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NEAR AND FAR FIELD AZIMUTHAL CORRELATIONS FOR EXCITED JETS

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Abstract

Azimuthal cross correlations have been studied in the acoustic far field of a subsonic jet excited along the jet column instability mode. Some preliminary measurements have also been done in the near field. Cross spectrum analysis shows that the azimuthal coherence is enhanced by excitation. The largest effects are obtained for observation angles lower than 45 deg., when filtering around the subharmonic of the perturbation. Fourier expansion of the circumferential correlation curves demonstrates that an energy transfer takes place from higher order modes to the lower ones.

Introduction

Bechert & Pfizenmaier (1) and Moore (2) have shown that, above a given threshold, pure tone excitation induces a broad band amplification of the noise emitted by high Reynolds number jets. The practical and fundamental applications of this phenomenon have led to numerous investigations of excited jets. Deneuville & Jacques (3) have described jet noise amplification in real situations where the perturbation is due to upstream or combustion noise. Moore (4) and Juvé & Sunyach (5) have used source location techniques to show that in an excited jet most of the noise is generated between three and four diameters downstream of the nozzle at all frequencies. In the experiments cited above the jet was excited along the jet column mode as defined by Zaman & Hussain (6). On the other hand Kibens (7, 8) has demonstrated that jet noise can be reduced through excitation along the shear layer mode. A discrete spectrum associated with a vortex pairing sequence is radiated while the broad band noise is decreased. It seems however that such a behaviour is limited to low Reynolds number jets with initially laminar boundary layers.

With the exception of the source location experiments, only one-point measurements are available for excited jets. To obtain information on the spatial coherence of the acoustic field, two-point measurements are needed, and particularly correlations between points on a circle coaxial with the jet. Such azimuthal correlations have received considerable attention in the recent years. Experiments have shown that the far field is relatively well organized which is highlighted by Fourier analysis demonstrating that only the first three azimuthal modes have an important contribution (Maestrello (9), Armstrong, Fuchs & Michel (10), Juvé, Sunyach & Comte-Bellot (11)). A number of models have been proposed to explain the high azimuthal coherence of the acoustic field (Fuchs & Michel (12), Ribner (13), Richarz (14), Fisher & Bonnet (15), Maestrello (16)), but interpretation of this coherence in terms of the structure of the source region is still a matter of debate.

This paper is devoted to experimental results on azimuthal pressure correlations and cross-spectra obtained with a jet excited along the column mode. Most of the measurements have been done in the far field but some preliminary results are also given for the near field.

Experimental method and apparatus

Test facilities

Measurements have been conducted in the anechoïc room of the Ecole Centrale de Lyon with a cold jet of exit diameter $D = 2$ cm and velocity $U = 135$ m/s (Mach number $M = 0.4$). The pure tone excitation was provided by a loudspeaker placed at the rear of the settling chamber. The level of the excitation was measured by a 3 mm diameter B & K microphone in the exit plane of the jet and in the absence of flow. The far field pressure was measured by two 12.7 mm diameter B & K microphones set on a circle (diameter 2 m) centered on the OX_1 axis of the jet, the azimuthal spacing being denoted by φ (Fig. 1). The azimuthal correlations have been obtained for five values of the observation angle θ : 20, 30, 45, 60 and 90 deg. An azimuthal array of twelve electret-type microphones (diameter 5 mm) was used in the near field. Measurements were done in the sections $X_1 = 3D$ and $X_1 = 5D$ at a radial distance $X_2 = 4D$.

Signal processing

The far field pressure signals were fed to two phased-matched filters B & K 2020 to reject the radiation at the excitation frequency and then recorded on magnetic tape for subsequent analysis. Cross-spectra measurements were done by a two-channel FFT Analyser Nicolet 660A. The upper limiting frequency was set to 20 kHz, the bandwidth of analysis being 50 Hz. The averaging was performed over 100 to 400 independant samples. The resulting cross-spectra were transferred to a PDP 11/23 mini-computer for further processing, such as frequency smoothing and complete rejection of the fundamental and the first harmonic of the excitation in order to obtain significant broad band cross-correlations.

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Results

A parametric study of the azimuthal field as a function of the Strouhal number ($St_D = fD/U$) and of the level ($\ell = \tilde{p}/\frac{1}{2}\rho u^2$) of excitation would be a formidable task. Therefore this paper will be concerned with measurements done for one particular value of these parameters, namely $St_D = 0.68$ and $\ell = 0.028$. Some results have been obtained for different values of the Strouhal number ($St_D = 0.45, 0.54, 0.88, 1.04$) and of the excitation level ($\ell = 0.01, 0.014, 0.02, 0.04$) and are available in a contract report (17). The results presented here are representative of the effects of the excitation in the range $0.4 < St_D < 0.9$ except for some differences which are quoted in the text.

