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Acoustic detection and quantification by antenna of large vibrating area

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Summary
Since several years, aeronautical industries have wished to improve internal acoustic comfort. Thus, acoustic localization tools are performed in order to determine what area of cabin sidewalls radiate noise in the cabin. Nevertheless, two problems must be solved. Firstly, classical localization techniques, like holography or beamforming, are based on free field hypothesis, while the medium is confined. Secondly, acoustic sources are partially or totally coherent. This implies to use reference microphones near sources to separate the contribution of each type of source or to solve an inverse method with a representation of these sources. So, the holography based on multiple references is suited to radiating of vibrating panels but must be used in near field to reduce effect of reflections and takes a long time to scan large radiating surfaces. On the other hand, the beamforming, very fast method to apply, is able to localize a sum of uncorrelated sources in a confined medium if the array is coupled with an acoustic mask (to avoid back waves). But, in the case of close correlated sources, the interferences between waves can be harmful to localization. So, the present paper deals with the feasibility of a beamforming method, associated to an inverse method dedicated to quantify correlated sources whose the distance is lower than the wavelength, thus in order to identify main acoustic pressure areas radiated by a vibrating panel. Instabilities in inversion method due to a high number of sources are taken into account thanks to a Regularization method whose convergence parameter is controlled by a localisation function assuming multiple sources (contrary to classical beamforming). The study configuration is performed, thanks to simulations on close correlated sources in-phase or in opposite of phase.

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1. Introduction
Since several years, aeronautical industries have wished to improve internal acoustic comfort. Thus, acoustic localization tools are performed in order to determine what area of cabin sidewalls radiate noise in the cabin. Nevertheless, two problems must be solved. Firstly, classical localization techniques, like holography or beamforming, are based on free field hypothesis, while the medium is confined. Secondly, acoustic sources are partially or totally coherent. This implies to use reference microphones near sources to separate the contribution of each type of source or to solve an inverse method with a representation of these sources. So, the holography based on multiple references (STSF) is suited to radiating of vibrating panels but must be used in near field to reduce effect of reflections and takes a long time to scan large radiating surfaces. On the other hand, one can show that the beamforming, which is a very fast method, is able to localize a sum of uncorrelated sources (statistically independent) [1], with or without a reference microphone. Moreover, it is less sensitive to reflections than holography [2] and can be used in confined medium [3] if the array is coupled with an acoustic mask (to avoid back waves). But, in the case of close correlated (coherent) sources, the interferences between waves can be harmful to localization.
So, the present paper deals with the feasibility of a technique based on beamforming localization to identify main acoustic pressure areas radiated by a vibrating panel in modal domain.

Figure 1 shows simulations applied to a sandwich composite panel representative of an helicopter trim panel (Nomex honeycomb structure placed between fiber glass / carbon layers - surface: 0.98 x 1.07 m²).

We compare, at 1 kHz, the pressure field (a) near panel (distance: 1 cm) to localization's function field, obtained thanks to a cross-shaped array of 16 microphones for each arm (length: 60 cm), placed at 7 cm or 26 cm from panel (b-c).

Figure 1. Pressure field near panel (a) and localization's function fields with cross array at 7 cm (b) and 26 cm (c) at 1kHz [4]

The main areas of radiating are localized by black circles. It turns out that sources close to the middle of field produce areas of high coherency dependent on the frequency resolution and interactions between sources. The other sources generate areas of large and strong coherency (continuous or discontinuous). One can notice that it is more difficult to localize and separate sources precisely for the higher distance of antenna. This is due to the fact that the localization's function is determined by making the assumption that the pressure field measured by the antenna comes from an alone monopole: the possible contribution of other pressure sources is neglected.

So, with the aim to quantify pressure fields radiated by a panel, we need to improve the characterization of radiating sources (location, amplitude and phase). This is the subject of following chapter.

2. Principle of improved beamforming

A cross shaped array, composed of N microphones on each arm, is suited to localisation of sources assumed to be monopoles.

After measuring acoustic pressure $P$ on the array, localization consists on searching contribution of each possible source and finding the position of the source on a focused plane.

Then, a source of unit amplitude is assumed to be placed at the point $S$, which moves in the focused volume:

$$U_n = e^{\frac{i}{\gamma} |\vec{R}_S - \vec{r}_n|}$$

with $\vec{R}_S$ is the distance between $S$ and the microphone number $n$.

During a measurement, the cross-spectral matrix is estimated thanks to periodigram method:

$$\Gamma_{m,n}(f) = \langle p_m(f) p_n^*(f) \rangle$$

The localization’s function is the product of the pressure and the fictive monopole:

$$\gamma^2 = \frac{U^\dagger \Gamma U}{\|U\|^2 Tr(\Gamma)}$$

where $^*$ is the conjugate transpostate and $Tr$ the trace operator.

The cross-spectral matrix can be expanded as:

$$\Gamma = \begin{pmatrix} 0 & \Gamma_{AB}^* \\ \Gamma_{AB} & 0 \end{pmatrix}$$

where A and B are relative to the two arms.

