Source Localization Technique for Impulsive Multiple Sources

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An improved multimicrophone array technique for the localization of helicopter rotor impulsive noise sources is described and validated by experiment. Two types of data processing are presented: a linear beam forming method and a multiplicative method. For a single source, both techniques give good results, but in the case of multiple-point sources, only the multiplicative method is sufficiently accurate. The multiplicative processing is applied to a helicopter rotor noise test in the CEPRA 19 anechoic wind tunnel. In the experiment the rotor blades are equipped with pressure transducers to give the blade/vortex interaction loci. Comparison between the array technique and the measured values presents good agreement when the flow effects (i.e., convection and refraction) are taken into account.

Introduction

THE problem of estimating the location of radiating sources from data collected by an array of transducers arises frequently in radar[1] and sonar[2] detection. Usually, the map of the sources is derived using linear arrays[3,4] and frequency domain signal processing. In aeroacoustics, such a technique is well fitted to the case of jet noise, where a linear distribution is expected for each frequency or Strouhal number. For helicopter rotor noise, the problem is different. First, sources are located on a disk, so the microphones have to be placed in such a way that the resolution capability is homogeneous on the rotor disk; it is convenient to place them on a sphere centered on the rotor hub. Second, due to the impulsive nature of the blade/vortex interaction (BVI) noise, it is easier to isolate each peak on the acoustic time signature than to deal with the frequency components of the total noise. That is why a time domain analysis has been chosen. The first step of the data processing is therefore to window the peaks in the microphone signals related to BVI before proceeding to the localization itself.

Discussion

Linear Beam Forming

A classical technique used to locate sources in time as well as in the frequency domain is the linear beam forming. If F is a focal point belonging to a domain including the rotor disk, the beam forming here consists in computing the quantity

$$Q(\hat{t},F) = \sum_{n=1}^{N} a_{F,n} \cdot p_n(\hat{t} + \tau_{F,n}) \tag{1}$$

where p_n is the received pressure at the nth microphone, $\hat{t}$ an assumed emission time, $\tau_{F,n}$ the propagation time from a focal point F to the nth microphone, $a_{F,n}$ the amplitude weighting of the nth pressure signal (defined later), and N the number of microphones.

In a first step, the BVI can be conveniently modeled by a rotating point source. It is assumed to emit an impulsive field that propagates in a medium at rest with sound velocity c (the effect of convection and refraction in wind-tunnel applications will be considered later). The source radiates from the location S belonging to the rotor disk and at times

$$\hat{t}_m = \hat{t}_E + m\,T$$

where $\hat{t}_E$ is one of the emission times, T the rotation period, and m an integer.

Since the phenomenon under study is periodic, the signal received at the nth microphone is analyzed during a time interval T and is then

$$P_n(t) = \frac{A}{R_{s,n}} \delta(t - \hat{t}_E - \tau_{s,n}) \tag{2}$$

where $\delta = 1$ for $t = \hat{t}_E + \tau_{s,n}$ and 0 for different t, A is the amplitude related to source S, $R_{s,n}$ the distance from the location S to the nth microphone, and $\tau_{s,n} = R_{s,n}/c$.

It is supposed that all the microphones are placed around the maximum of radiation of the acoustic source under study (upstream and downward of the rotor plane for the BVI). Thus, no directivity factor is included in A.

The linear beam forming of Eq. (1) in the time domain takes the form

$$Q(\hat{t},F) = A\left[\frac{\displaystyle\sum_{n=1}^{N} \frac{\delta(\hat{t} + \tau_{F,n} - \hat{t}_E - \tau_{s,n})}{R_{F,n} \cdot R_{s,n}}}{\displaystyle\sum_{n=1}^{N} \frac{1}{R_{F,n}^2}}\right] \tag{3}$$

The weighting coefficients $a_{F,n}$ have been chosen equal to

$$a_{F,n} = \frac{1/R_{F,n}}{\displaystyle\sum_{n=1}^{N} (1/R_{F,n}^2)} \tag{4}$$

to maximize signal-to-noise ratio in presence of white Gaussian noise.

