Fast in-flight cabin interior sound source localization

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Abstract: Helicopter cabin interiors are relatively noisy environments, negatively affecting the comfort of both crew and passengers. In order to determine the impact of the noise on the passengers, the source path analysis approach can be used, similar as to the automotive industry. Until recently, such extensive analysis was hampered by a lack of adequate acoustic instrumentation, requiring various sorts of sensors and a huge amount of testing time. Apart from that, some traditional methods prohibit in flight testing. In this paper, a new sound source localization technique is presented that allows simultaneously the localization of sound sources in the helicopter interior as well as the determination the sound level at certain passenger positions. Not only interior panel vibrations but also acoustic leaks can be found. The method works in a broad frequency range, in flight, real time, for both coherent and non coherent sources. First results are presented.

1. Introduction

Helicopter cabin interiors are relatively noisy environments, negatively affecting the comfort of both crew and passengers. In order to determine the impact of the noise on the passengers, the source path analysis approach can be used, similar as used in the automotive industry.
The source path contribution measurement method can be used to find out how loud individual sound sources are perceived in a noisy environment at a certain listening position. The method consists of two parts, the source strength determination and the transfer path determination.
The two measurements (the source strength and the path) can be done separately from each other. The source is measured during operation. The path is measured when all sources are switched off.

2. Source strength determination

Two methods exist to measure the source strength, the surface velocity method and the sound intensity method.

2.1. Surface velocity method

The surface velocity measurement is described by prof. Fahy (ISVR, England, [4]) and used by many companies [1], [2]. The surface velocity, that is the particle velocity in close proximity of a surface, is used to determine the source strength. Traditionally the surface velocity is approximated by measuring the structural vibration by the use of accelerometers or a laser vibrometer. These methods to measure the structural vibration are very time consuming. Apart from that, only the structural velocity is measured, airborne leaks cannot be handled. Many surfaces in for example a car cabin are not so suited for mounting of accelerometers, and in some cases the mass loading will significantly influence the measurement. It is not possible to reach all locations with a laser. Now, with the introduction of a particle velocity sensor (the Microflown) it is possible to measure the surface velocity directly [2], [3]. This way of measuring the surface velocity reduces the measurement time considerably and acoustic leaks are also measured.

At lower frequencies the bending modes of acoustic structures are long so to measure the velocity of the structure the number of velocity probes can be limited. At higher frequencies the wavelength of the vibration in the structure becomes shorter and more velocity sensors are required per unit area. Due to this, the method becomes less effective at higher frequencies. In cars the practical upper limit of this method in the order of 1~2kHz. The upper frequency where the velocity method can be used practically is expected somewhat higher than 1-2kHz because the hull structure of the helicopter is stiffer than a car.

2.2. Sound intensity method

For higher frequencies the intensity method is used. Traditionally pp intensity probes where used for this method. However pp probes cannot be used in environments with a lot of extraneous noise sources and reflections (such as a helicopter) [12]. So to be able to use a pp intensity probe normally the complete interior of the vehicle under test is filled with damping material and at the measurement location the damping material was removed and a 'window' was created. Therefore this method was also called 'the window method' [2], [10]. Drawbacks of the window method are the enormous effort, the disturbance of the interior acoustics and real life test runs are impossible.
The quality of a pu intensity measurement is not affected by extraneous noise sources or reflections [12]. Therefore the traditional 'window method' can now be done without the need of damping material. Because of this the method can be done fast and during real live operation [5], [6], [8], [9], [10], [14], [16].

At lower frequencies noise sources may be coherent (i.e. the phase of the source influences the perceived sound pressure at the listeners position). With the intensity method the phase information is lost so therefore this method cannot be used at lower frequencies. In principle this method has no upper frequency limit. The lower limit in a car appears to be in the order of 250Hz to 500Hz. In a helicopter the lower limit is expected to be lower than in a car due to highly reflective interior.

