DEVELOPMENT OF EXPERIMENTAL METHOD FOR AZIMUTHAL MODE MEASUREMENT FOR JET-WING INTERACTION NOISE

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Jet-wing interaction noise might become an important problem for modern passenger aircraft with high and ultra-high bypass turbofan engines. Development of theoretical and numerical models for this noise generation mechanism requires additional information on the noise source, such as azimuthal modal content of the acoustic field, which can be used for adjusting the models and enable development of noise reduction methods. The azimuthal mode amplitudes and directivities for jet-wing interaction noise have never been measured before. As a result, the objective of the present work consists in development of an experimental method that would enable performing such measurements.

Keywords: aeroacoustics, azimuthal modes, jet-wing interaction noise

1. Introduction

Advances in modern aeroengines have allowed them to be significantly quieter, but also have given importance to other noise sources of aircraft. One of such sources is jet-wing interaction noise, which is caused by closer installation of the engines to the wing due to higher bypass ratio of the engines, so that their turbulent jets are in the vicinity of the wing (e.g., a deflected flap for an aircraft configuration with the engines under the wing) and interaction of the wing surface with the jets or their nearfield gives rise to additional noise.

A number of studies on jet-wing interaction noise [1-3] have shown that the noise generation mechanism is sensitive to the geometrical parameters of the problems. On the one hand, this allows for an effective way to reduce noise via small changes in the geometrical parameters (e.g. flap deflection angle); on the other hand, this complicates modeling of the noise generation mechanism, so that additional information on the noise source would be desirable.

Such additional information could be obtained from the azimuthal content of jet-wing interaction noise. Measurements of the directivities of azimuthal modes of noise have already proved helpful, for instance, in validating Tam's theory of supersonic jet noise [4] and in developing a noise reduction method for a cylinder in the cross-flow [5]. However, the azimuthal mode amplitudes and directivities for jet-wing interaction noise have never been measured before. As a result, the objective of the present work consists in development of an experimental method that would enable performing such measurements, and then measure azimuthal modes of the jet-wing interaction noise.

2. Development of the experimental method

The method of measuring azimuthal modes (Azimuthal Decomposition Technique - ADT) proposed in TsAGI [6] and used for studying jet noise generation mechanisms typically utilizes a microphone array of 6 microphones uniformly spaced along the azimuthal angle, which is moved along the jet axis to allow azimuthal mode directivities to be determined (Fig. 1). This method was recently modified to account for the presence of the hard floor [7], and was successfully applied for determining azimuthal modes of aeroengine jet noise at the open test rig [8].

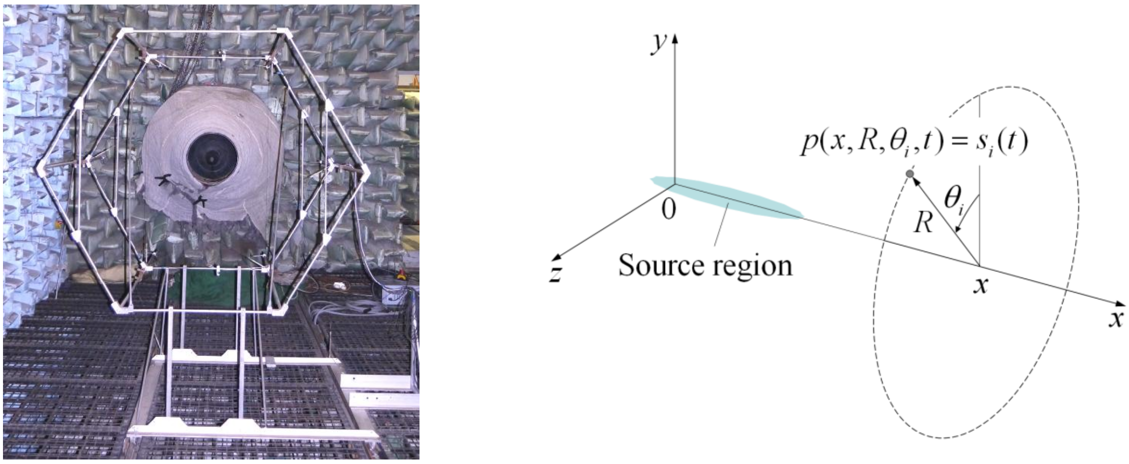


Figure 1: Photo of ADT measurements in anechoic chamber AC-2 TsAGI (left) and the coordinate system used in the paper (right).

