Journal of Sound and Vibration (1980) **71**(3), 319–332

INTERMITTENCY OF THE NOISE EMISSION IN SUBSONIC COLD JETS†

D. JUVÉ, M. SUNYACH AND G. COMTE-BELLOT

Laboratoire de Mécanique des Fluides, An Associated Laboratory of the Centre National de la Recherche Scientifique, Ecole Centrale de Lyon, 69130 *Ecully, France*

(*Received* 3 *July* 1979, *and in revised form* 29 *January* 1980)

Intermittency of the noise emission has been investigated by means of measurements of instantaneous cross-correlation between the far field acoustic pressure and the velocity component in the jet towards the microphone (pressure signal allowing for the acoustic propagation time). The noise is found to be associated with active periods of the second time derivative of the velocity signal. A conditional sampling procedure with a criterion based on the amplitude of this derivative, has made it possible to show that 50% of the noise is produced during only 10 to 20% of the time. The sections of the jet considered are located between 4 and 10 diameters from the nozzle, a region in which most of the averaged jet noise originates. An attempt to establish a relationship with the large scale structures of the jet has also been made. Examination of various time traces seems to indicate that the noise emission would take place at the upstream side of the large structures where most of the non-turbulent fluid is being caught up and rapidly entrained.

1. INTRODUCTION

It is, at present, generally believed that the growth of a free shear layer is linked to the development of large coherent structures. The most significant works on this topic have been recently reviewed by Laufer [1] and Roshko [2]. In the case of jets, the process of growth is not so clear but several workers have obtained strong evidence for the existence of spatially coherent eddies superimposed on the usual fine grained turbulent field, at least in the first four or five diameters. These structures were for example observed by Sunyach [3] by the detection of sharp temperature gradients across the whole shear layer of a slightly heated plane jet. Fuchs [4] reported very high values of the filtered cross-correlations of fluctuating pressure in the mixing zone, especially for circumferential separation. In later work, Lau and Fisher [5] used conditional sampling techniques to obtain the main signature of the velocity near the inner edge of the shear layer and showed that this signature could support the possible existence of toroidal vortices in the mixing layer. Further, Tataki and Kovasznay [6] suggested a statistical theory for vortex merging which gave a probability density function of the spacing between neighbouring vortices in agreement with the experiments of Brown and Roshko [7].

That these organized structures can play an important role in the noise generation process has been anticipated by some workers. Ffowcs Williams [8] emphasized the possible effectiveness in this process of strong accelerations or decelerations of the flow, while Laufer, Kaplan and Chu [9] proposed that vortex pairing could be the main mechanism. These suggestions have recently received indirect support from some experiments. Moore [10] has indeed shown that narrow-band acoustic excitation upstream

† Some of the material in this paper was presented at the Spring Meeting of the Institute of Acoustics, Cambridge, England, 4–7 April 1978.

0022–460X/80/150319+14 $02.00/0

of the nozzle improves the orderly structure of the jet and simultaneously increases the acoustic broad-band level. Juvé, Sunyach and Comte-Bellot [11] have observed that only low order azimuthal modes exist in the far field acoustic pressure, whatever the frequency considered. More directly, Dahan, Elias, Maulard and Perulli [12] obtained very large values of the coherency between the signal from a radiometer focussed in the mixing layer and the far field acoustic pressure for a hot jet ($T \simeq 900°$K, $U \simeq 420$ m/s) at a small angle of observation. Assuming a simple division of the acoustic and aerodynamic fields into coherent and incoherent parts they concluded that at least half of the acoustic field is linked to the coherent aerodynamic field.

The exact physical mechanism involved in the evolution of the large scale structures of the jet, and in the subsequent noise generation, has not yet, however, been fully understood. The problem is of considerable interest as it should be easier to model the development of these structures and their radiation properties than in the case of fine grained turbulence. In fact, some promising studies are available, for example that of Michalke and Fuchs [13] which is appropriate for low order azimuthal components of the flow field. Liu [14] described some properties of the radiation of unstable waves on the shear layer. More recently, Ffowcs Williams and Kempton [15] modelled the abrupt pairing of vortices and were able to predict, with surprisingly good accuracy, the overall sound intensity of excited jets.

In this paper the authors report some results related to the instantaneous point emission of a low subsonic cold jet. They have, in fact developed a non-averaged version of the causality correlation method pioneered by Siddon and Rackl [16] in which appears the product of the second temporal derivative of the velocity in the jet by the acoustic pressure in the far field, the proper delay time of the acoustic analogy being taken into account. The method makes it possible to demonstrate that the point acoustic emission is a very intermittent process in the zones which contribute most to the noise. Although the method is not able, in its present state of development, to detect what precise aerodynamic events are associated with the noise emission, an attempt is made to relate the most active periods of emission to the jet development process, which gives a new insight into the role of the large scale structures.

2. OUTLINE OF THE NON-AVERAGED CAUSALITY TECHNIQUE

By use of Lighthill's acoustic analogy [17, 18], taken in the Proudman form [19], the acoustic pressure at a point $\vec{X}$ in the far field can be expressed by

$$p(\vec{X}, t) = \frac{\rho_0}{4\pi c_0^2 R} \int_V \left[\frac{\partial^2}{\partial t^2} U_r^2(\vec{x}, t)\right]_{\tau_0} \mathrm{d}\vec{x}, \qquad (1)$$

where ρ_0 is the ambient density, c_0 the ambient speed of sound, $\vec{x}$ is the position vector in the jet volume V, $r = \|\vec{X} - \vec{x}\|$, $R = \|\vec{X}\|$, U_r is the velocity component in the direction of the point of observation $\vec{X}$ (cf. Figure 1) and τ_0 is the acoustic delay time r/c_0.