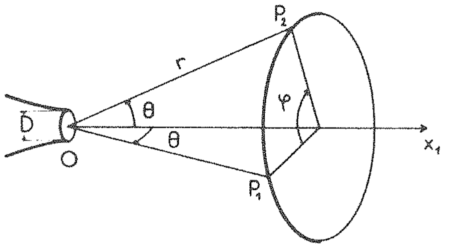

Fig. 1 - Geometry for two microphone correlations.

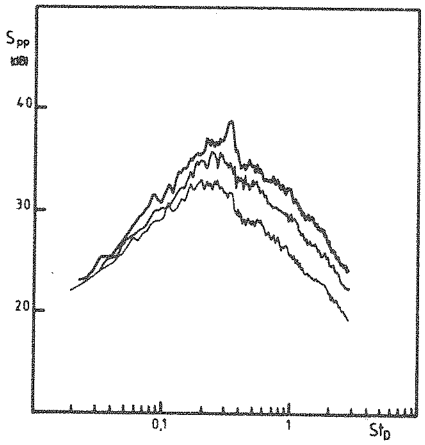

Fig. 2 - Far field pressure spectra for an angle of observation $\Theta = 45$ deg.
— unexcited jet ; — excited jet, $St_D = 0.68$, $\ell = 0.014$;
— excited jet, $St_D = 0.68$, $\ell = 0.028$.

Far Field Spectra

Typical far field spectra are given in Fig. 2 for an observation angle $\Theta = 45$ deg. and for two levels of excitation (the contributions to the frequency of the perturbation and its first harmonic have been suppressed). For the low level of excitation, we observe an increase of the power spectral density over a large frequency range, a classical behaviour (1, 2). However for the higher level and in addition to the broad band amplification, the spectrum displays a distinct hump centered on the subharmonic of the excitation frequency. This result has to be compared with the work of Kibens (7, 8) and Zaman & Hussain (6). For a low Reynolds number jet excited along the shear layer mode, Kibens reported acoustic spectra showing a set of discrete peaks associated with a vortex pairing cascade. However this behaviour seems to require that the initial boundary layer be laminar. Zaman & Hussain have demonstrated that in the turbulent velocity spectra a subharmonic hump exists even with a tripped boundary layer, when the jet is excited around $St_D = 0.85$, and in the present jet such a behaviour has been found for $0.5 < St_D < 0.9$. The link between the existence of a subharmonic in the aerodynamic field and acoustic radiation at this frequency must yet be non linear as the former is present for low excitation while the latter requires high levels. Moreover acoustic emission at the subharmonic presents a marked directivity as it can be detected only for observation angles $\Theta \leq 45$ deg., for $St_D = 0.68$ and 0.88.

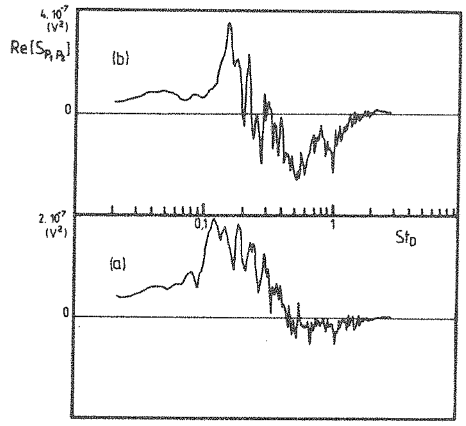

Fig. 3 - Real part of cross-spectra (raw data) for an angle of observation $\Theta = 60$ deg., and an azimuthal spacing $\varphi = 180$ deg. ;
(a) Excited jet, $St_D = 0.68$;
(b) Clean jet.

Far Field Azimuthal Correlations

Theoretical background.