The method can be described as follows. Consider a signal $p(x, R, \theta, t)$ due to a sound source. Let $p(x, R, \theta, t)$ in each time moment be represented with acceptable accuracy by a superposition of the first N azimuthal modes (from 0 to $N-1$):

$$p\left(x,R,\theta,t\right)\approx a_0\left(x,R,t\right)+\sum_{n=1}^{N-1}\left(a_n\left(x,R,t\right)\cos n\theta+b_n\left(x,R,t\right)\sin n\theta\right)$$

where the amplitudes $a_n(x, R, t)$ and $b_n(x, R, t)$ are unknown. If the microphone array consists of M microphones s_i with angular coordinates θ_i, $i = 1\ldots M$, the amplitudes are related to the microphone signals by a linear equation

$$Q\mathbf{f} = \mathbf{s},$$

$$Q=\begin{bmatrix} 1 & \cos\theta_1 & \sin\theta_1 & \cdots & \sin\left(\left(N-1\right)\theta_1\right) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & \cos\theta_M & \sin\theta_M & \cdots & \sin\left(\left(N-1\right)\theta_M\right) \end{bmatrix},\ \mathbf{f}=\begin{pmatrix} a_0\left(x,R,t\right) \\ a_1\left(x,R,t\right) \\ b_1\left(x,R,t\right) \\ \vdots \\ a_{N-1}\left(x,R,t\right) \\ b_{N-1}\left(x,R,t\right) \end{pmatrix},\ \mathbf{s}=\begin{pmatrix} s_1\left(t\right) \\ s_2\left(t\right) \\ \vdots \\ s_M\left(t\right) \end{pmatrix}.$$

Implementation of ADT by TsAGI typically employs $M = 6$ microphones, uniformly distributed over the circle ($\theta_i = (i-1)\,\pi / 6$, $i = 1 \ldots 6$) to measure $N = 3$ azimuthal modes, which are given by the expression

$$\mathbf{f} = Q^{-1}\mathbf{s}$$

$$Q=\begin{bmatrix}1 & 1 & 0 & 1 & 0 & 1\\ 1 & 1/2 & \sqrt{3}/2 & -1/2 & \sqrt{3}/2 & -1\\ 1 & -1/2 & \sqrt{3}/2 & -1/2 & -\sqrt{3}/2 & 1\\ 1 & -1 & 0 & 1 & 0 & -1\\ 1 & -1/2 & -\sqrt{3}/2 & -1/2 & \sqrt{3}/2 & 1\\ 1 & 1/2 & -\sqrt{3}/2 & -1/2 & -\sqrt{3}/2 & -1\end{bmatrix},\quad Q^{-1}=\begin{bmatrix}1/6 & 1/6 & 1/6 & 1/6 & 1/6 & 1/6\\ 1/3 & 1/6 & -1/6 & -1/3 & -1/6 & 1/6\\ 0 & \sqrt{3}/6 & \sqrt{3}/6 & 0 & -\sqrt{3}/6 & -\sqrt{3}/6\\ 1/3 & -1/6 & -1/6 & 1/3 & -1/6 & -1/6\\ 0 & \sqrt{3}/6 & -\sqrt{3}/6 & 0 & \sqrt{3}/6 & -\sqrt{3}/6\\ 1/6 & -1/6 & 1/6 & -1/6 & 1/6 & -1/6\end{bmatrix}$$

The number ($N = 3$) of azimuthal modes is sufficient for farfield measurements of isolated jet noise, but with regard to the jet-wing interaction noise it is not known *a priory* that in this case the higher modes can be neglected as well. Therefore, to allow determining the larger number of azimuthal modes, it is pertinent either to increase the number of microphones in the microphone array or to optimize their positions by making use of the optimization procedure [9] that maximizes the dynamic range of the microphone array for the given number of microphones and modes of interest as has been done for induct mode measurements [10]. In the present paper, the former approach is pursued.

