HELICOPTER CABIN INTERIOR NOISE ASSESSMENT USING SCAN & PAINT TRANSFER PATH ANALYSIS

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Direct sound field visualization is not always the best way to assess complex noise problems. Maps of sound pressure, particle velocity or sound intensity in the vicinity of a panel might not be directly related to the pressure contribution at a certain position. Transfer Path Analysis (TPA) has been implemented for many years to evaluate this case scenario. The most common measurement procedures require the use of large microphone arrays, meaning high cost, time and frequency limitations. However, using particle velocity sensors in combination with scanning techniques had been proven to enhance the efficiency and accuracy of measurements performed under stationary conditions. The method "Scan & Paint" makes use of only one PU probe which is manually swept along the surface while a video is recorded. Combining the audio with the positional information extracted from the video is possible to create fast sound pictures. A two steps measurement approach is implemented: first the cabin interior is scanned under operational conditions and then the process is repeated exciting the sound field with a monopole source. This paper presents a fast and accurate method for characterizing local sound pressure contributions across a helicopter interior. The obtained results showed that narrowband mapping reveals the location of dominant noise sources even at low frequencies, expanding the conventional frequency limits of pressure-based techniques.

1. INTRODUCTION

One common problem in vehicle interior noise is reducing the sound pressure level at the passenger's ears. The interior noise of an aircraft is important for both comfort and occupational health reasons. To improve the acoustic performance of the vehicle interior, a reliable method for sound source detection is often required. The final goal is to reduce the noise at some specific points inside the enclosure with the minimum impact on production cost and weight.

An accurate and cost-effective transfer path analysis (TPA) method can be based on the unique properties of the Microflown acoustic particle velocity sensor. Although different methodologies for near-field sound source localization are available on the market, sound pressure-based measurement methods rely on indirect calculations of the volume velocity of the different noise sources. This fact will lead to have many limitations since several assumptions are required.

Apart from scientific considerations any methodology should be also "friendly" in term of cost, time and background knowledge required for post-processing. In this paper a fast acoustic particle velocity scanning approach for sound source localization is adapted for highly demanding measurement conditions such as rotorcraft testing.

An airborne Transfer Path Analysis (TPA) is performed to rank the sound pressure contribution from each part of the vehicle, analyzing both the source strength and the way they affect the human ear. This problem is normally referred to as "Panel Contribution Analysis". In the technical literature, several experimental techniques can be found that address this problem. Most commonly used methods are window-based techniques [1], intensity measurements [2], laser scanning vibrometry measurements [3], beam forming [4] and holographic technologies [5,6] using sensor arrays.

The method proposed is a velocity-based solution called "Scan & Paint TPA" [7,8] which makes use of only one probe that is swept along the surface acquiring particle velocity and pressure information in the vicinity of the radiating structures. Reciprocal transfer functions are required to record information which describes how the environment affects the sound radiated from every surface of the cabin towards the studied reference position. They are measured by a second sweep with the same probe and a monopole sound source exciting the sound field from the reference position.

Previous works on airborne transfer path analysis for velocity based methods showed the potential of combining multichannel volume velocity measurements with acoustic transfer paths for predicting sound pressure at a certain reference position [9-11]. Nonetheless, there is a lack of evidence if velocity-based scanning measurement techniques could be also suitable for assessing helicopter cabin interior noise.

2. THEORY

In order to assess the underlying theory behind panel contribution analysis into a cabin interior, a general approach can be taken. Let us start defining a cavity $\mathbf{S}$ which surface excites the sound field when it is under operating conditions. Then, an infinitesimal small area $\mathbf{M}$ can be defined inside $\mathbf{S}$ for studying how different areas of the cavity 'contribute' to a point at $\mathbf{M}$. Figure 1 shows a sketch of the scenario described above.