At small angles of observation θ (for example $\theta = 30°$), it is generally accepted that the shear noise term (linear in the fluctuating velocity) is largely dominant over the self-noise [20, 21], so that

$$p(\vec{X}, t) \simeq \frac{2\rho_0}{4\pi c_0^2 R} \int_V \bar{U}_r \left[\frac{\partial^2}{\partial t^2} u_r(\vec{x}, t)\right]_{\tau_0} \mathrm{d}\vec{x}, \qquad (2)$$

in which $\bar{U}_r$ and u_r denote the mean and the fluctuating values of U_r respectively. Multiplying the two members of this relation by $p(\vec{X}, t)$ the authors of reference [21]

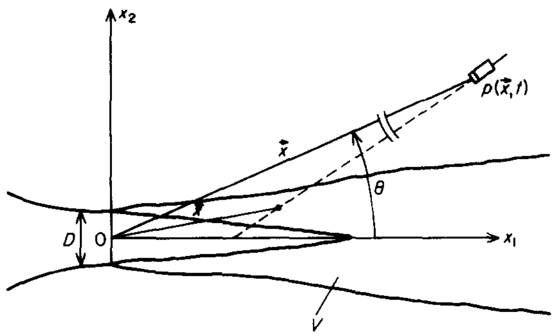

Figure 1. Geometry of the jet and main notation.

obtained

$$p^2(\vec{X}, t) \simeq \frac{\rho_0}{2\pi c_0^2 R} \int_V \bar{U}_r p(\vec{X}, t) \frac{\partial^2}{\partial t^2} u_r(\vec{x}, t-\tau_0)\, d\vec{x}, \tag{3}$$

and defined the instantaneous contribution of the point $\vec{x}$ to the noise intensity at $\vec{X}$ by

$$j(\vec{X}, \vec{x}, t) = \frac{\bar{U}_r}{2\pi c_0^3 R} p(\vec{X}, t) \frac{\partial^2}{\partial t^2} u_r(\vec{x}, t-\tau_0). \tag{4}$$

In the usual (i.e., time averaged) causality technique, the random process is assumed stationary, so that

$$\overline{p^2}(\vec{X}) = \frac{\rho_0}{2\pi c_0^2 R} \int_V \bar{U}_r \left[\frac{\partial^2}{\partial \tau^2} C_{pu_r}(\vec{X}, \vec{x}, \tau)\right]_{\tau_0} d\vec{x} \tag{5}$$

where C_{pu_r} is the co-variance between p and u_r. This form has led Siddon and Rackl [16] to define the local contribution to the noise intensity as

$$\bar{j}(\vec{X}, \vec{x}) = \frac{\bar{U}_r}{2\pi c_0^3 R} \left[\frac{\partial^2}{\partial \tau^2} C_{pu_r}(\vec{X}, \vec{x}, \tau)\right]_{\tau_0} \tag{6}$$

(usually denoted by i in the literature). Since the source distribution is frequency dependent, it is of value to define the mean contribution to the noise at frequency f. Following Lee and Ribner [22] one can do this introducing filtered cross-correlations at frequency f and with bandwidth Δf. The relation in which the phase information is fully taken into account through the use of the exact delay time τ_0 is then

$$\hat{j}(\vec{X}, \vec{x}, f, \Delta f) = (2\pi \bar{U}_r / c_0^3 R) f^2 \hat{C}_{pu_r}(\vec{X}, \vec{x}, f, \Delta f, \tau_0 - 1/2f), \tag{7}$$

where $\hat{C}_{pu_r}$ is the co-variance between signals filtered through phase matched filters of width Δf (typically $\Delta f = 0{\cdot}3f$). Expression (7) can also be rewritten as

$$\hat{j}(\vec{X}, \vec{x}, f, \Delta f) = (2\pi \bar{U}_r / c_0^3 R) f^2 \hat{R}_{pu_r}(\vec{X}, \vec{x}, f, \Delta f, \tau_0 - 1/2f) \hat{E}_p(\vec{X}, f, \Delta f) \hat{E}_{u_r}(\vec{x}, f, \Delta f), \tag{8}$$

in which $\hat{R}_{pu_r}$ stands for the time averaged correlation coefficient between the filtered signals p and u_r, and $\hat{E}_p$ and $\hat{E}_{u_r}$ for the r.m.s. values of the filtered signals p and u_r, respectively (for a filter bandwidth Δf).

In this paper we concentrate mainly on the results obtained through the use of the instantaneous relation (4). However, some results obtained through the time averaged formula (8) are also given since they do present some new aspects. There is also a need for selecting the main locations for investigation of the instantaneous acoustic emission.

3. EXPERIMENTAL SET-UP

3.1. AERODYNAMIC CIRCUITRY

All the measurements were made in the anechoic chamber of the Ecole Centrale de Lyon, the dimensions of which are 6·1 m × 4·6 m × 3·3 m with a cut-off frequency of about 100 Hz. The jet had an exit diameter $D = 2$ cm and an exit velocity $U_j = 135$ m/s. It was supplied by a centrifugal fan through two specially built silencers (Figure 2); the first was

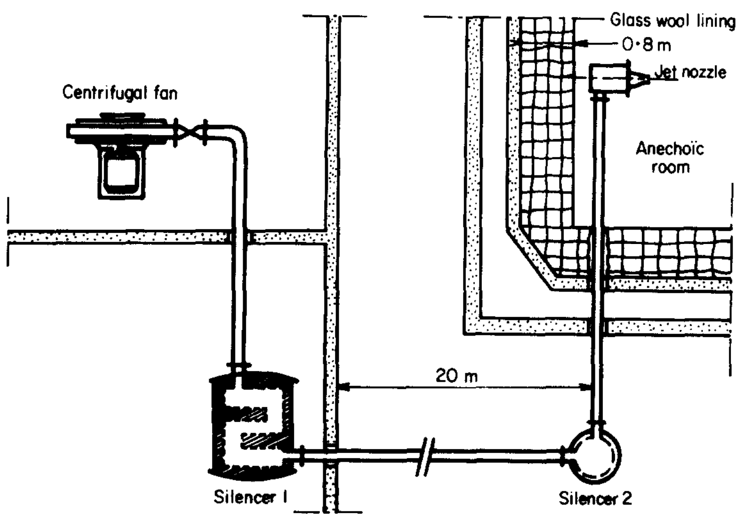

Figure 2. Schematic diagram of experimental facilities.