The emitted sound power of the surface is measured and this value is transformed as if it came from a point source. The transformation from sound power to monopole source strength is also allowed for surfaces with damping properties. The sound power of a monopole on a rigid surface in equals [5], [6], [7], [9]:

$$P = \frac{\rho c k^2 |Q^2|}{2\pi} \approx \frac{\rho \omega^2}{4\pi c} |Q^2| (2-\alpha) \quad (1)$$

Where α is the diffuse field absorption coefficient (plane wave approximation). The diffuse field absorption coefficient is approximated in situ using the measurement data from the path determination, see further below. The equivalent source strength is derived from this:

$$|Q^2| = \frac{4\pi c P}{\rho \omega^2 (2-\alpha)} \quad (2)$$

Sound power is determined by measuring a number of sound intensity points in a certain area relatively close to the surface. The intensity and sound power values contain no phase information so the method can only be used when sources are not coherent.

With the Microflown based method both methods (velocity and intensity method) can be done in one measurement. It greatly improves the measurement time and the measurement bandwidth [2], [8], [10].

3. Determination of the path

The path can be determined in two ways: the direct determination and the reciprocal determination. The direct method uses a monopole at the location of each source (when it is not in operation) and measures the amount of pressure at the listeners position.

In the reciprocal way, a monopole sound source is placed at the listener's position and the pressure is measured at the source position. The reciprocity principle states that the measured path is the same as the path from source to listener's position. In many NVH applications the measurements of acoustic transfer functions are often much easier done reciprocally.

A typical application is the measurement of acoustic transfer paths of sound radiated from a vehicle's engine to the driver's ear. The engine compartments of today's cars are almost completely filled with the engine itself and its various subsystems. Therefore a microphone can be installed much easier than a speaker, whereas in the cabin there should be enough space for a sound source.
When measuring reciprocally, e.g. with a sound source inside the cabin, all transfer paths are excited - and thus can be measured - simultaneously. This means a significant time reduction compared with the direct method, where each transfer function of interest has to be measured separately.

4. Reciprocity

4.1. Principle of reciprocity

The reciprocal method to determine the path states that the transfer function *p/Q* between a monopole sound source (*Q*) and the resulting sound pressure field (*p*) is unchanged if one interchanges the points where the monopole source is placed and where the sound pressure field is measured, irrespective of the acoustical environment [4].
Inside a helicopter the transfer path from the listener's position to the sound source location can be measured by a reciprocal method: a monopole sound source is placed on the listener's position and with a pressure microphone at the source position the transfer function can be determined.
According to the reciprocity principle the path from the monopole source to the pressure microphone is the same as from the sound source to the sound pressure field at the listener's position. However this is only true if the sound source has a true monopole behavior, which is not very likely. The surface velocity method and the sound power method both make an approximation so that the source can be seen as a monopole source.

For the surface velocity method the situation is sketched in Fig. 1.

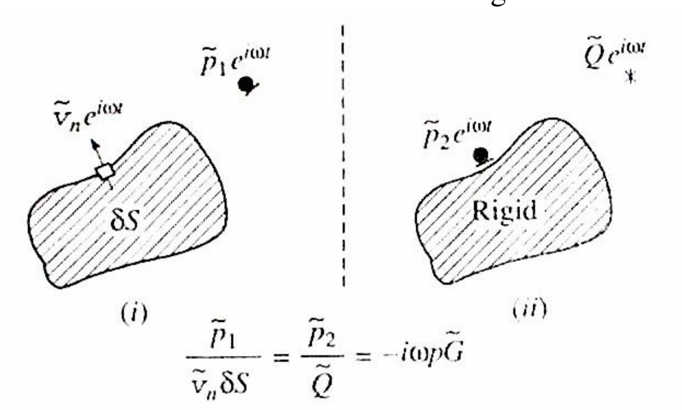

Fig. 1: Reciprocity of surface velocity and sound pressure with a monopole and sound pressure, from [4].