Performances of the cross-shaped array, in neglecting cross-spectral terms of microphones which are on the same arm ($\Gamma_{AA}$ and $\Gamma_{BB}$), allows to have performances similar to a full square array [5].
The localization’s function, representative of a coherency, becomes:

\[ \chi^2 = \frac{\sum_{i,j \in \Omega} U_i^* \Gamma_{ij} U_j}{\sum_{i \in A} |U_i|^2 \sum_{j \in B} |U_j|^2} \]  

(5)

An isolated source is well localized at the maximum of the localization’s function (=1), whatever its location in focused plane, but more the distance to the middle of array increases, more the area of maximum is wide. Moreover, low level side lobes (ghost sources) appear because of signal processing.

To reject ghost sources and to reconstruct amplitudes / phases of real correlated sources, we suggest minimising the difference between measured and theoretical acoustic pressure at N array microphones, with the following formulation:

\[ F(S) = Tr \left[ (p_{mes} - p_{theo}) (p_{mes} - p_{theo})^H \right] \]  

(6)

\( p_{theo} \) takes into account presence of \( Q \) correlated sources (real and ghost sources) localized thanks to localization’s function. We obtain a Source vector \( S \) (complex) that is used as input of a model of radiated pressure (Figure 2):

\[ S = A^H A^{-1} A^H p_{mes} \]  

(7)

The algorithm can also consist in extracting, from localization’s function, areas (or distributions) of correlated sources that satisfy a minimum threshold, instead of local maxima.

One can deduce a new localization’s function \( \chi^2_S \) (called “multi-sources”) from measured and theoretical acoustic pressure:

\[ \chi^2_S = \frac{\sum_{i,j \in \Omega} P_{theo,i}^* \Gamma_{ij} P_{theo,j}}{\sum_{i \in A} \sum_{j \in B} |P_{theo,i}|^2 |P_{theo,j}|^2} \]  

(8)

that tends toward 1 when the Source vector is correctly estimated.

To improve the quantification of sources, especially in low frequency range (when the distance of correlated sources are much lower than the wavelength), one can introduce a regularization parameter \( \alpha \) applied to the inverse problem, whose value depends on the convergence of \( \chi^2_S \) towards 1. The satisfying Source vector must verify a minimum value of \( \chi^2_S \) (Figure 3).

\[ S = \left[ A^H A^{-1} A^H p_{mes} \right] \]  

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(7)
Table I. Simulated cases with IBICS or IBACS algorithms

<table>
<thead>
<tr>
<th>Case</th>
<th>Source location (m) - (x,y)</th>
<th>Amplitude / phase°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0.3, 0.25) (0.3, 0.35)</td>
<td>1 / 0° 1 / 0°</td>
</tr>
<tr>
<td>2 or 3</td>
<td>(0.25, 0.3) (0.35, 0.3) (0.4, 0.4) (0.5, 0.4)</td>
<td>1 / 0° or 1 / 180° 1 / 0° or 1 / 180°</td>
</tr>
</tbody>
</table>

One can notice that, with IBICS algorithm, monopoles (white circles) are identified as an alone source, radiating as a monopole. On the other side, IBACS algorithm proposes a distribution of 421 correlated sources around real sources, whose radiated pressure field at 5 cm is in accordance with real pressure field (surface : 0.6 x 0.6 m²).

For more sources (4), at 1 or 2 kHz, in phase or in opposite of phase by pair (cases 2 and 3 – Figures 5 and 6), an array at 5 cm and using of IBACS algorithm supply generally satisfying pressure fields, even if obtained distribution of sources is more complex than in reality.

Nevertheless, for case 3 at 1 kHz, significant differences are observed which are due to a "ill posed-problem" for this particular configuration "source / array". One can notice besides that, if each pair of close sources is simulated separately, the algorithm finds right solutions.

For a farther array (30 cm) and case 2 (Figure 7), the obtained source area is larger but pressure fields are yet in accordance with real fields.

4. Conclusions

Algorithms adapted to identification and quantification of close correlated sources are presented. Formulations supply models of isolated sources (IBICS) or area of sources (IBACS). Despite the large number of sources taken into account in models, pressure fields deduced from IBACS algorithm can be similar to real fields, confirming the robustness of algorithm with regularization technique and a new localization's function suited to "multi-sources", to study correlated sources whose distances are lower than the wavelength (λ/6 to λ/3).

Nevertheless, to avoid "ill posed-problems" met for particular configurations "source / array", one can consider to link several array measurements and signal processing in an alone minimization, in order to highlight the best candidates among all the sources.

Acknowledgement

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References

Figure 4. Close correlated sources of "case 1" at 1kHz - Distance "Source plane / array": 5 cm

IBICS and IBACS algorithms.

Figure 5. Close correlated sources of "case 2" at 1 and 2 kHz - Distance "Source plane / array": 5 cm

IBACS algorithm.
Figure 6. Close correlated sources of "case 3" at 1 and 2 kHz - Distance "Source plane / array": 5 cm IBACS algorithm.

Figure 7. Close correlated sources of "case 2" at 1 and 2 kHz - Distance "Source plane / array": 30 cm IBACS algorithm.