located immediately downstream of the fan and the second just upstream of the entrance into the anechoic chamber. These two silencers were separated by some 20 meters of flexible tube in which the air velocity never exceeded 6 m/s. The inside of the plenum chamber upstream of the nozzle was lined with glass wool in order to obtain a continuous variation of its section towards the final converged section, the contraction ratio of which was 36 to 1. With two screens (mesh size ≃ 1 mm) in the plenum chamber, the turbulent intensity in the exit plane was reduced to around 0·3%.

3.2. SIGNAL PROCESSING

A matter of concern inherent to the correlation technique is that the noise generated by the measuring probe placed in the jet must be negligible compared to that of the neighbouring turbulent volume (as pointed out by Fisher and Harper-Bourne [23]). This condition was not exactly fulfilled in Rackl's [24] or Seiner's [25] work, so that their results cannot be considered as sufficiently accurate within the first four jet diameters. To overcome this difficulty the authors have developed a special hot wire probe for the overall acoustic tests. The solid prongs of this probe were kept outside the flow. Two fine wires only (of diameter ≃ 100 μm) supporting the sensitive hot wire (of diameter $d \simeq 10$ μm and length $l \simeq 2$ mm) remained in the flow; a sketch of the probe is given in Figure 3. The probe was fed by a modified constant temperature anemometer Disa 55 D 01. By comparison with a standard probe it was verified that no discernible vibration took place in the

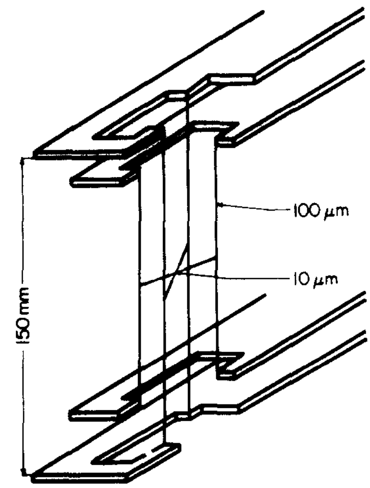

Figure 3. Sketch of the special hot wire probe designed for the measurement of the local contribution to the noise intensity.

frequency range of interest. It was also verified, from the extensive analysis of Strohl and Comte-Bellot [26], that the present probe does not introduce significant aerodynamic perturbations. For the noise generated by the probe use of the method proposed by Rackl [24] provides an estimate showing that for $x_1/D=4$, it is down to 1% of the noise generated by the neighbouring turbulent correlation volume. A conventional probe (Disa 55 P 01) was used, however, when investigating the instantaneous acoustic emission, with the probe body set perpendicular to the jet axis. Because of the second time derivative on which expression (4) is based, it was necessary to improve the high frequency quality of the signal u_r up to around $f^*=2$ (the dimensionless frequency $f^*=fD/U_j$). The effect of the solid prongs did not seem to be critical in the sections considered in this study (i.e., $x_1/D=4$, 5 and 10). Systematic comparisons between the two types of probes have indeed shown that the broadband correlation coefficient R_{pu_r} measured by the conventional probe was too large by about 20% at $x_1/D=5$ and 8% at $x_1/D=10$, the shape of the curves being unchanged. These modifications seem acceptable and lower than those estimated recently by Richarz [27] on theoretical grounds. Moreover the authors' results for the level of the correlation coefficient are in agreement with unpublished measurements by Schaffar [28] using the Laser Doppler Anemometry technique in a high subsonic jet.

The velocity component u_r in the direction of the microphone was obtained simply by setting the hot wire at an angle θ to the jet axis. The high aspect ratio of the wire ($l/d \simeq 200$ for the present probe and $l/d \simeq 400$ for the Disa probe) makes it possible to neglect the cooling by the velocity component parallel to the wire (noted by Champagne, Schleicher and Wehrmann [29]). Another source of error which has to be estimated is the rectification of the velocity signal in very high intensity turbulence. Tutu and Chevray [30] have investigated the case of jets and found that the error is large near the outer edge, but very small in the vicinity of the jet axis, where all the time traces examined in the present work have been recorded.

The far field acoustic pressure was measured by a standard 1/2 in microphone (Brüel and Kjaer (B & K) 4133) located at 2 m from the jet.

In all the experiments the pressure and velocity signals were first recorded on a multitrack FM tape recorder with a bandwidth of 20 kHz (Schlumberger MP 5521). The filtered correlations were obtained through the use of band proportional analyzers (B & K 2107, $\Delta f/f=0{\cdot}29$) and a digital correlator (Hewlett Packard (HP) 3721 A). The study of the instantaneous product $p(t+\tau_0)\partial^2 u_r(t)/\partial t^2$ was conducted via digital processing on an HP 21 MX minicomputer. The tape was replayed at half the recording velocity, and the signals were fed through two anti-aliasing filters which were set to a frequency of 8 kHz ($f^* \simeq 2, 5$). They were sampled at a rate of 20 kHz, the most useful frequencies lying between 0·5 and 3 kHz (i.e., $0{\cdot}15 \leqslant f^* \leqslant 1$); this rate permitted both a correct signal visualization and an optimum quality for the second derivative of u_r.