Hence, the total field at a receiver point may be estimated by summing the product of measured (or calculated) surface velocities sampled at a set of discrete points of the surface.

The transfer function p_2/Q is determined between the monopole source strength and (blocked) sound pressures on the surface of the (rigid) body with a pressure microphone placed close to the surface. This method is only valid if the surface impedance is high, i.e. a rigid surface. An extension of the method that allows for non rigid surfaces is discussed below.

4.2. Coherent and incoherent sound sources

Apart from methods to determine the source strength, there are also two categories of sound sources that have to be considered: coherent noise sources and incoherent noise sources.
If two sources S1 and S2 are coherent, the perceived sound pressure is depending on the phase of the sources. The perceived sound pressure equals the source times the path.
The auto spectrum of the perceived pressure $P_1=TF_1 x\, S_1$ and $P_2=TF_2 x S_2$ is given by:

$$S_{pp} = \lim_{T\to\infty} \int_{-T}^{T} \int_{BW} (P_1+P_2)(P_1+P_2)\,df\,dt = \lim_{T\to\infty} \int_{-T}^{T} \int_{BW} \left(P_1^2+P_2^2+2P_1P_2\right) df\;dt$$
$$= S_{p_1p_1} + S_{p_2p_2} + 2\lim_{T\to\infty} \int_{-T}^{T} \int_{BW} P_1P_2\,df\;dt \qquad (3)$$

If two sources are incoherent, the last term of Eq. (3) is zero, if the sources are coherent the last term is relevant.
The last term will be zero if the phase between P1 and P2 alters in a certain bandwidth, over time or over a certain space. If the phase is changing over time, the sources are not correlated. The averaging over a certain space is something that is somewhat difficult to do in practice.
Even when two sources are fully correlated (e.g. two loudspeakers that are electrically powered in the same way), their influence can be incoherent at a certain point in space. This is because the auto spectrum is always determined in a certain bandwidth. If the environment where the sources are placed is highly reflective, there will be a high number of paths from the sources to the receiving point where the pressure is measured. (The phase of the path varies a lot in such case.) For each frequency deviation (or position deviation) the phase at the receiver point is varying in an unpredictable manner. The result of this will be that the last term of Eq. (3) becomes zero.
If two correlated sources are placed at a certain distance in an anechoic environment, it is likely that the sources are also coherent up to a high frequency. If the same sources are placed in a reverberant environment, it is likely that the sources are not coherent.

4.3. Transition frequency

Normally the source may be coherent at low frequencies and they become incoherent at higher frequencies. The frequency where coherent sources become incoherent is called the transition frequency. There are two mechanisms that can cause source to become non coherent. The source behavior can be non correlated and the acoustic environment can be causing correlated sources to have a non coherent behavior. If the sound pressure caused by the two sources is incoherent, in practice this means that the last term of Eq. (3) is approximately zero:

$$2\lim_{T\to\infty} \int_{-T}^{T} \int_{BW} P_1P_2\,df\;dt \approx 0 \qquad (4)$$

If sources S_1 and S_2 are correlated, the sources S_1 and S_2 and the product S_1S_2 is constant in time and bandwidth. The transfer function is not varying in time so:

$$\int_{BW} TF_1 \times TF_2\,df \approx 0 \qquad (5)$$

If the frequency integrated product of complex transfer functions is approximately zero, the sources will be non coherent. If sources are non coherent, the intensity method can be applied but also the velocity method. The phase of the transfer function does not have to be used when the velocity method is applied. The phase of the velocity signal is also not required and this makes measurements easier: measurements may be taken point by point without the need of a reference.

4.4. Absorbing boundaries

The source path contribution problem splits up in source determination and path determination. Normally the path is measured in a reciprocal way. The position of the sound pressure microphone and the sound source are exchanged and the path from the listener position to the source is measured. The reciprocity principle is valid in the presence of absorbing boundaries. However in a practical situation the sources that are measured inside e.g. a car are not monopoles. And the reciprocity principle holds only if the sources are monopoles. Two conditions have to be met before the method is valid.