The acoustic field is homogeneous in the azimuthal direction and non swirling around OX_1. The space-time correlation $R_{p_1p_2}(\varphi,\tau)$ is then a periodic and even function of the azimuthal spacing φ , and an even function of the delay time τ. The spatial correlation coefficient $R_{p_1p_2}(\Theta,\varphi)$ as well as the real part of the cross-spectrum $Re[S_{p_1p_2}(\Theta,\varphi,f)]$ can therefore be developed as azimuthal Fourier series :

$$R_{p_1p_2}(\theta,\varphi) = \sum_{m=0}^{\infty} a_m(\theta)\cos m\varphi$$

$$S_{p_1p_2}(\theta,\varphi,f) = \sum_{m=0}^{\infty} a_{m,f}(\theta)\cos m\varphi$$

with

$$\sum_{m=0}^{\infty} a_m = \sum_{m=0}^{\infty} a_{m,f} = 1$$

where the cross-spectrum is normalised by the auto spectra. Such expansions have been introduced by Michalke & Fuchs (18) as a basis for a theory on the noise generated by circular jets derived from Lighthill's acoustic analogy. The $a_{m,f}$ coefficient represents the contribution of mode m to the acoustic energy for a given observation angle Θ and frequency f.

Experimental results.

Fig. 3 displays typical cross-spectra vs. Strouhal number measured for Θ = 60 deg. and an azimuthal spacing φ = 180 deg. For the clean conditions, the real part of cross-spectrum is positive at low frequencies and negative above $St_D \simeq 0.3$. In the latter range the pressure signals are thus of opposite signs on opposite sides of the jet. The range over which $Re[S_{p_1p_2}]$ remains positive is increased by excitation while the negative values are lowered. We can therefore conclude that, in this special case, the azimuthal coherence is enhanced by excitation. This will be developed in the following paragraphs.

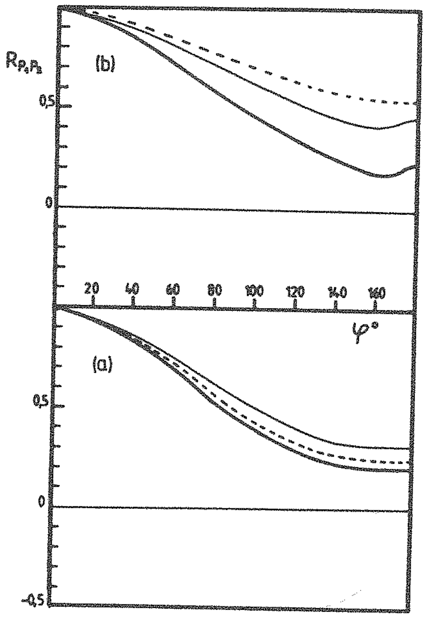

Fig. 4 - Azimuthal cross-spectra for an angle of observation Θ = 30 deg.
(a) Excited jet, $St_D = 0.68$; (b) Clean jet ;
— $St_D = 0.15$; --- $St_D = 0.34$; ▬ $St_D = 0.6$.

For the sake of comparison, we have plotted on each Figs 4 to 7 the results of the cross-correlations obtained with the excitation (top part of the figure) and without it (bottom part of the figure). The clean jet measurements are an extension of our previous work (11) in which the signal processing was different ; the new results are fully consistent with the older ones.

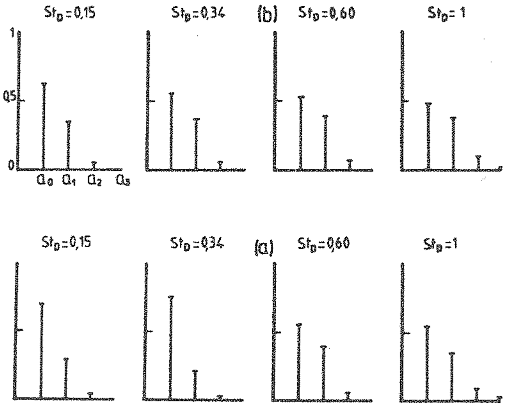

Fig. 5 - Fourier components of the azimuthal cross-spectra for an angle of observation Θ = 30 deg.
(a) Excited jet, $St_D = 0.68$; (b) Clean jet.

The observation of the cross-correlation functions, or more precisely of the cross-spectra, on Figs 4, 6, 7 and of the associated modal expansions (Fig. 5, tables 1 and 2) reveals the following facts :

- The characteristics shape of the azimuthal correlations as a function of the observation angle Θ (11) is not strongly affected by the excitation. The dominant modes are : m = 0 for Θ = 30 deg., m = 1 and 2 for Θ = 60 deg. and m = 2 for Θ = 90 deg.

- For each angle Θ significant differences are however apparent between the excited jet and the non excited jet.