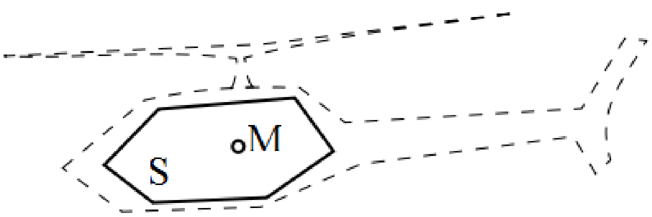

Figure 1 - Schematic overview of the surfaces involved in the derivation

The theoretical derivations of an expression for calculating the pressure contribution at $\mathbf{M}$ follow Hald [5,12] and Kinsler [13]. First of all, it is necessary to define two different measurement conditions: when a monopole source at $\mathbf{M}$ is exciting the sound field (reciprocal transfer function measurements); and when the monopole is switched off and the cavity $\mathbf{S}$ is producing the noise (noise measurements).

Two sets of variables can be distinguished depending on the measurement conditions. p^{TF} and u^{TF} are defined as the pressure and particle velocity during the reciprocal transfer function measurements. On the other hand, p and u are the pressure and particle velocity during the noise measurements.

As have been pointed out by Hald, for deriving an expression which describes the fundamental relation of panel noise contribution analysis it is necessary to start using the definition of acoustic reciprocity ,

$$(\mathbf{1}) \qquad \int_{M} (\boldsymbol{p^{TF}u - p\,u^{TF}})\boldsymbol{dM} + \int_{S} (\boldsymbol{p^{TF}u - pu^{TF}})\boldsymbol{dS} = \mathbf{0}$$

The integral of particle velocity u across the entire surface $\mathbf{M}$ will be zero due to there is no net energy going throughout $\mathbf{M}$ during the noise measurements. Furthermore, the pressure p can be integrated over $\mathbf{M}$ during the noise measurements obtaining the reference pressure p_r. Besides, integrating the particle velocity over $\mathbf{M}$ during the transfer function measurement will lead to obtain the volume velocity of the monopole source Q. This leads to

$$(2) \qquad -p_r Q + \int_{S} (p^{TF}u - p\,u^{TF})\mathrm{d}\mathbf{S} = 0$$

The interior surface of the enclosure can be assumed acoustically rigid for low frequencies. This implies that the normal velocity of $\mathbf{S}$ is nearly zero during the transfer path measurement. Based on this assumption, Equation 2 simplifies to

$$(3) \qquad p_r = \int_{S} \frac{p^{TF}}{Q} u \,\mathrm{d}\mathbf{S}$$

Equation 3 presents the base equation of most velocity-based panel noise contribution methods for mid-low frequency analysis. It relates the pressure at the reference position p_r with the combination of particle velocity u and acoustic transfer functions p^{TF}/Q measured across $\mathbf{S}$.

So far, arbitrary signals have been considered on the derivation but for real scenarios it would be necessary to deal with random signals. Moreover, Equation 3 cannot be used directly with scanning measurements because the source velocities are recorded one-by-one during a scanning such that the phase differences between source velocities at different points are unknown. To solve these problems, Equation 3 is rewritten firstly multiplying by the complex conjugate version of the pressure reference p_r^* and then taking the expected values $E(\quad)$ of the different terms that could be treated as random variables, hence

$$(4) \qquad E(p_r p_r^*) = \frac{1}{A_m} \int_{S} \frac{p^{TF}}{u_m} E(u\, p_r^*)\,\mathrm{d}\mathbf{S}$$

where u_m is the particle velocity at $\mathbf{M}$ during the transfer path measurements; and A_m is the area of $\mathbf{M}$. Next, Equation 4 can be expressed by a combination of auto spectras and cross-spectras, i.e.

$$S_{p_r p_r} = \frac{1}{A_m} \int_{\mathbf{S}} \frac{S_{p^{TF} u_m}}{S_{u_m u_m}} S_{u p_r} \, d\mathbf{S} \quad (5)$$

where $S_{p_r p_r}$ is the autospectrum of the pressure reference; $S_{p^{TF} u_m}$ is the cross spectrum between the pressure at $\mathbf{S}$ and velocity at $\mathbf{M}$ both during the transfer function measurements; $S_{u_m u_m}$ is the autospectrum of u_m; and $S_{u p_r}$ is the cross-spectrum between velocity at $\mathbf{S}$ and the reference pressure.