Careful check of the acoustic time delay r/c_0 has been made, which involved measurement of the sound velocity before each recording as well as control of the phase responses of all the electronic circuitry.

4. MEAN ACOUSTIC PROPERTIES OF THE JET

4.1. OVERALL ACOUSTIC PROPERTIES

The acoustic intensity measured at an angle of 90° to the jet axis fits a power law of the type $I \sim KU_j^n$ where $n \simeq 7{\cdot}5$ when $M = U_j/c_0 \geqslant 0{\cdot}3$, which is in good agreement with carefully conducted experiments (such as those of Lush [31] and Ahuja [32]). Moreover the overall sound pressure level obtained at a Mach number of 0·39 compares fairly well with the values of Lush [31] and Moore [10] when appropriate corrections were made for the differences in the jet exit diameter and in the distance of observation. The "excess noise" due to unsteady mass and momentum fluxes through the nozzle exit has been found to be negligible. It has been evaluated by the causality correlation method at a velocity of 100 m/s [33]. Even for this very low value it has been shown that more than 95% of the noise was due to the turbulent mixing.

Since all precautions have been taken in order to avoid upstream aerodynamic as well as acoustic disturbances, which could have excited the jet, the present facility can therefore be considered as producing a "clean" jet noise.

4.2. ACOUSTIC SOURCE STRENGTH DENSITY

From now on, we concentrate on the shear noise, observed at $\theta = 30°$, so that the mean acoustic strength density is given by expression (8). It is important to note that in this expression, it is the value of the correlation coefficient at the exact delay time $\tau_0 = r/c_0$ that has to be taken into account, and not the value of the nearest maximum as is often taken in similar work by other authors (e.g., Rackl [24] and Seiner [25]).

Integration of $\hat{\jmath}(\vec{X}, \vec{x}, f, \Delta f)$ over a section of the jet gives the contribution $\hat{J}(\vec{X}, x_1, f, \Delta f)$ to the noise per unit slice of jet. In practice $\hat{\jmath}$ is measured (for the exact delay time) with a step of 0·1 D along the jet diameter located in the plane defined by the jet axis and the microphone ($-0{\cdot}7 \leqslant x_2/D \leqslant 0{\cdot}7$). The circumferential integration of $\hat{\jmath}$ at a given radius was then approximated by 2π times the mean value $\frac{1}{2}[\hat{\jmath}(x_2, f, \Delta f) + \hat{\jmath}(-x_2, f, \Delta f)]$ and the integration over x_2 performed in the usual manner. In the first integration it is supposed that $\hat{\jmath}$ presents a monotonic variation with the azimuthal angle, an assumption which is plausible as the frequencies considered are relatively low (for $f^* = 0{\cdot}6$ one has $\lambda \simeq 4D$). Furthermore, the recent and systematic measurements of Richarz [27] permit one to estimate that the errors are not larger than about 15%.

The contributions $\hat{J}$ have been obtained for three characteristic values of the reduced frequency f^* (0·15, 0·30, 0·60) around the maximum of the acoustic spectrum (see Figure 4). Results are given in Figure 5 in the dimensionless form

$$\hat{J}^*(\vec{X}, x_1^*, f^*, \Delta f^*) = (c_0^5 R^2/\rho_0 U_j^8 D)\hat{J} \text{ with } x_1^* = x_1/D, \tag{9}$$

and two results are of particular interest.

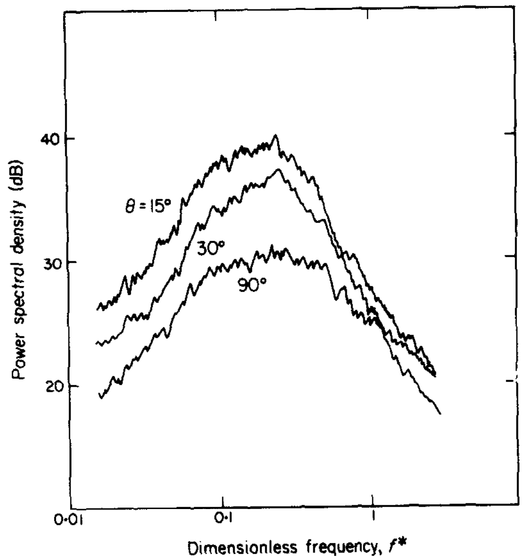

Figure 4. Power spectral density of the radiated acoustic pressure at three different angles. $\theta = 90°$, 30° and 15°. Jet nozzle diameter $D = 20$ mm, jet velocity $U_j = 135$ m/s.

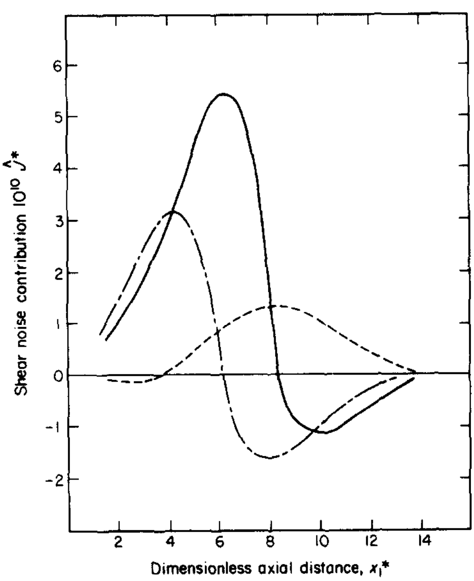

Figure 5. Downstream distribution of shear-noise contribution per unit-slice of jet for three values of the dimensionless frequency ($\theta = 30°$). ---, $f^* = 0{\cdot}15$; ——, $f^* = 0{\cdot}30$; —·—, $f^* = 0{\cdot}60$. Jet nozzle diameter $D = 20$ mm; jet exit velocity $U_j = 135$ m/s.