1) Proper source strength determination, so the radiated true sound power and the true particle velocity of the source without the influence of background noise.

2) The proper conversion from the source determination (either intensity or velocity) to an equivalent point source.

The reciprocity relation can be noted in a more general form by writing [17], (parts of this paragraph is a summary from [18]):

$$\iint_S u_2 \cdot n\, p_1 dS = \iint_S u_1 \cdot n\, p_2 dS \tag{6}$$

p_1 and u_1 and p_2 and u_2 are two arbitrary sound fields in two arbitrary points in a certain volume V that is enclosed by the surface S and *n* is the is a surface normal vector pointing into the volume V. So p_1 is the sound pressure in point one in sound field one and u_1 is the particle velocity in point two in sound field one. Subsequently p_2 is the sound pressure in point one in sound field two and u_2 is the particle velocity in point two in sound field two.

Let p_1 and u_1 be the operational sound p, u field with sources outside the surface S. For this sound field, the surface S_{ear} is blocked (rigid) and we seek the pressure p_{ear} on the blocked surface. Let p_2 and u_2 be the sound field p_Q and u_Q created by a source inside the 'ear canal' with the 'ear canal' open. The volume velocity Q through S_{ear} must in this case be known (measured).

We now split up the integral on the left-hand side of Eq. (6) in contributions from the partial surfaces:

$$\iint_S u_2 \cdot n\, p_1 dS = \iint_S u_Q \cdot n\, p dS = \iint_{S_{panel}} u_Q \cdot n\, p dS + \iint_{S_{ear}} u_Q \cdot n\, p dS + \iint_{S_{Source}-S_{ear}} u_Q \cdot n\, p dS \tag{7}$$

and from the assumption of a rigid source surface and an additional assumption of a constant operational sound pressure $p=p_{ear}$ across the blocked 'ear canal', S_{ear}, the previous alters in:

$$\iint_S u_2 \cdot n\, p_1 dS = \iint_{S_{panel}} u_Q \cdot n\, p dS + p_{ear} \iint_{S_{ear}} u_Q \cdot n\, dS = \iint_{S_{panel}} u_Q \cdot n\, p\, dS + p_{ear} Q \tag{8}$$

Because of the rigid source surface and that the ear canal surface S_{ear} is blocked for the operational sound field u·n=0 on the source and S_{ear}. For the integral on the right-hand side of Eq. (6) we therefore get:

$$\iint_S u_1 \cdot n\, p_2 dS = \iint_S u \cdot n\, p_Q\, dS = \iint_{S_{panel}} u \cdot n\, p_Q\, dS \tag{9}$$

These expressions are substituted in Eq. (6):

$$\iint_{S_{panel}} u_Q \cdot n\, p\, dS + p_{ear} Q = \iint_{S_{panel}} u \cdot n\, p_Q\, dS \tag{10}$$

And thus:

$$p_{ear} = \iint_{S_{panel}} \left[\frac{p_Q}{Q} u_n - \frac{u_{Q,n}}{Q} p \right] dS \tag{11}$$

Where p_Q/Q is the transfer function of the measured pressure at the surface caused by the reference sound source Q. This is the same as explained above. The ratio $u_{Q,n}$/Q is the transfer function of the normal particle velocity measured at the surface caused by the reference sound source Q. This value is zero when the surface is rigid. These transfer functions are measured when all extraneous sound sources are switched off.

u_n is the normal particle velocity at the surface in an operational measurement and p is the sound pressure in an operational measurement.