It should also be noted that ADT measurements were previously performed without coflow. The presence of coflow, which has a large diameter, might require positioning the microphones at so large distance R from the source that is prevented by the geometrical parameters of the experimental facility, at least for some range of azimuthal angles. In this case the microphones have to be distributed not along the full circle, but be located in a limited range of azimuthal angles.

To address these issues, a preliminary experimental study of azimuthal modes of jet-wing interaction noise was performed with the microphone array comprising an increased number of microphones, and then different post-processing procedures were applied to the measured data.

3. Measurements of azimuthal modes of jet-wing interaction noise

The measurements were performed in anechoic chamber AC-2 TsAGI for a simplified geometry when the wing is modeled by a plate (Fig. 2), which is an aluminum rectangle 1.2 x 0.35 m^2 with 3 mm thickness. Cold jet with the velocity V_j = 135 m/s (M_j = 0.4) issued from a round profiled nozzle of diameter D = 40 mm located at x = 0. The relative position of the nozzle and the plate is given by $h = D$, $L = 3.16D$ (Fig. 2). Both isolated jet and installed configurations were studied.

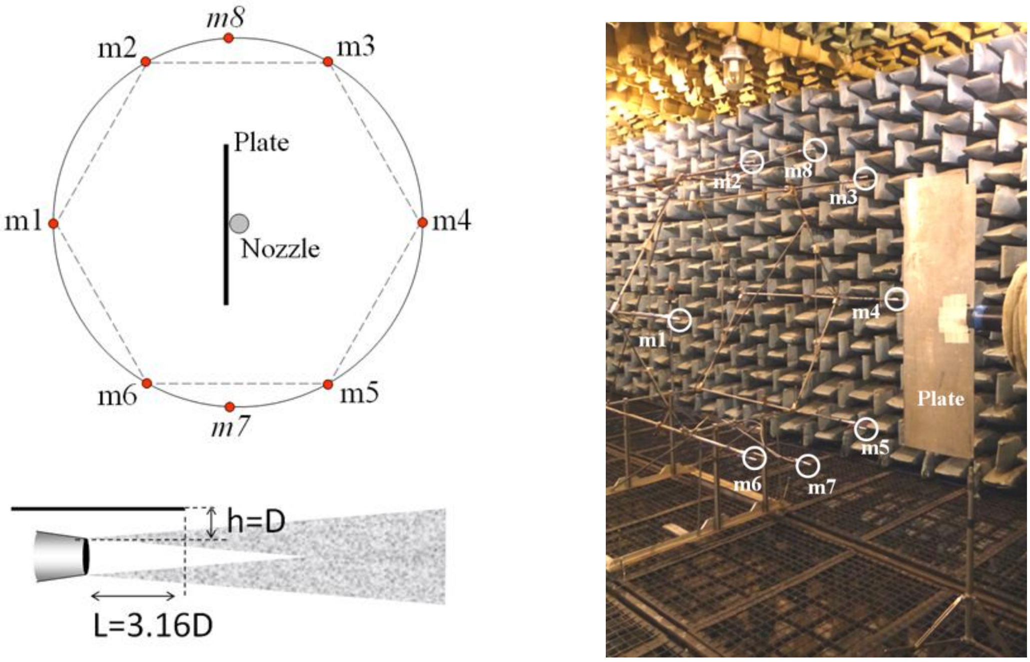


Figure 2: Sketch (left) and photo (right) of the experimental configuration

Acoustic pressure was measured by 8 ½" Bruel & Kjaer microphones (type 4189) with 8 Bruel & Kjaer preamplifiers type 2669 (frequency range 40 – 25600 Hz, sensitivity 50 mV/Pa) installed in the azimuthal array as shown in Fig. 2. Microphones marked as *m*1 - *m*6 constitute the basic configuration of the ADT array used for measurements of isolated jet noise. Microphones *m*7 and *m*8 were added in the array in order to ensure adequate resolution of the azimuthal content of the installed configuration, i.e. to check whether the higher azimuthal modes are small. The microphone array could be moved along the jet axis from $x = -0.5$ to $x = 2$ m ($x/D = -12.5 \ldots 50$).