The method consists in computing $Q(\hat{t},F)$ at a given time $\hat{t}$ for all points F scanning the space where a source may exist: it is here a 2×2 m square in the plane $z = 0$ enclosing the rotor disk in the experiments described later (radius $r = 0.958$ m). This gives an elementary map. Points F giving a nonzero amplitude of Eq. (3) are obtained for

$$\tau_{F,n} = \tau_{s,n} + (\hat{t}_E - \hat{t}) \tag{5a}$$

$$R_{F,n} = R_{s,n} + c(\hat{t}_E - \hat{t}) \tag{5b}$$

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These expressions define circles centered on the projection of each microphone in the rotor plane, with radius $R_{F,n}$. These circles have a common intersection point S when the imaging function Q is maximum, i.e., when $\hat{t} = \hat{t}_E$ and when the focal point F corresponds to the source location S.

Calculation is repeated for all values of t belonging to a time interval T:

1) At time $\hat{t} \neq \hat{t}_E$, a map consists in N circles each bearing an amplitude of the order of A/N, possibly intersecting but without a common intersection. Depending on the number of intersections, the amplitude of Eq. (3) covers the range

$$[A/N, A(N-1)/N] \tag{6}$$

2) At time $\hat{t} = \hat{t}_E$, the N circles intersect at the source location with an amplitude A.

It is natural to inquire if linear beam forming can be used efficiently to locate rotating sources emitting at different times and locations. This situation is encountered in practice when a blade intersects several vortices during one revolution. To investigate this aspect, we consider the localization with $N = 8$ acoustic signals of two point sources: the dominant source S_1 with an amplitude A_1 radiating at time $\hat{t}_{E_1}$ and another source S_2 with an amplitude $A_2 = A_1/8$ radiating at time $\hat{t}_{E_2} \neq \hat{t}_{E_1}$. The maps computed at $\hat{t} = \hat{t}_{E_1}$ and $\hat{t} = \hat{t}_{E_2}$ are displayed in Fig. 1. The location of source S_1 is well retrieved. On the other hand, the location of source S_2 is not clearly found, although the calculation has been performed at its emission time. In fact, the location of S_2 is completely masked by values of $Q(\hat{t},F)$ due to the dominant source S_1 for which $A_1/8 \leq Q_1(\hat{t},F) \leq 7A_1/8$ if $\hat{t} \neq \hat{t}_{E_1}$ [see Eq. (6)].

Multiplicative Method

A multiplicative method has been developed to overcome the problems of the linear processing. Instead of $Q(\hat{t},F)$, the following function is computed:

$$H(\hat{t},F) = \left| \prod_{n=1}^{N} p_n(\hat{t} + \tau_{F,n}) \cdot R_{F,n} \right|^{1/N} \tag{7}$$

In the case of a single source described by Eq. (2), the main advantage of this new formulation is that $H(\hat{t},F)$ is nonzero only when all the circles defined by Eq. (5) intersect at a single location, i.e., at time $\hat{t} = \hat{t}_E$ and for $F \equiv S$. Although the multiplicative method has a much better resolution than linear beam forming, it must be emphasized that it is also less robust. It is more sensitive to background noise and to errors in propagation delay estimation. To reduce such a risk, $p_n(\hat{t} + \tau_{F,n})$ in Eq. (7) is replaced by

$$\max[p_n(\tilde{t} + \tau_{F,n})] \tag{8}$$

where $\tilde{t}$ belongs to the interval $[\hat{t} - \Delta t/2, \hat{t} + \Delta t/2]$. The value of Δt depends on the precision of the time delay estimation. This corresponds to replacing the circles defined in Eq. (6) by rings of thickness $c \cdot \Delta t$. The localization in time as in space becomes slightly less accurate, but much more robust. Since the map is nonzero only if the calculation time $\hat{t}$ corresponds to an emission time of one of the sources, the method is capable of generating a quantitative map of locations of multiple sources and also of their intensities. This global map is defined by