In practical cases, the surface $\mathbf{S}$ has to be discretized by dividing it into a limited number of panels N. Consequently, Equation 5 leads to

$$S_{p_r p_r} = \frac{1}{A_m} \sum_{n=1}^{N} \frac{S_{p^{TF} u_m}}{S_{u_m u_m}} S_{(u p_r, n)} A_n \quad (6)$$

where A_n defines the area of each panel n.

3. INSTRUMENTATION

All measurements were carried out using a Microflown PU probe which contains a pressure microphone along with a particle velocity sensor. Furthermore, a GRAS random incidence microphone was used for measuring the reference pressure at the passenger's ear. A Microflown low frequency monopole sound source was utilized to perform the reciprocal transfer function measurements. In addition, 2 cameras "Logitech Webcam Pro 9000" were required for recording the different sections evaluated.

4. METHODOLOGY

The goal of the measurement procedure is to be able to localize and rank the dominant noise sources within a spectral region of interest. For this purpose, two main issues have to be addressed separately: noise sources and acoustic environment. The pressure at the reference position will be caused by the combination of how much noise the panels are inputting into the acoustic environment and how the environment itself affects the sound radiated. This statement can be inferred from the theoretical basis introduced in Section 2. Following this principle, the measurement procedure can be split into two parts: reciprocal transfer path measurements and particle velocity measurements.

4.1. Reciprocal transfer paths

During the first stage, the noise sources under assessment must be switched off. Then the sound field is excited with a monopole source at a reference position. A low frequency monopole source was used along with a particle velocity sensor as a reference (see Figure 2) while pressure was measured scanning the surface interior surfaces. Frequency limitations of reciprocal transfer function measurements are constrained by the effective working range of the monopole. Most panel contribution methods are not suitable for assessing low frequency problems. In order to demonstrate that "Scan & Paint TPA" can be applied even in such a challenging frequency region, a monopole source with an effective frequency range from 30 Hz to 500 Hz was used.

Figure 2 – Measurement setup during transfer path scanning measurements

Scanning measurement techniques conventionally require time stationary conditions in order to evaluate different points of the sound field homogenously. Consequently, the monopole source was driven with random white noise band pass filtered between 20 Hz and 500 Hz.

"Scan & Paint" is a sound mapping technique based on mixing sound variations across a sound field with the relative position information of the probe extracted from a video. For simple scenarios were the excitation sources are within one visible plane, one camera angle is enough to follow the probe position during the whole measurement. However, a helicopter interior is a complex scenario where one camera angle is not enough. Moreover, the camera should be as perpendicular as possible to the measured plane in order to reduce any optical errors due to the projection on the 2D picture (video frames). From the previous it is evident that each vehicle interior requires different cameras angle distribution, depending on its internal dimensions and configuration.

In this paper a Eurocopter EC120 was studied with 2 camera angles allocated in the roof and pilot seat. Due to the fact that there is no global coordinate system established (the probe position is always relative to the background image), the cameras should be fixed during the testing process. Good fixing is essential for the successful combination of velocity and transfer functions measurements.

Once all the cameras are fixed they will be used individually for recording the different sections while acquiring transfer functions from the reference volume velocity source to the pressure nearby the surface. In order to evaluate different passenger spots it would be necessary to place the monopole in each position and scan again all the surfaces. In this paper only one reference position was assessed. The time needed for setting up the experiment and acquiring the transfer path data was about 15 minutes.

4.2. Particle velocity

Similar to the standard Scan & Paint, the particle velocity in operational conditions is measured by scanning the surface with a PU probe. Again, due to the limitations of conventional scanning techniques, time stationary conditions are needed for performing the measurements. In the case studied, the measurements were carried out in the Lelystad Airport (the Netherlands) during the conventional 10 minutes warm-up time of the helicopter. Unwanted events (such as manipulation noise) were avoided in the post-processing stage by evaluating the spectrogram of the scanning transducer.