In order to obtain the contribution Δp_{ear} to the ear pressure p_{ear} from a segment ΔS_{panel} of the panel surface S_{panel} we integrate only over that part of the boundary:

$$\Delta p_{ear} = \iint_{\Delta S_{panel}} \left[\frac{p_Q}{Q} u_n - \frac{u_{Q,n}}{Q} p \right] dS \tag{12}$$

If a panel segment is a locally reacting impedance surface with impedance Z. Without a sound pressure acting on the surface, the panel would have an operational vibration velocity $u_{s,n}$. Then the particle velocities normal to the surface for the operational and the transfer function measurements are given as follows:

$$u_n = u_{S,n} + \frac{p}{Z} \quad and \quad u_{Q,n} = \frac{p_Q}{Z} \quad on \ \Delta S_{panel} \tag{13}$$

If these assumptions are inserted in Eq. (12),

$$\Delta p_{ear} = \iint_{\Delta S_{panel}} \left[\frac{p_Q}{Q} (u_{S,n} + \frac{p}{Z}) - \frac{p_Q}{Q} \frac{p}{Z} \right] dS = \iint_{\Delta S_{panel}} \frac{p_Q}{Q} u_{S,n} \ dS \tag{14}$$

It shows that the effect of the surface impedance Z is cancelled.

5. Measurements

5.1. Measurement equipment

To prove the functionality of the measurement system only one measurement is done inside a Eurocopter EC120. A 20 x 30cm panel is measured with a 12PU handheld acoustic camera, a mobile data acquisition system HEIM DIC24, HEIM PWAC power supply, an uninterruptible power supply and a battery pack.