Firstly, the most active zone for noise generation in the predominant frequency band is the transition region located at the end of the potential core ($4 \leq x_1^* \leq 10$). In fact, the maximum of the contribution per unit slice moves downstream when the frequency decreases, its location being at $x_1^* = 8{\cdot}5$, 6 and 4 for $f^* = 0{\cdot}15$, $0{\cdot}30$ and $0{\cdot}60$ respectively. For these three frequencies, the sound emission is negligible beyond 14 D. Recently similar conclusions have been drawn through the use of far field techniques by Chu and Kaplan [34], Billingsley and Kinns [35] and Fisher, Harper-Bourne and Glegg [36]. The distributions of equivalent acoustic sources obtained by these authors would appear to peak somewhat more downstream than those of the present work, but this can be due to a relatively low resolution of their systems.

Secondly, the present work reveals the existence of locally negative contributions to the noise. This was foreseen in 1973 by Ffowcs Williams [37], who emphasized the fact that the acoustic source strength is not, strictly speaking, a local property, but results from an integration over the whole volume of the jet. As a consequence, the effective presence of these regions strongly supports the existence of large radiating structures instead of the conventional picture of small uncorrelated eddies distributed throughout the jet. In the results presented by other authors, it is sometimes possible to observe these locally negative contributions (see, for example, reference [24], page 57) but such values were suppressed and replaced by positive values arbitrarily taken at the nearest maximum. On the other hand, observations of locally negative contributions have also been made recently by Schaffar [28] by the use of Laser Doppler Anemometry to measure the velocity fluctuations u_r.

The consistency of the present results is confirmed by the fact that integration over x_1^* of the contribution per unit slice compares fairly well with the measured acoustic intensity for the three frequencies investigated: differences between measured and estimated values are within 3 dB [33]. At variance with this, the estimated broadband level obtained by Rackl [24] was ten times greater than the measured one. The attention paid to the exact retarded time τ_0 as well as the construction of a special hot wire probe which avoids the contamination of the acoustic field have therefore made possible a substantial improvement in the results previously obtained through the causality technique.

5. INSTANTANEOUS ACOUSTIC EMISSION

The points considered for this investigation are located in the region where most of the shear noise emission takes place: i.e., in the rearrangement region downstream of the end of the potential core. The points selected are then A($x_1^* = 4$, $x_2^* = 0{\cdot}25$), B($x_1^* = 5$, $x_2^* = 0$) and C($x_1^* = 10$, $x_2^* = 0$), and the angle of observation for the radiated noise is $\theta = 30°$ from the jet axis.

5.1. EXAMINATION OF THE TIME TRACES

As already seen (section 2, equation (4)) the instantaneous noise emission can be deduced from the joint measurements of the radiated acoustic pressure and of the second time derivative of the velocity fluctuation in the jet in the direction of observation. In Figures 6(a)–(c) for points A, B and C respectively, characteristic time traces are therefore given for the following signals (7·5 ms long): the turbulent velocity component $u_{30}(t)$; the second time derivative $u_{30}''(t)$; the radiated acoustic pressure p_{30} delayed by the acoustic propagation time τ_0, being hence $p_{30}(t+\tau_0)$; the instantaneous product of the last two signals, which corresponds to the instantaneous noise emission $j(t)$ defined by expression (4).

Detailed inspection of these time traces reveal the following phenomena of interest.

(i) The second derivative $u_{30}''(t)$ offers periods of activity with one or more high amplitude peaks.

(ii) There are important contributions to the signal $j(t)$ associated with the periods of activity of $u_{30}''(t)$.

(iii) For the points A and B located near the end of the potential core, the periods of activity coincide frequently with the end of a marked deceleration of the flow. Significant samples are enhanced by boxes in Figures 6(a) and (b) and the corresponding contributions