Figure 3 – Performing a scanning measurement in operational conditions

Similarly to the reciprocal transfer function measurements, each individual section was recorded from its corresponding camera angle performing sweeps with a PU probe close the surface. The difference between conventional “Scan & Paint” is that, relative phase information of the different sections is required. This issue is solved by using a reference microphone at the passenger’s position to have a fixed phase reference for synchronize all measurements in a relative sense.

5. RESULTS AND DISCUSSION

Acquiring pressure, particle velocity and their corresponding acoustic transfer functions allow us to study the spatial variations of those quantities along with the intensity and pressure contribution distribution across the cabin. Information was continuously acquired performing scanning sweeps close to the surfaces. Consequently, it has been necessary to discretize the surface interior to associate spatial areas to the signal acquired. The results presented in this section had been produced analyzing areas of 0.08 by 0.08 m, leading to high spatial resolution results.

Three main noise sources had been identified after analyzing the particle velocity maps of side and front cabin: control panel, ceiling and top window. Figure 5 presents the spectra of the different critical areas.

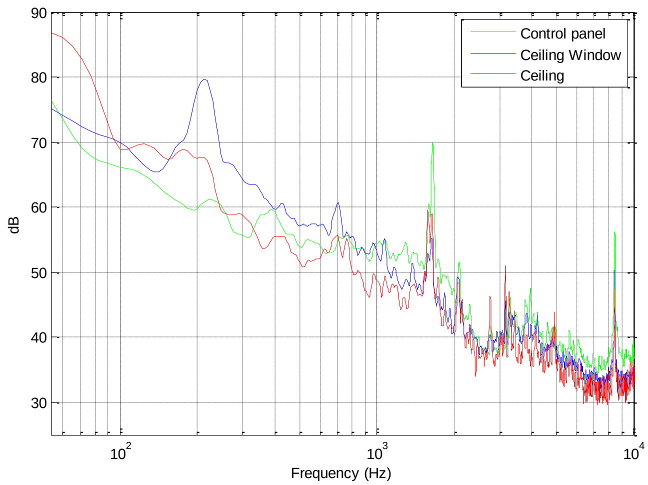

Figure 4 - Comparison of particle velocity spectra between different panels

Each one of them becomes dominant at different spectral areas. The ceiling had a remarkable importance below 100 Hz; it is about 10 dB higher than any other surface. Assessing the first prominent peak in the spectra, around 220 Hz, the ceiling window is apparently dominant. Next, a high level tonal component can be seen at 1600 Hz. The control panel has the highest particle levels in this part of the spectrum. Assessing the particle velocity distribution across the surface gives a good estimation of the local source strength of the cabin interior. Nonetheless, it is necessary to apply transfer path analysis to evaluate the individual pressure contribution to the passenger's ear. Equation (6) allows combining local velocity variations with the transfer path measurements to estimate pressure contribution from each area. The effective range of the monopole (30-500 Hz) supposes a limitation for applying transfer path analysis for high frequency sources. Hence, results had been assessed using transfer path analysis below 500 Hz, and particle velocity mapping had been used to localize high frequency noise sources.

Figure 5 presents a narrow band pressure contribution map of the left side of the helicopter, focused in the low frequency range, between 50 Hz and 100 Hz. The dynamic range of the picture had been adjusted to visualize 10 dB of sound pressure, making transparent areas with lower levels. As can be seen, there are a group of areas located at the ceiling which has a stronger influence in this low frequency region, becoming the dominant noise source.