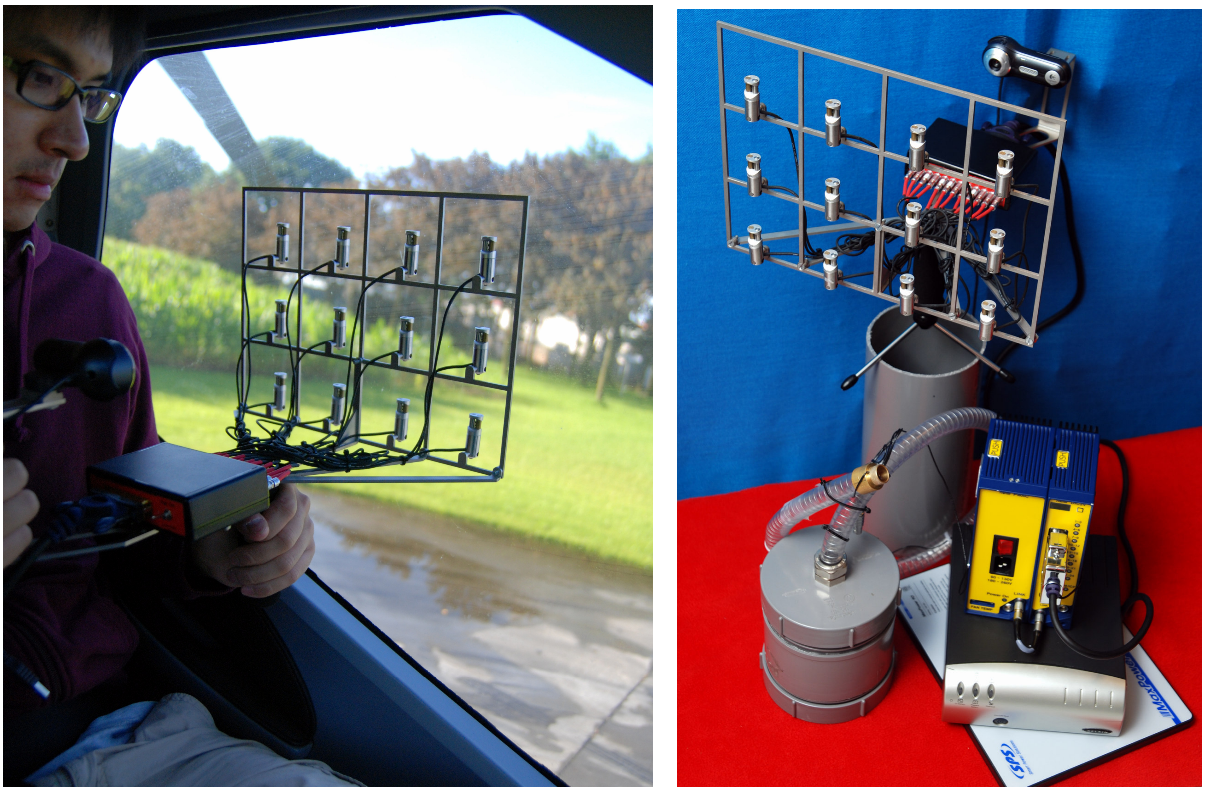

Fig. 2: In situ measurements in a helicopter with a PU acoustic camera and a mobile data acquisition system.

5.2. Measurement of the path

The first step in the procedure is the measurement of the path from listener's position to the test surface. During the path measurement the helicopter is not in operation. The path is measured with a monopole sound source with a known volume velocity and a measurement of the sound pressure and the particle velocity close to the surface under test.

The monopole source is realized as a high impedance loudspeaker with a tube that has a small diameter compared to the wavelength of the emitted sound. A reference velocity sensor (a Microflown) at the end of the tube is used to measure the volume velocity, since the volume velocity is given by the particle velocity times the area of the tube (see Fig. 2 at the left side below). When the monopole sound source is operated, the particle velocity and the sound pressure are measured close to the surface. The transfer functions p_Q/Q and $u_{n,Q}/Q$ are measured in this way, (see Eq. (12)).

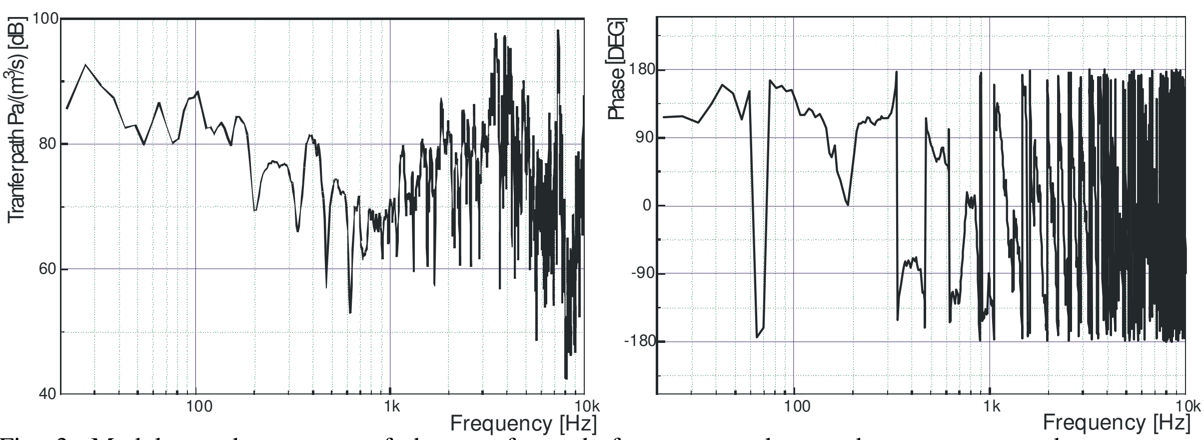

Fig. 3: Modulus and argument of the transfer path from monopole sound source to sound pressure at the measurement location.