To investigate the effect of coflow, a relatively low-speed regime of coflow was included in the test matrix. It was found that for coflow velocity V = 30 m/s and the positions of the microphone array not very far downstream ($x/D \leq 50$) the microphone array did not appear affected by hydrodynamic pulsations of the coflow in the frequency range typical for the noise of $M_j = 0.4$ jet, thus allowing the array to be used for azimuthal mode measurements. However, the diameter of the microphone array has to be increased in order to enable experiments with higher coflow velocities and further downstream position of the microphones; these cases are not addressed in the present study.

Let us first analyze the total signals s_i measured by microphones without modal decomposition. In Fig. 3, the spectra of the isolated and installed jet, measured by 'under-the-wing' microphone *m*4, are shown for different observation angles (corresponding to different array positions). It can be seen that installation noise dominates at frequencies up to *St*~0.6, and that it is more pronounced for sideline directions where jet noise is weak enough.

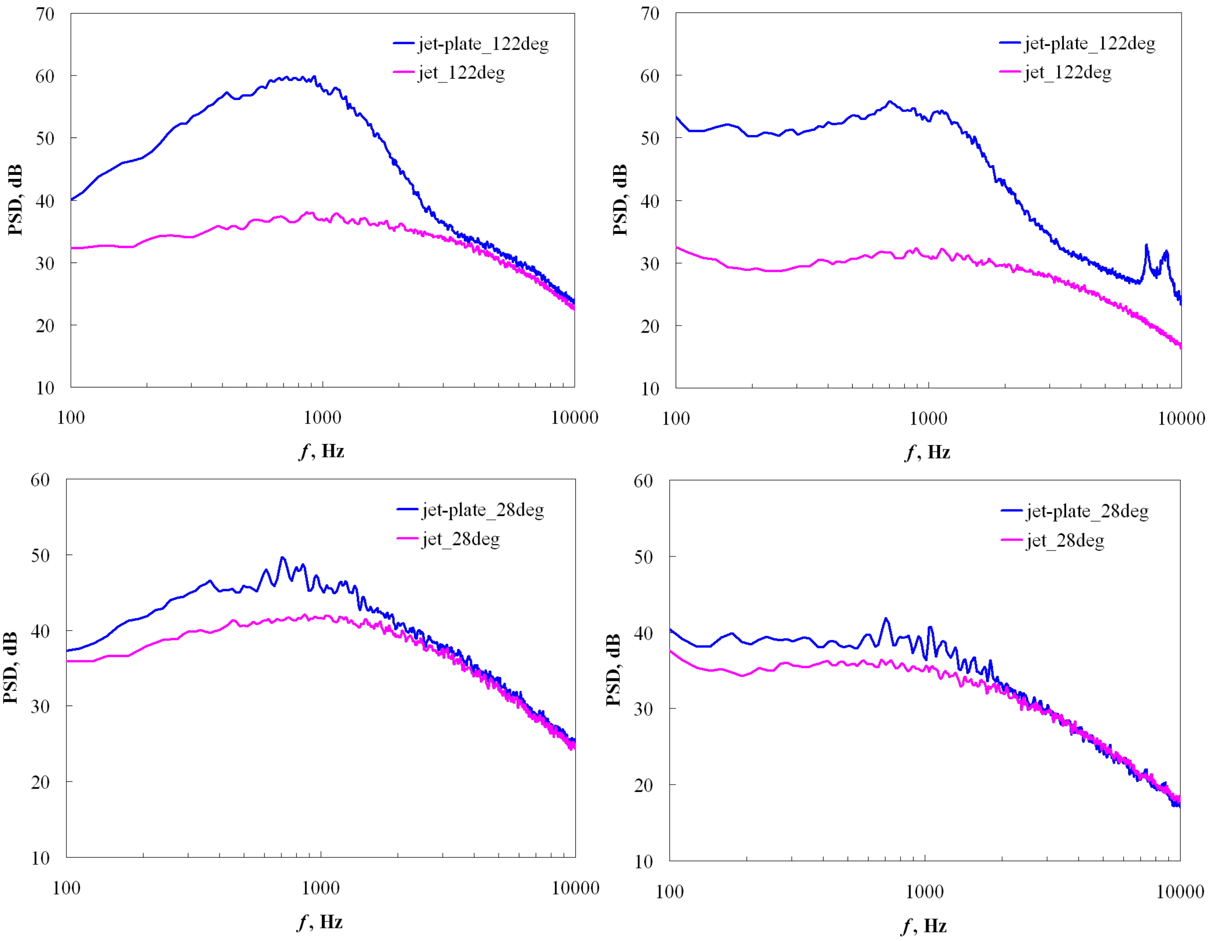
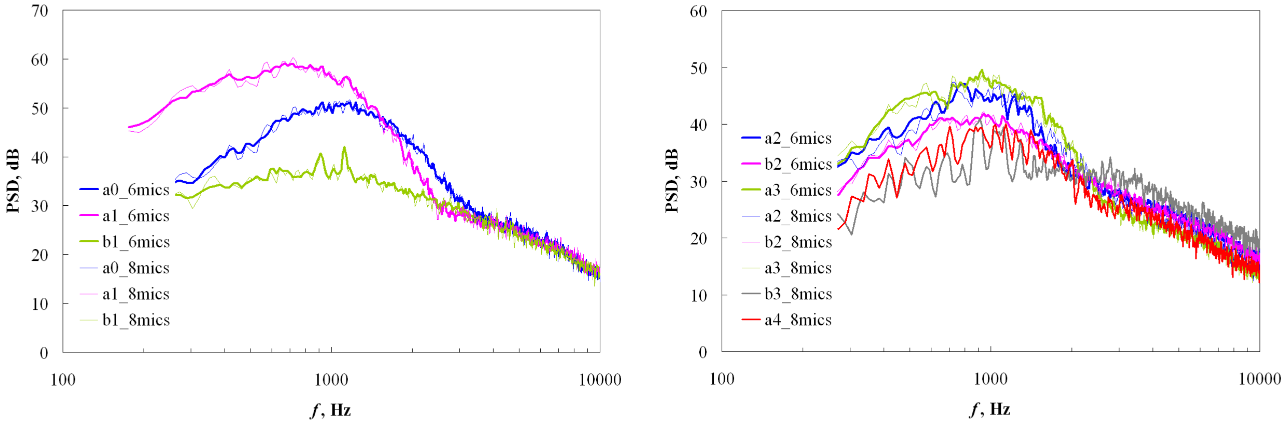