It is for Θ = 30 deg. that the differences are the most important. We note first that the correlation level is enhanced by excitation for all the frequencies studied. The enhancement is very dependant upon the frequency and show a definite maximum for the subharmonic of the excitation. For example, for φ = 180 deg. the cross spectral level takes the values 0.25 without excitation, and 0.54 with excitation, being thus more than doubled. The modal expansion shows that an energy transfer takes place from mode 1 and to a lesser extent mode 2 to the axisymmetric one. For the subharmonic frequency mode 0 represents then 74 % of the total energy, which is a very large contribution.

For the clean jet the measurements show that the higher the frequency the lower the coherence. In the excited jet this trend is not respected : the coherence is higher for $St_D = 0.34$ (the subharmonic) than for $St_D = 0.15$. This demonstrates that the source structure can significantly alter the azimuthal pattern of the noise emission.

For Θ = 45 deg. in the clean jet case, the correlations decrease more rapidly with φ than for Θ = 30 deg. and exhibit a negative loop for φ > 80 deg. In the excited jet the range over which the correlations remain positive is increased while in the negative zone the absolute level of correlation is reduced. The subharmonic suffers the most important change, the correlation is positive on the whole circumference of the jet. The modal expansion (table 1) shows that mode 1 is dominant in the non excited case. When excitation is applied energy is transferred from this mode to the axisymmetric one (table 2).

For Θ = 60 and 90 deg., the effects of the excitation are less important than for Θ = 30 or even 45 deg. However it is possible to observe that mode m = 1 at 60 deg. and mode m = 0 at 90 deg. are enhanced at the expense of mode m = 2. This results in a higher azimuthal coherence of the acoustic far field.

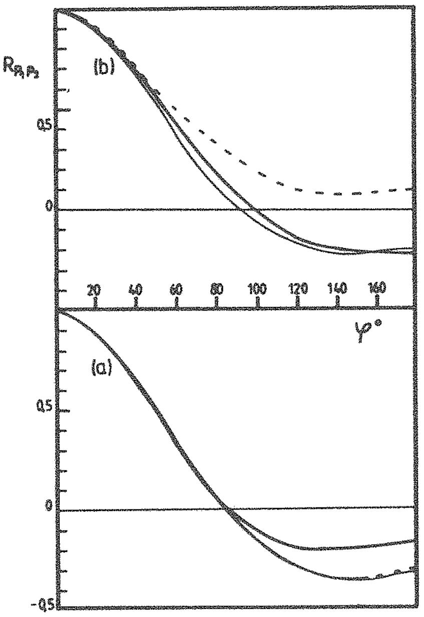

Fig. 6 - Azimuthal cross-spectra for an angle of observation Θ = 45 deg. (same symbols as in Fig. 4).

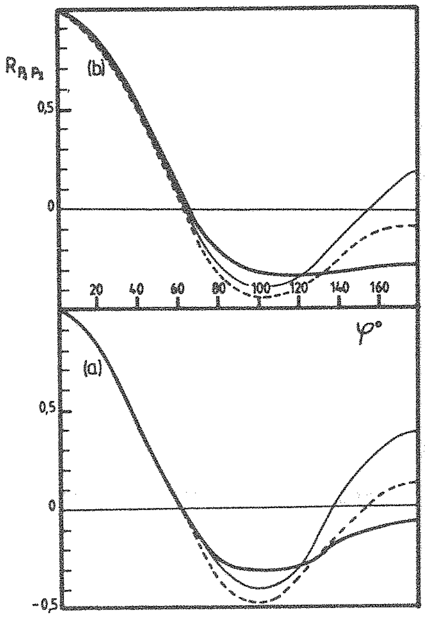

Fig. 7 - Azimuthal cross-spectra for an angle of observation Θ = 60 deg. (same symbols as in Fig. 4).

Table 1 - Contributions to the acoustic field of the first three azimuthal modes vs. Strouhal number. Θ = 20, 30, 45, 60 and 90 deg. (unexcited jet).

Θ	20 deg.				30 deg.				45 deg.				60 deg.				90 deg.			
St_D	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1
a_0	0.83	0.75	0.68	0.56	0.60	0.55	0.50	0.47	0.11	0.13	0.16	0.18	0.16	0.09	0.06	0.08	0.24	0.25	0.20	0.16
a_1	0.15	0.18	0.21	0.33	0.34	0.36	0.38	0.38	0.64	0.59	0.54	0.48	0.24	0.38	0.44	0.40	0.08	0.08	0.20	0.26
a_2	0.01	0.02	0.01	0.04	0.05	0.06	0.08	0.10	0.20	0.21	0.20	0.18	0.52	0.47	0.38	0.28	0.53	0.54	0.40	0.29

Table 2 - Contributions tothe acoustic field of the first three azimuthal modes vs. Strouhal number. Θ = 20, 30, 45, 60 and 90 deg. (excited jet, St_D = 0.68).