The surface properties are best seen if the ratio of both transfer functions is displayed:

$$\frac{p_Q}{Q} / \frac{u_{n,Q}}{Q} \rho c = Z_{surface} \tag{15}$$

If the $Z_{surface}$ approximates unity the surface is fully absorbing and if the impedance is high, the second term in Eq. (12) can be neglected. From this surface impedance the diffuse field absorption coefficient α is estimated by [15]:

$$R = \frac{Z_{surface} - 1}{Z_{surface} + 1} \; ; \; \alpha = 1 - |R|^2 \tag{16}$$

The diffuse field absorption coefficient is required to calculate the equivalent source strength for the intensity method. In Fig. 4 the modulus and the argument of the measured impedance at the measurement location is shown. As can be seen, the impedance is high and the phase between pressure and velocity is approximately 90 degrees, indicating that the surface is highly reflective. As expected, at the measurement location the absorption is low (right plot). Because the absorption at the measurement location is low, the second term ($p^*u_{n,Q}/Q$) of Eq. (12) can be neglected.

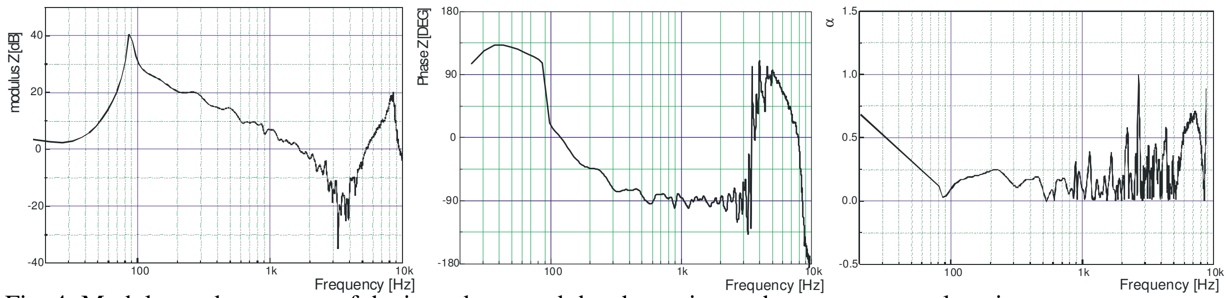

Fig. 4: Modulus and argument of the impedance and the absorption at the measurement location.

The total setup time is approximately two minutes for one path measurement. After this allow twenty seconds per path measurement.

5.3. Measurement of the sound emission of the surface

The second step of the procedure is the measurement of the source, in this case the interior of the helicopter. Both sound pressure and particle velocity are measured close to the surface under test; here a part of the back window is measured. Because the measured impedance is high, only the velocity is needed for the lower frequencies. For higher frequencies the intensity method is used.

5.4. particle velocity field

The emitted particle velocity field of the window is derived with only the velocity signals of the 12PU acoustic camera. In Fig. 5 (left) the individual velocities at the surface are shown. The equivalent sound pressure (that is the complex surface velocity times the complex transfer function) of this measurement is shown in Fig. 5 (right). This calculation is only indicative because below 1kHz sources may be coherent.

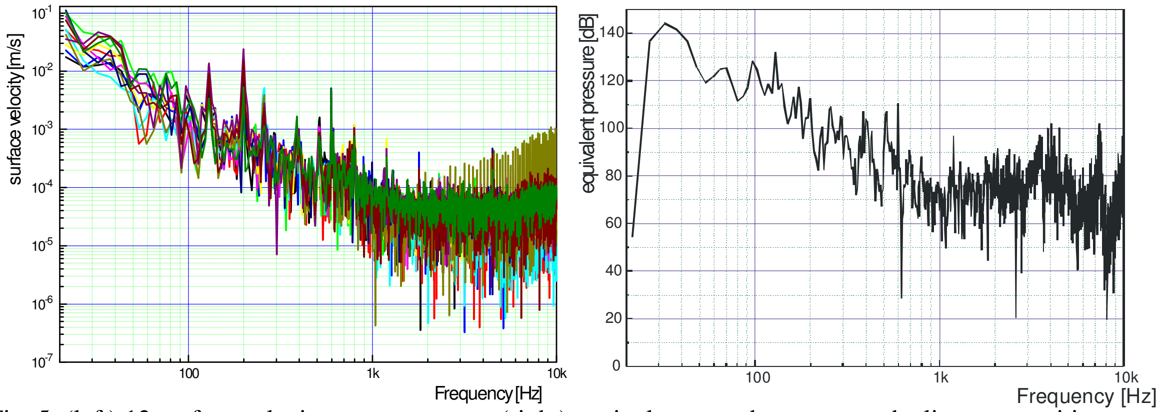

Fig. 5: (left) 12 surface velocity measurements, (right) equivalent sound pressure at the listeners position.