Figure 3: Far-field spectra of the isolated and installed jet in static (left frames) and flight (right frames) conditions, the observation angles corresponding to array positions $x/D = -12.5, 37.5$. Measurements by microphone *m*4.

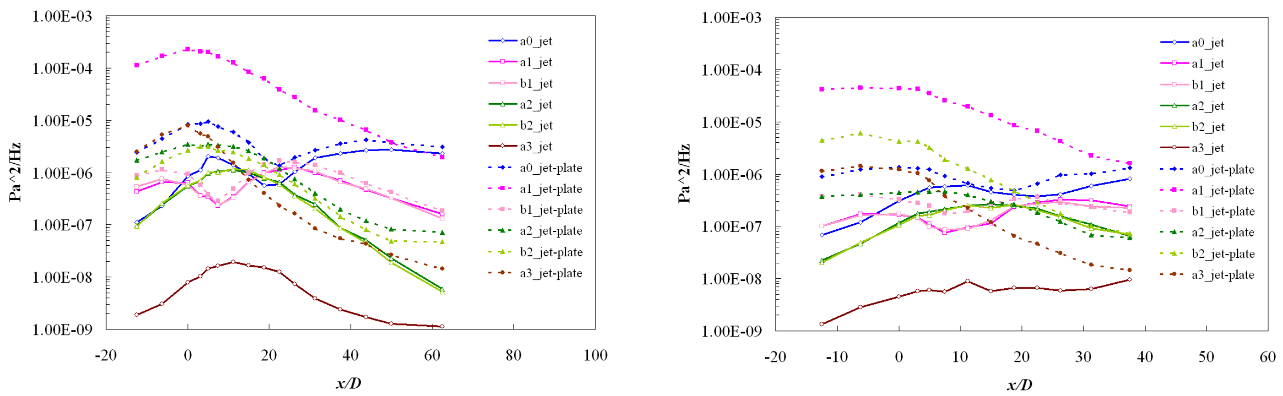
The spectra of azimuthal modes of jet-wing installation noise measured at *x*/*D* = -12.5 by using 6 and 8 microphones are compared in Fig. 4. It is seen that the collapse of the spectra is very good, and the amplitude of 4th mode is indeed small for the frequencies *St* < 0.6 where installation noise dominates. The results mean that the standard 6-microphone array is sufficient for measuring azimuthal modes of jet-wing installation noise in the farfield.