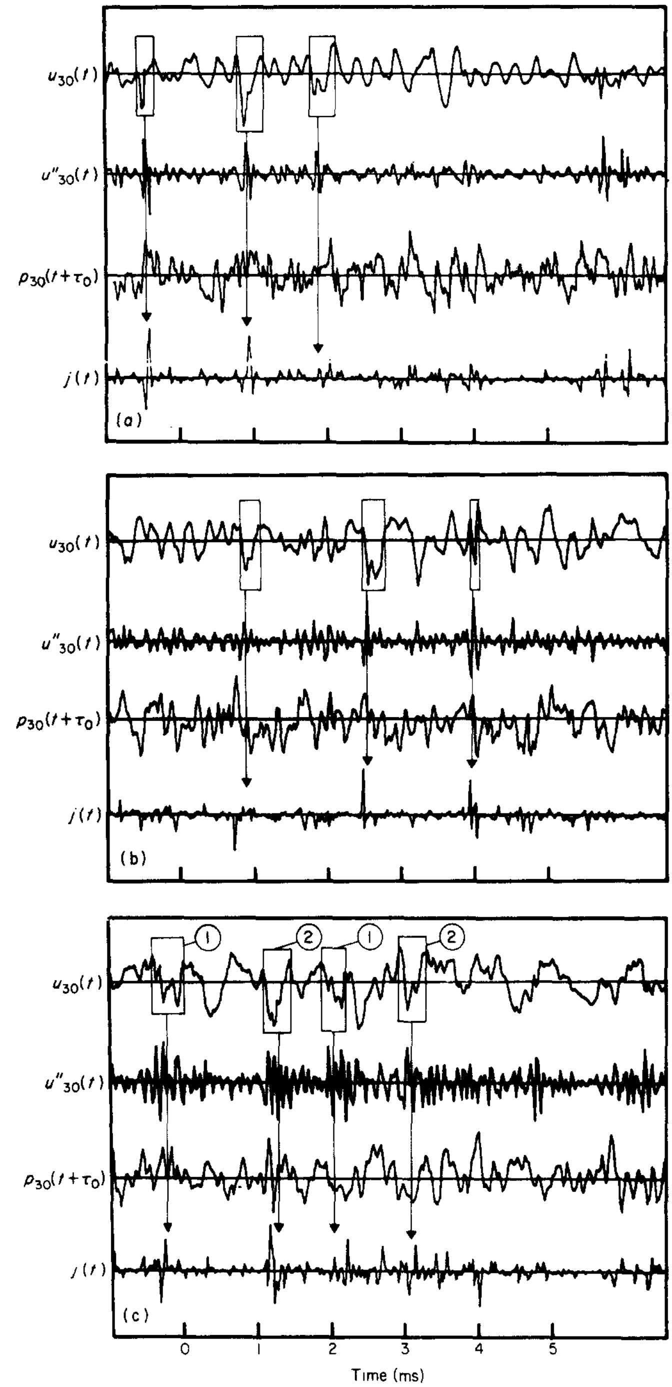

Figure 6. Time traces of instantaneous contribution to the noise at (a) point A ($x_1^* = 4$, $x_2^* = 0{\cdot}25$); (b) point B ($x_1^* = 5$, $x_2^* = 0$); (c) point C ($x_1^* = 10$, $x_2^* = 0$).

to $j(t)$ are pointed out by arrows. The signature of the signal u''_{30} included in these boxes can be compared to the instantaneous radial velocity traces obtained by Acton [38] using numerical modelling of axisymmetric jet flows (see also reference [15], p. 677). Two of the most significant patterns from reference [15] are reproduced in Figure 7, in which the first

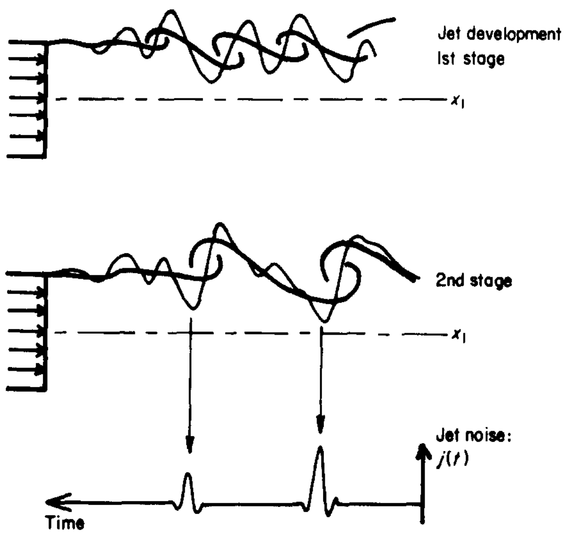

Figure 7. Sketch showing the development of an axisymmetric jet (from reference [15]) and the associated instantaeous emission $j(t)$ (present work).

and the second stages refer respectively to computation results obtained before and after the pairing process. It appears that the velocity trace corresponding to the second stage is very similar to the typical signature obtained in the present work. The major components of the signal $j(t)$ are then believed to occur on the upstream side of the vortices where most of the entrainment from outside takes place.

(iv) For point C which is located far downstream of the end of the potential core, the observed signals are more complex. However, the most significative contribution to the noise seems to be associated with velocity traces which always present one sharp front, either decelerated or accelerated, the other front exhibiting notable oscillations (see the part indicated by boxes in Figure 6(c)). The two types of signature of these traces, denoted 1 and 2, are explained by means of the sketch given in Figure 8 in which are indicated velocity traces associated with structures orginating from radially opposite regions of the annular mixing layer. Either of these structures would more or less approach the jet axis and induce their own signature to the hot wire in a random sequence. The situation is then similar to that described by Sabot and Comte-Bellot [39] in the inner region of a turbulent pipe flow. The possibility of deep crevices extending up to the jet axis, in sections $x_1/D \simeq 10–15$, is also supported by the recent work of Chevray and Tutu [40].

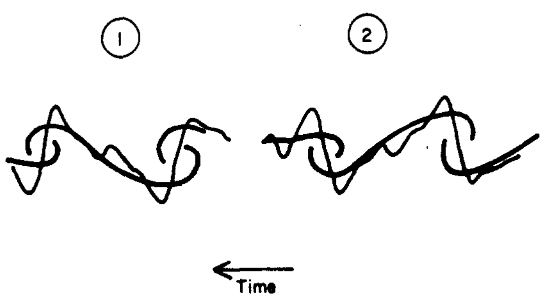

Figure 8. Sketch showing the velocity signatures ① and ② produced by vortex structures originating from opposite azimuthal directions. ——, Dye line; ——, radial velocity trace.

Even if all the detailed phenomena are not fully understood, these time traces are evidence for the intermittency of the local acoustic emission. The next step is therefore an attempt to obtain quantitative information.

5.2. CONDITIONAL STUDY OF $j(t)$

The link between the intermittency in the noise generation and the intermittency of u''_{30} suggests the use of the latter signal to achieve a conditional average. The authors have in fact chosen to sample $j(t)$ by using a criterion for the amplitude of u''_{30}. Conditional averaged values of $R_{pu''_{30}}$ and of j have been obtained depending upon γ, the percentage of time when $|u''_{30}| > H$ (H being an adjustable threshold). It is clear from Figures 6(a)–(c) where no DC value has been suppressed, that the average value $\bar{j}$ of $j(t)$ is very low: a typical value of the correlation coefficient between p and u'' is 0·01. Such a value has allowed the authors to choose long integration times in order to obtain a statistically significant result; more precisely the product of the bandwidth of u''_{30} by the integration time (BT product) is around 100 000.

