for the simple aluminium panels with respect to the flow velocity

Figure 9 below compares the panel response for the three different panels p0.5mm, p0.8mm and p1.2mm for 60m/s and tbl excitation. The figure confirms the strong influence of the coincidence effect on the peak frequency for the maximum power input.

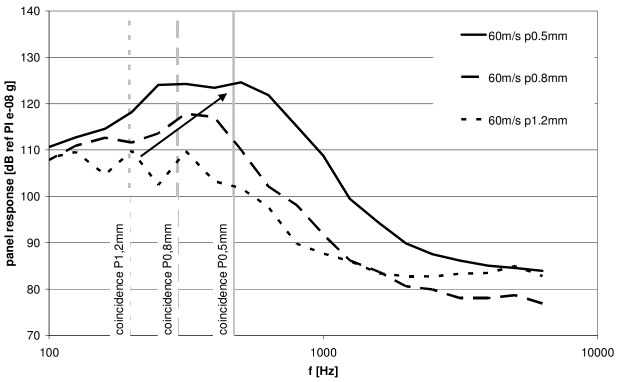

FIG. 9 panel response, comparison of panels, acc2 for 60m/s, tbl

Further evidence is given by the normalised response R_P, being the panel response based on the excitation and considering the mass law:

(2) $R^* = S_R - S_E + 10 \cdot \lg\left(m''^2\right)$ in [dB] [3]

with S_R being the panel response autospectra, S_E being the wall pressure fluctuation autospectra and *m"* being the panel mass per area *m" = ρ h*. This normalisation considers the influence of the panel mass per area which would be the dominant effect for acoustic excitation.

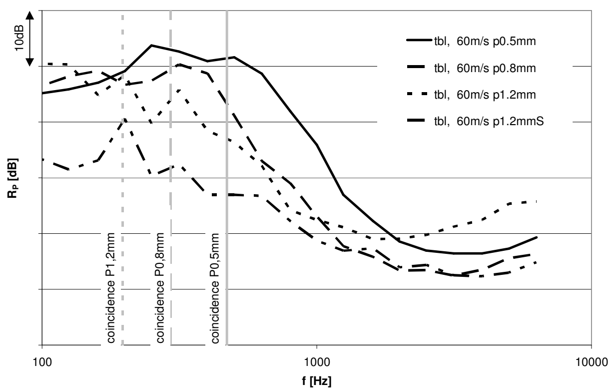

FIG. 10 Normalised panel response for 60m/s, tbl

The normalised panel response proves that the maximum power input is close to the estimated coincidence peak frequency and that for thinner and lighter panels the frequency range for an efficient response is clearly extended in the mid frequency region. For high frequencies no significant differences among the panels are observed. In addition to the simple panels also a stiffened panel with a thickness of again 1,2mm is presented. The increase of stiffness leads to a clearly reduced response, particularly for lower frequencies. Although the coincidence peak frequency for complex structures is not easily estimated, equation (1) shows that an increase of stiffness significantly reduces the peak frequency. For the present case a beneficial mismatch of the excitation with the panel coincidence behaviour significantly reduces the power input.

6.3. The noise radiation

The radiated sound power S_P is normalised in a similar way as it has been done for the response. A normalised transmission index *TI** is defined by

(3) $TI^* = S_P - S_E + 10 \cdot \lg\left(m''^2\right)$ [3]

with S_P being the measured sound power, S_E being the wall pressure fluctuation autospectra and *m"* being the panel mass per area *m" = ρ h*. For a comparison with results from different experimental set-up's an additional normalisation with the panel area and the frequency would be considered, however, for the present study these parameters are constant and therefore not further taken into account.

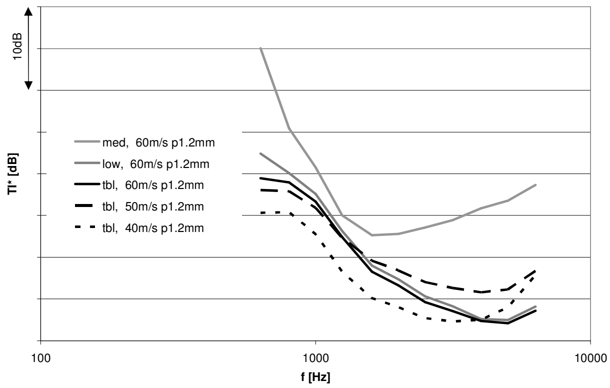

FIG. 11 Normalised sound power for the p1.2mm panel, different velocities and turbulence intensities

According to the above described restrictions the sound power can be analysed only for frequencies above 630 Hz. Figure 11 shows the normalised transmission index for p1.2mm for different excitations. For the different flow velocities the normalisation obviously works so that only minor differences in the normalised radiated sound power are observed. The increase at very high frequencies here is detected to be an exterior disturbance and should not be further considered here.

For the med TA, however, a significantly increased power output is observed. It seems to be an indication that an increase in the turbulence intensity results in a disproportionate increase of the transmitted power.

Figure 12 shows the normalised sound power for different panels. Due to the frequency restrictions the observed differences from the panel response for the stiffened and not stiffened panel are not visible, for frequencies clearly above the hydrodynamic coincidence, however, the stiffness seems to have only minor influence on the transmission behaviour. For the significantly thinner panel p0.5mm it can be concluded that the gradient between transmission close to coincidence and clearly above coincidence is much higher than for the heavier panels.

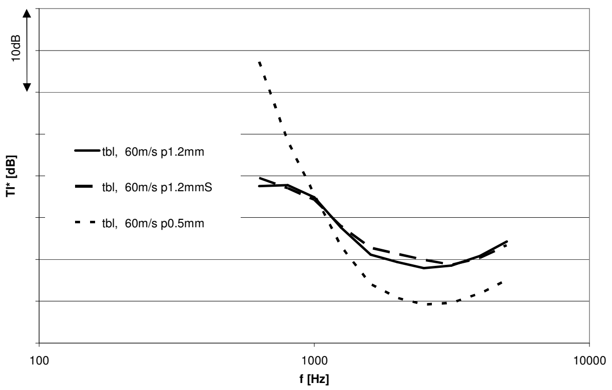

FIG. 12 Normalised sound power for three different panels for 60m/s, tbl

7. CONCLUSIONS AND FUTURE ACTIVITIES

The initial intention of the performed study was to prove the ability to determine experimentally within a large wind tunnel the vibroacoustic response due to turbulent flow excitation. It can be concluded that this ability has been proven very successfully and that a very valuable database has been generated improving the understanding of turbulent boundary layer noise excitation mechanisms.

The results show that hydrodynamic coincidence plays a key role in the excitation and transfer mechanisms for flow induced noise. A controlled mismatch of the excitation characteristic and the panel coincidence may lead to a significantly reduced power input.

The results do also give indications that an increase in the turbulence intensity results in a disproportionate and therefore non-linear increase of the transmitted power. However, the results do also show that the experimental work in this field is quite sophisticated and requires certain experience. A number of open questions do still exist in this field.

The authors intend to apply the gained know how and to extend the gained experience within future studies to further elaborate strategies for aircraft structures aiming at low interior noise levels. Particular interest is focussed here on the experimental check out of real aircraft structures due to turbulent flow excitation in large wind tunnel facilities.

8. ACKNOWLEDGEMENT

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