(a) (b)

Figure 4: Far-field spectra of the installed jet noise in static conditions for the array position *x/D* = - 12.5 obtained by the full set of 8 microphones and standard 6-microphone array.

The data shown in Fig. 4 correspond to a single position of the microphone array. Fig. 5 provides directivities of azimuthal modes for *St* = 0.1 for both isolated jet and installed configurations, with and without coflow. The presence of coflow significantly modifies azimuthal mode directivities, which can partly be attributed to the change in noise generation characteristics and partly to the effect of sound refraction by coflow mixing layer.



(a) (b)

Figure 5: Directivities of the azimuthal modes of the isolated and installed jet for *St* = 0.1 in static (a) and flight (b) conditions obtained by the standard ADT array.

The most prominent features of the graphs shown in Fig. 5 consist in the dominance of a_1 mode and the large amplitude of a_3 mode of installation noise, which are typically small for the isolated jet case. This result can be explained by the fact that installation noise produced by the scattering of the nearfield pulsations on the trailing edge has a specific structure, which is symmetric in amplitude with respect to the scattering plane (wing) with the phase shift π between the over- and under-the-wing positions [11] (Fig. 6). Such a field structure should give rise to the odd cosine modes a_{2n+1} in the azimuthal content (in the considered coordinate system). Since the experimental data show that mode a_1 dominates all other modes, the azimuthal directivity of installation noise is close to that of a dipole perpendicular to the plate [11].

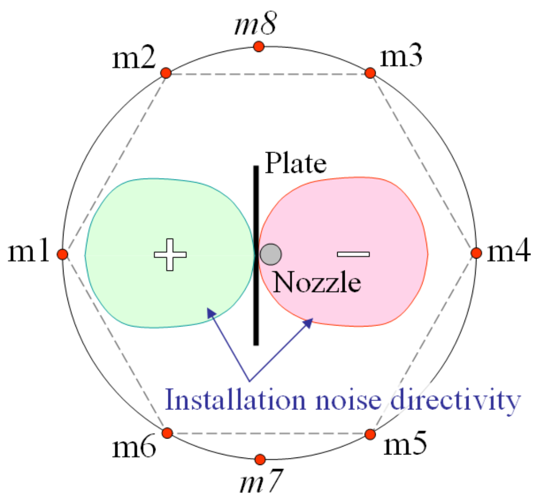


Figure 6: Typical azimuthal directivity of the installation noise explaining measured azimuthal mode content.

Therefore, it makes sense to develop a method that allows measuring the dominant a_1 mode of jet-wing installation noise for higher coflow velocities and further downstream positions of the microphones.

In general, a_1 mode can be obtained by using just 2 opposite microphones, *m*1 and *m*4. The results of mode measurements of installation noise with these 2 microphones and with the full 8-microphone array (Fig. 7) indeed demonstrate a good collapse for a_1 spectra and significant differences for the other azimuthal modes.