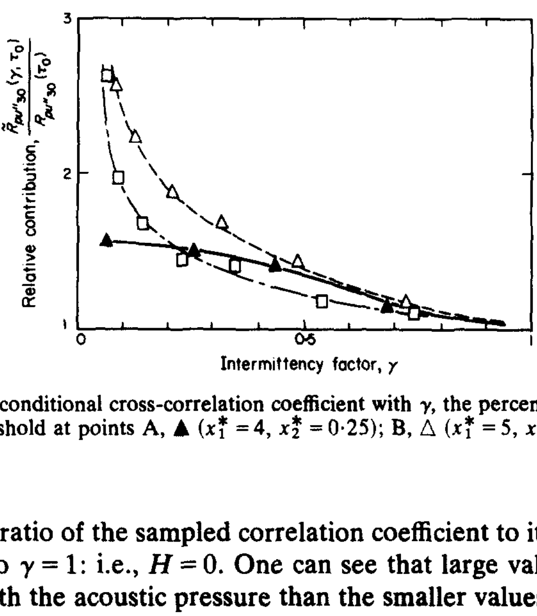

Figure 9. Variation of conditional cross-correlation coefficient with γ, the percentage of time when $|u''_{30}|$ is greater than a given threshold at points A, ▲ ($x_1^* = 4$, $x_2^* = 0{\cdot}25$); B, △ ($x_1^* = 5$, $x_2^* = 0$) and C, □ ($x_1^* = 10$, $x_2^* = 0$).

Figure 9 gives the ratio of the sampled correlation coefficient to its conventional value which corresponds to $\gamma = 1$: i.e., $H = 0$. One can see that large values of u''_{30} are more closely correlated with the acoustic pressure than the smaller values. This is particularly well verified at points B and C since Figure 9 shows that the amplitude of the correlation is multiplied by a factor greater than two, when only the largest amplitudes of u''_{30} are retained.

Figure 10 indicates the percentage of acoustic energy emitted versus γ. In particular, the intermittency is the greatest for point B, located just at the end of the potential core: 10% of the time can then provide 50% of the total contribution to the noise.

6. CONCLUSION

The intermittency of the noise emission of subsonic cold jets has been demonstrated by investigating the instantaneous contribution to the noise in the most efficient noise producing region which extends mainly from 4 to 10 diameters. Use of a conditional sampling procedure based upon an amplitude criterion for the second time derivative of the velocity leads to quantitative results. In particular it is observed that 50% of the emitted noise is produced during only about 10 to 20% of the time. The downstream

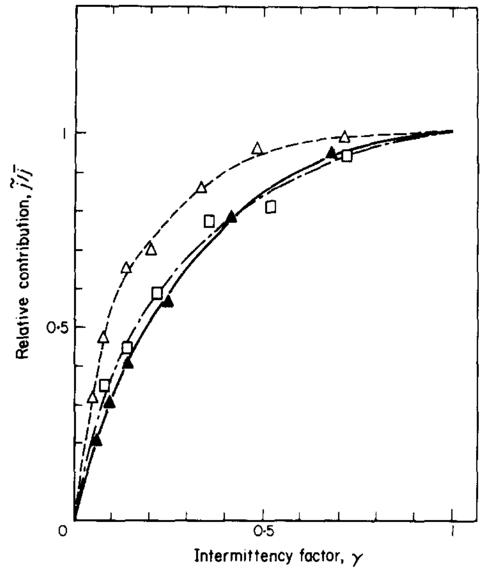

Figure 10. Variation with γ of conditional contributions to the noise from points A, ▲ ($x_1^* = 4$, $x_2^* = 0{\cdot}25$); B, △ ($x_1^* = 5$, $x_2^* = 0$) and C, □ ($x_1^* = 10$, $x_2^* = 0$).

development of the most efficient patterns shows that a connection may exist between the noise emission and the interacting process of the large scale structures. By the examination of various time traces, a possible conclusion is that the noise emission is located at the upstream side of the large structures where most of the external fluid is suddenly entrained into the jet. In these areas strong decelerations or accelerations take place in the radial direction, depending on the azimuthal origin of the large scale structure. Future detailed investigations will probably involve simultaneous visualization of the flow and multipoint analysis.

REFERENCES

1. J. LAUFER 1975 *Annual Review of Fluid Mechanics* **7**, 307–326. New trends in experimental turbulence research.
2. A. ROSHKO 1976 *American Institute of Aeronautics and Astronautics Journal* **14**, 1349–1357. Structure of turbulent shear flow: a new look. Dryden research lecture.
3. M. SUNYACH 1971 *Doctor Sciences Thesis No.* 37, *Université de Lyon.* Contribution à l'étude des frontières d'écoulements turbulents libres.
4. H. V. FUCHS 1972 *Journal of Sound and Vibration* **23**, 77–99. Space correlations of the fluctuating pressure in subsonic turbulent jets.
5. J. C. LAU and M. J. FISHER 1975 *Journal of Fluid Mechanics* **57**, 299–337. The intrinsic structure of turbulent jets.
6. R. TATAKI and L. S. G. KOVASZNAY 1978 *Physics of Fluids* **31**, 153–156. Statistical theory of vortex merger in the two dimensional mixing layer.
7. G. L. BROWN and A. ROSHKO 1974 *Journal of Fluid Mechanics* **64**, 775–816. On density effects and large structure in turbulent mixing layers.
8. J. E. FFOWCS WILLIAMS 1973 *AGARD Conference Proceedings No.* 131 *on Noise Mechanisms, Brussels.* Impulsive sources of aerodynamic sound.
9. J. LAUFER, R. D. KAPLAN and W. T. CHU 1973 *AGARD Conference Proceedings No.* 131 *on Noise Mechanisms, Brussels.* On the generation of jet noise.
10. C. J. MOORE 1977 *Journal of Fluid Mechanics* **80**, 321–367. The role of shear-layer instability waves in jet exhaust noise.