Θ	20 deg.				30 deg.				45 deg.				60 deg.				90 deg.			
St_D	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1	0.15	0.34	0.60	1
a_0	0.87	0.87	0.68	0.58	0.69	0.74	0.54	0.53	0.20	0.38	0.22	0.25	0.12	0.05	0.04	0.06	0.42	0.34	0.20	0.18
a_1	0.12	0.10	0.22	0.31	0.28	0.21	0.35	0.34	0.57	0.42	0.57	0.48	0.34	0.45	0.54	0.47	0.02	0.06	0.22	0.23
a_2	-	0.01	0.01	0.03	0.03	0.02	0.04	0.07	0.16	0.14	0.15	0.15	0.46	0.41	0.30	0.25	0.47	0.49	0.37	0.32

réduction
du mode 0 !

Preliminary Near Field Azimuthal Measurements

To complete the far field measurements, it was decided to study the influence of the excitation on the azimuthal structure of the near acoustic field as a function of the downstream distance to the nozzle. The main problem for measurements in the vicinity of the jet is associated with the superposition of the acoustic field with the induced hydrodynamic pressure. In view of the literature (Maestrello (19)), it was thought that at a radial distance $X_2/D = 4$, only the acoustic field would be measured in the sections $X_1/D = 3$ and $X_1/D = 5$. In practice this was found not to be correct for the lower part of the spectrum ($St_D < 0.3$), and only preliminary results are presented here, the low frequencies being simply filtered out. "Broad band" correlations ($0.3 < St_D < 3$), are displayed in Fig. 8 for the clean and the excited jet. The most striking feature is that changes are very small compared to the observations in the far field : for $X_1/D = 3$, the azimuthal correlations for the two cases are hard to distinguish over the whole circumference. For $X\ /D = 5$, the excitation increases the azimuthal coherence, but the differences are slight. Measurements for other sections and cross-spectrum analysis are however needed before definitive conclusions might be drawn.

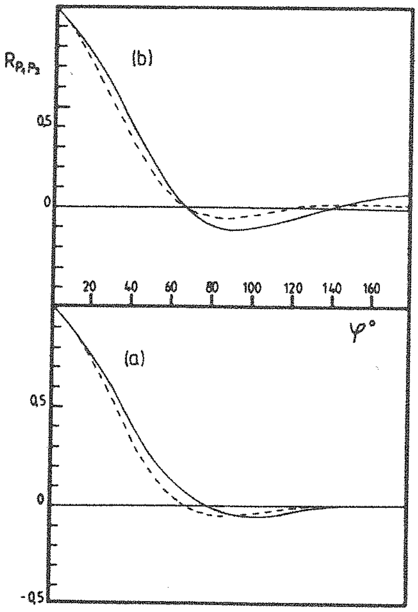

Fig. 8 - Azimuthal broad band correlations in the near field
(a) excited jet, $St_D = 0.68$;
(b) clean jet ;
--- $X_1 = 3D$, $X_2 = 4D$; — $X_1 = 5D$, $X_2 = 4D$.

Conclusions

The far field azimuthal cross-spectra of a jet excited along the jet column mode ($St_D = 0.68$) have been obtained for five values of the observation angle $\Theta = 20$, 30, 45, 60 and 90 deg. The associated expansions in azimuthal modes have also been given, besides preliminary results for the near field.

The main results are the following :

. For $\Theta = 20$, 30 and 45 deg., the far field spectra show a distinct hump centered at the subharmonic of the excitation which may be related to the formation of a subharmonic by vortex pairing in the aerodynamic field. This phenomenon was also noticed for a Strouhal number of excitation of 0.88.

. Excitation enhances the azimuthal correlations. In terms of Fourier constituents this is associated with an energy transfer from higher modes to the lower ones. The enhancement of the azimuthal coherence is especially important for $\Theta = 30$ and 45 deg., at the subharmonic frequency of the excitation.

. Preliminary measurements in the near field seem to indicate that in the sections $X_1/D = 3$ and $X_1/D = 5$, the effects of excitation are smaller than in the far field.

It is hoped that these results would be of some interest to test the various models proposed to explain the azimuthal coherence of the far field. They give indeed some information on the influence of the structure of the source region while other parameters are kept constant (M, St_D, He). In view of the near field measurements the axial structure of the source may be important. In this case Maestrello's two rings model (16) would be relevant.

Acknowledgements

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