5.5. Intensity field

At higher frequencies the intensity field is determined from the measured data by taking the real part of the cross spectrum between sound pressure and particle velocity. The result is shown in Fig. 6 (left). The sound power is calculated from this and the equivalent monopole is derived with Eq. (2), the absorption that was measured is taken into account. From the equivalent monopole the equivalent sound pressure level at the listener's position is calculated, see Fig. 6 right (black line) by multiplying the equivalent monopole result with the magnitude of the transfer function. For comparison the equivalent sound pressure determined with the velocity method is shown in grey. As can be seen: from 100Hz upwards both methods give comparable results.

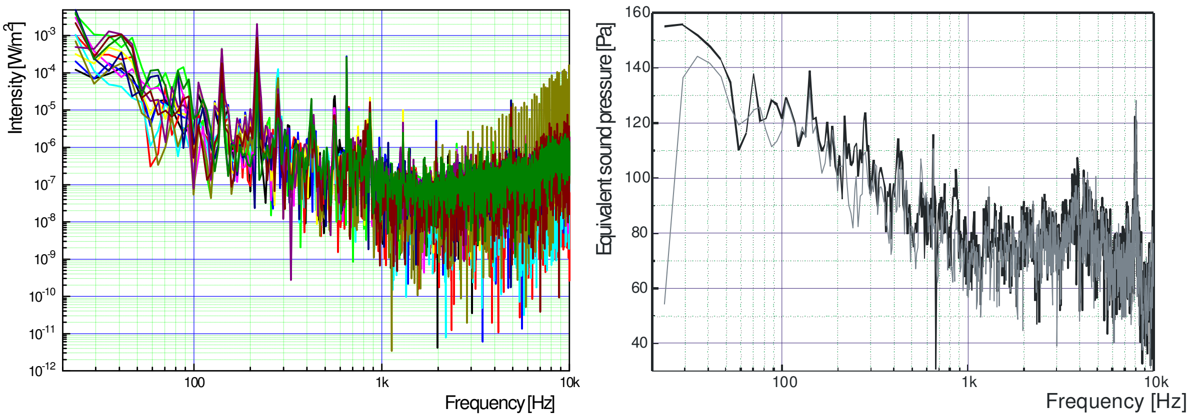

Fig. 6: (left) 12 intensity measurements, (right) equivalent sound pressure at the listeners position.

The intensity method assumes that all sources are non coherent. Therefore the results of all measurements can be simply summed without taking the phase information into account. This is a mayor advantage compared with the velocity method.

The measurement of one 20x30cm panel is done in approximately 20seconds.

6. Conclusion / discussion

A method to measure in-flight, fast and in situ sound sources in a helicopter is presented. It is possible to measure broad banded both the sources at the surface and the transfer path of which the sound pressure level at a listeners position can be determined.
Two measurement techniques are presented. The velocity method for lower frequencies and the intensity technique for higher frequencies. Initial results show that due to the stiff bodywork of a helicopter cabin the velocity method works at higher frequencies than inside a car interior. The

intensity method starts to work at lower frequencies than in a car interior because the reflective interior causes sources to become incoherent at lower frequencies.
Due to this, both methods can be used in a broad bandwidth. The velocity method can be used in a 20Hz-10kHz bandwidth and the intensity method can be used in a 100Hz-10kHz.

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