11. D. JUVÉ, M. SUNYACH and G. COMTE-BELLOT 1979 *American Institute of Aeronautics and Astronautics Journal* **17**, 112–114. Filtered azimuthal correlations in the acoustic far field of a subsonic jet.
12. C. DAHAN, G. ELIAS, J. MAULARD and M. PERULLI 1978 *Journal of Sound and Vibration* **59**, 313–333. Coherent structures in the mixing zone of a subsonic hot free jet.
13. A. MICHALKE and H. V. FUCHS 1975 *Journal of Fluid Mechanics* **69**, 179–205. On turbulence and noise of an axisymmetric shear flow.
14. J. T. C. LIU 1974 *Journal of Fluid Mechanics* **62**, 437–464. Developing large-scale wavelike eddies.
15. J. E. FFOWCS WILLIAMS and A. J. KEMPTON 1978 *Journal of Fluid Mechanics* **84**, 673–694. The noise from the large-scale structure of a jet.
16. T. E. SIDDON and R. RACKL 1971 *82nd Meeting of the Acoustical Society of America, Denver.* Cross correlation analysis of flow noise with fluid dilatation as source fluctuation.
17. M. J. LIGHTHILL 1952 *Proceedings of the Royal Society* **A211**, 564–587. On sound generated aerodynamically I. General theory.
18. M. J. LIGHTHILL 1954 *Proceedings of the Royal Society* **A222**, 1–32. On sound generated aerodynamically II. Turbulence as a source of sound.
19. I. PROUDMAN 1952 *Proceedings of the Royal Society* **A214**, 119–132. The generation of noise by isotropic turbulence.
20. J. M. SEINER and G. REETHOF 1974 *American Institute of Aeronautics and Astronautics Meeting, Washington Paper* 74-4. On the distribution of source coherency in subsonic jets.
21. D. JUVÉ, M. SUNYACH and J. BATAILLE 1976 *Comptes rendus de l'Académie des Sciences, Paris,* **283B**, 269–272. Application de la méthode de causalité à l'étude du bruit d'un jet subsonique.
22. H. K. LEE and H. S. RIBNER 1972 *Journal of the Acoustical Society of America* **52**, 1280–1290. Direct correlation of noise and flow of a jet.
23. M. J. FISHER and M. HARPER-BOURNE 1973 *Institute of Sound and Vibration Research Report No. CR* 73/21. Jet noise generation and suppression, Part I: Source location.
24. R. RACKL 1973 *Ph.D. Thesis, University of British Columbia.* Two causality correlation techniques applied to jet noise.
25. J. M. SEINER 1974 *Ph.D. Thesis, Pennsylvania State University.* The distribution of jet source strength intensity by means of a direct correlation technique.
26. A. STROHL and G. COMTE-BELLOT 1973 *Journal of Applied Mechanics, Transactions of the American Society of Mechanical Engineers* **40E**, 661–666. Aerodynamic effects due to configuration of X-wire anemometers.
27. W. G. RICHARZ 1978 *University of Toronto Institute for Aerospace Studies, Report No.* 230. Direct correlation of noise and flow of a jet using laser Doppler.
28. M. SCHAFFAR 1978 *Franco-German Research Institute, Saint-Louis France Report R* 109–78. Relation de cause à effet entre les fluctuations de vitesse d'un jet froid et le bruit émis près de l'axe.
29. F. H. CHAMPAGNE, C. A. SCHLEICHER and D. H. WEHRMANN 1967 *Journal of Fluid Mechanics* **28**, 153–175. Turbulence measurements with inclined hot-wires, Part 1: Heat transfer experiments with inclined hot-wire.
30. N. K. TUTU and R. CHEVRAY 1975 *Journal of Fluid Mechanics* **71**, 785–800. Cross-wire anemometry in high intensity turbulence.
31. P. A. LUSH 1971 *Journal of Fluid Mechanics* **46**, 477–500. Measurements of subsonic jet noise and comparison with theory.
32. K. K. AHUJA 1973 *Journal of Sound and Vibration* **29**, 155–168. Correlation and prediction of *jet noise.*
33. D. JUVÉ 1978 *Thèse de Docteur-Ingénieur Lyon No.* 291. Analyse par une méthode d'intercorrélation de l'émission acoustique moyenne et instantanée d'un jet subsonique.
34. W. T. CHU and R. E. KAPLAN 1976 *Journal of the Acoustical Society of America* **59**, 1268–1277. Use of a spherical concave reflector for jet-noise source distribution diagnosis.
35. J. BILLINGSLEY and R. KINNS 1976 *Journal of Sound and Vibration* **48**, 485–510. The acoustic telescope.
36. M. J. FISHER, M. HARPER-BOURNE and S. A. L. GLEGG 1977 *Journal of Sound and Vibration* **51**, 23–54. Jet enginer noise source location: the polar correlation technique.
37. J. E. FFOWCS WILLIAMS 1973 *AGARD Conference Proceedings No.* 131, *On Noise Mechanisms, Brussels.* Technical evaluation report.

38. E. ACTON 1976 *Ph.D. Thesis Cambridge University Engineering Department.* A modelling of large jet eddies.
39. J. SABOT and G. COMTE-BELLOT 1976 *Journal of Fluid Mechanics* **74**, 767–796. Intermittency of coherent structures in the core region of fully developed pipe fllow.
40. R. CHEVRAY and N. K. TUTU 1978 *Journal of Fluid Mechanics* **88**, 133–160. Intermittency and preferential transport of heat in a round jet.