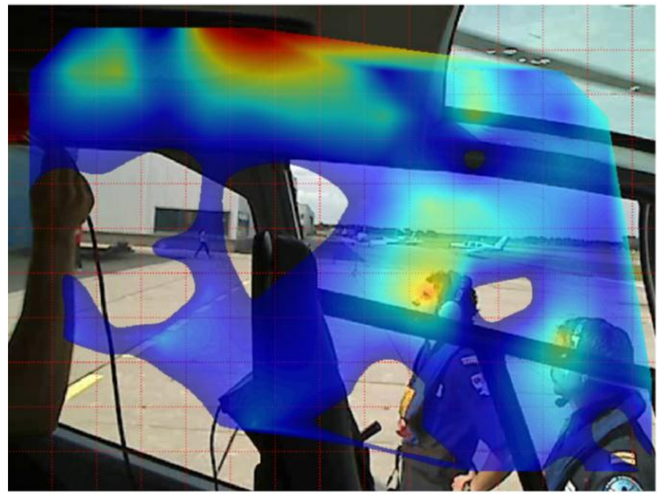

Figure 5 – Pressure contribution mapping between 50 Hz and 100 Hz with a 10 dB dynamic range

Furthermore, Figure 6 illustrates the pressure contribution map at the first resonant peak found in the spectrum, around 220 Hz. The dynamic range had been also adjusted to 10 dB showing clearly that in this frequency range is the ceiling window which becomes the dominant noise source.

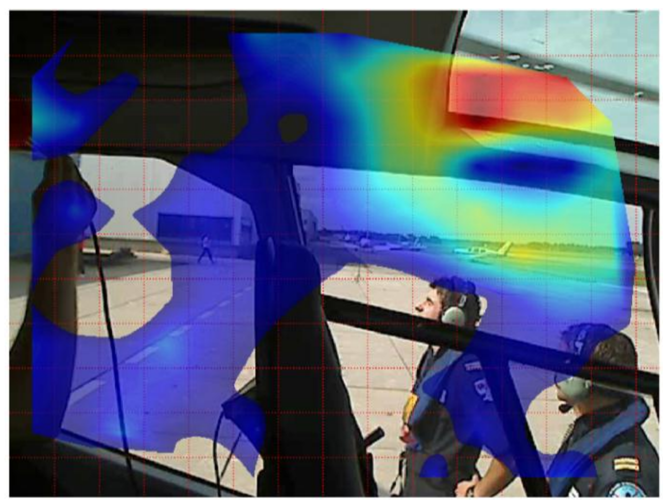

Figure 6- Pressure contribution mapping between 180 and 250 Hz with a 10 dB of dynamic range

Even though it was not possible to measure the transfer path for the third frequency region under concern, a particle velocity mapping had helped to localize the location of the source. Figure 7 shows a narrow band particle velocity map between 1500 and 1800 Hz. It is clear that the main noise problem is localized at the control panel of the helicopter.

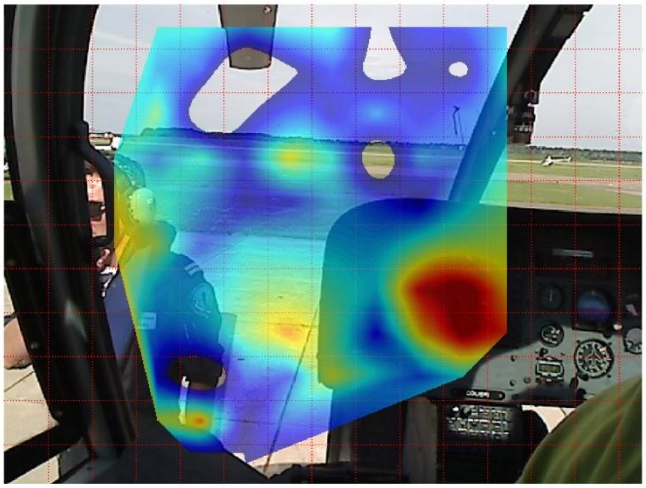

Figure 7 – Particle velocity mapping between 1500 and 1800 Hz with a 6 dB of dynamic range

6. CONCLUSIONS

The new measurement technique “Scan & Paint TPA” has been successfully validated for helicopter interior assessment under stationary conditions.

The clear sound maps provide evidence of the measurement success. It is important to highlight the good results obtained at low frequencies, which most conventional pressure-based measurement methods are not able to assess.

Surface velocity maps are useful for studying the volume velocity distribution across an enclosure surface. Nevertheless, pressure contribution mapping is required in order to find a clear method for identifying which areas have a stronger impact in the reference passenger position.

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