$$I(F) = \sum_{j=1}^{J} H(\hat{t}_j,F) \tag{9}$$

and is obtained by summing all the nonzero maps computed at different times $\hat{t}_j$. To validate the multiplicative method, we again consider the localization of sources S_1 and S_2. Figure 2 shows the result of $I(F)$ computed on one period T; locations and amplitudes of sources S_1 and S_2 are well retrieved.

Verification by a Wind-Tunnel Test

The test presented in this paper was performed during a joint experiment of the U.S. Army Aeroflightdynamics Directorate and ONERA in the CEPRA 19 anechoic wind tunnel.[5,6] It is an open-jet facility, which was equipped with a 3-m nozzle for this test.

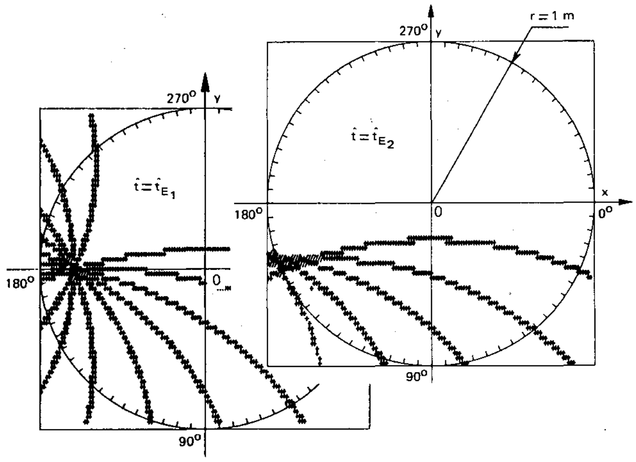

Fig. 1 Numerical simulation of linear processing for the localization of two point sources: 1) S_1 ($x_1 = -0.8$ m, $y_1 = z_1 = 0$), $A_1 = 1$, $\hat{t}_{E_1} = 10$ ms; 2) S_2 ($x_2 = -0.7$ m, $y_2 = -0.5$ m, $z_1 = 0$), $A_2 = A_1/8$, $\hat{t}_{E_2} = 9$ ms. Maps computed at times $\hat{t} = t_{E_1}$ and $\hat{t} = t_{E_2}$ (see exact source locations on Fig. 2).

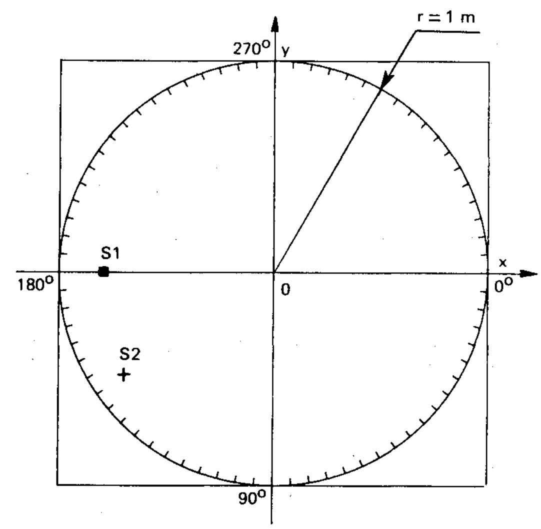

Fig. 2 Multiplicative method using same simulation as in Fig. 1. Map obtained by summing all the maps computed on one period (it is zero except at S_1 and S_2 locations).