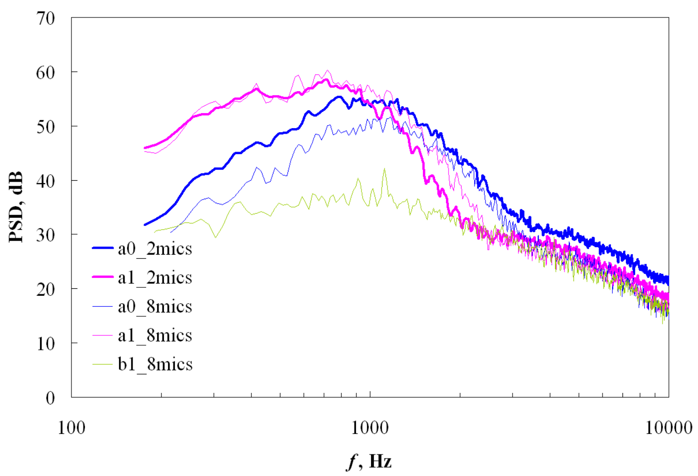


Figure 7: Far-field spectra of the installed jet noise in static conditions for the array position $x/D = -12.5$ obtained by the full set of 8 microphones and a pair of microphones *m*1-*m*4.

It is worthwhile to note, however, that to ensure good measurements of a_1 mode the pair of microphones should be oriented along the dipole axis corresponding to this mode (Fig. 6). It means that making use of the other pairs of opposite microphones may give rise to significant errors in measurement of a_1 mode. As an illustration, Fig. 8 shows a comparison for mode directivities obtained with the standard 6-microphone array and two pairs of microphones: *m*1-*m*4 and *m*2-*m*5. The discrepancy in the results for a_1 obtained with the latter is quite apparent.

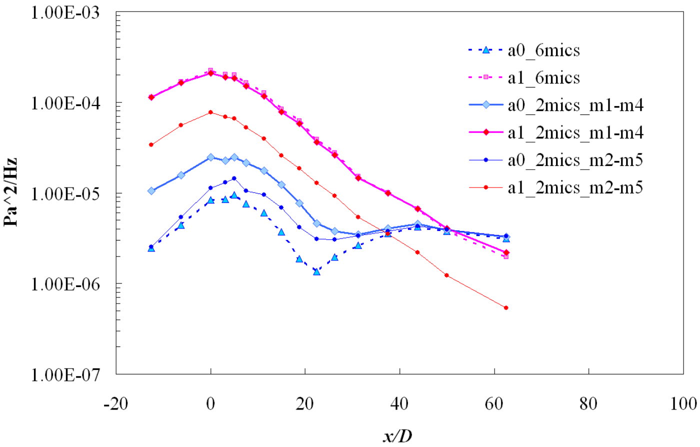


Figure 8: Directivities of the azimuthal modes a_0 and a_1 of the installed jet in static conditions obtained by the standard ADT array and two pairs of microphones $m1$-$m4$ and $m2$-$m5$.

As a final remark, let us note that the measured azimuthal content of farfield noise depends on the position of the microphone array with respect to the noise source. In the present study the center of the array coincides with the jet axis (see Fig. 2) for measuring both isolated jet and installed configurations. However, the noise source of jet-plate interaction is obviously localized on the trailing edge of the plate and thus is shifted by distance $h = D$ from the jet axis. This shift does not seem to affect the mode amplitudes at low frequencies, but in the higher frequency range when the shift is comparable with the wavelength, this displacement of the sound source might manifest itself in transferring energy between different azimuthal modes. This problem can be circumvented by either shifting the microphone array by the same distance h to align the center of the array and the sound source, or introducing the appropriate time delays in post-processing of microphone signals $s_i(t)$.

4. Conclusions

A method for measuring azimuthal modes of jet-wing interaction noise has been proposed. It is shown that the azimuthal content of installation noise can be reliably obtained by utilizing the standard 6-microphone array for ADT measurements. The approach is used to measure amplitudes and directivities of azimuthal modes of jet-wing interaction noise for the first time, both with and without coflow. The effect of coflow on the azimuthal modes for isolated jet and installed configurations is thus obtained.

It is shown that the first mode (a_1) is dominant in the modal content. This enables a formulation of the method to determine this mode with two microphones ($m1$-$m4$), which can be applied for measuring this mode in AC-2 TsAGI for higher coflow velocities and further downstream positions of the microphones.

This work was supported by the Ministry of Education and Science of the Russian Federation under the grant no. 14.628.21.0006 (project code RFMEFI62816X0006) as a part of the EU project “ASPIRE”.

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