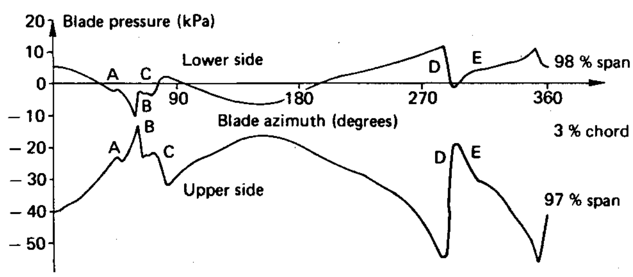

Fig. 3 Blade pressure measurements from two transducers on the lower and upper sides at blade tip.

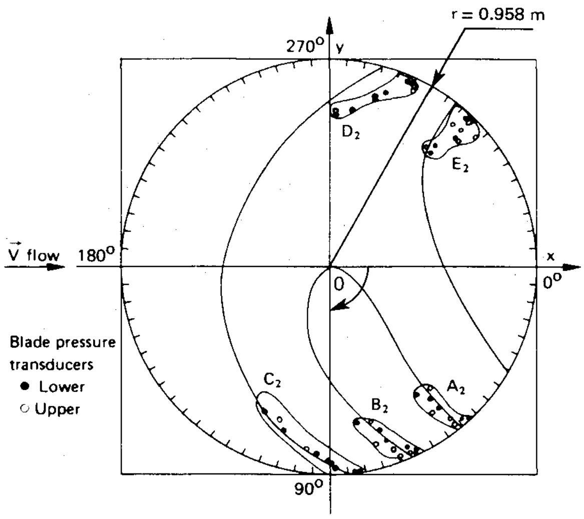

Fig. 4 Blade/vortex interaction loci from blade pressure transducers (end of BVI) and rigid wake calculation (solid lines).

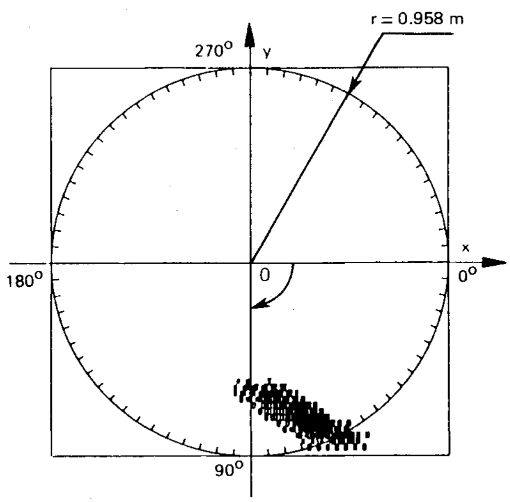

Fig. 5 Map of main positive peak source: multiplicative processing including convection and refraction effects.

The two-bladed model rotor was instrumented with 50 blade pressure transducers measuring the upper surface, lower surface, and differential pressures acting on the blades. These transducers were mainly located in the leading-edge region and from about 75% span to the tip. Such an experiment is thus very useful to validate the present study, since source localizations can be directly compared to measurements on blades. Figure 3 presents pressure signals on the upper and lower sides of the blade. Blade/vortex interactions appear as sudden changes on the pressure, named A through E. Three interactions (A,B,C) happen on the advancing side and two (D,E) on the retreating one, although interaction E is not very intense. Considering all the pressure transducers on the 3% chord line, the location of the end of each interaction can be plotted as shown in Fig. 4.

For the far-field acoustic measurements, some of the microphones were placed in the free jet and experienced convection. The other ones were out of the flow, but were influenced by refraction through the free jet shear layer. Data processing is thus carried out using Eq. (7) with propagation delay $\tau_{F,n}$ including these effects calculated by an acoustic ray model. The result of source localization is shown in Fig. 5 for the main positive peak on acoustic time histories (eight microphones were used); it compares well with the direct measurement of interaction B in Fig. 4.

Conclusions

An improved multimicrophone array technique using a multiplicative method has been developed and applied to determine noise source locations in a complex situation (viz. helicopter rotor blade/vortex interaction noise). The common linear beam forming was shown to be inadequate for the task. A technique to improve the robustness of the multiplicative method was discussed.

References

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