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ACOUSTICS 2012

Scattering of wavepacket by a flat plate in the vicinity of a turbulent jet

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We present an investigation on the effect of the presence of a flat plate in the vicinity of turbulent, subsonic jets. Experiments have been performed to measure the changes in the velocity field and in the sound radiation for a number of Mach numbers and distances between the plate and the jet axis. Results show a significant increase of sound radiation at lower frequencies with dipolar behaviour. There is exponential decay of the scattered sound with the plate distance, in agreement with scattering of the evanescent waves in the jet near field. The tailored Green's function for the semi-infinite plate shows that the scattered field at the normal direction to the jet axis is significant for axially-aligned compact quadrupoles, in contrast to the free-field case. This suggests that wave-packet sources, which are known to drive the near pressure field of free jets, may be responsible for the measured scattered sound.

1 Introduction

An investigation of the installation effect presented by the proximity of an aircraft wing to its propulsive jet is undertaken by means of experimental measurement, analysis and modelling. A simplified experimental configuration is considered, comprising a single-stream isothermal jet in static conditions, the wing being mimicked by a flat diffractive surface. The configuration is similar to that of Mead and Strange[7].

The effect of jet-wing distance on the radiated sound is assessed as a function of the jet acoustic Mach number. The acoustic signature of the system is analysed by means of two farfield microphones, disposed (see figure 1(*b*)) so as to allow the dipolar signature of the scattered field to be easily identified. Pitot and hot-wire measurements are used to probe the flow field.

The main results of the work are as follows. (1) The hypothesis of Mead & Strange, that the sideline amplification is due to scattering of the hydrodynamic nearfield of the jet by the edge, is confirmed. Observations supporting this hypothesis include: an exponential dependence of the sideline amplification on jet-wing distance; a Helmholtz scaling of the amplified part of the sound spectra; a velocity exponent of less than 6; strong coherence (up to 0.8) between the two diametrically-opposed microphones, and a phase that corresponds to a compact edge dipole. (2) When the jet grazes the plate, this position being identified when the jet mean-flow becomes deformed, a change is observed in the phase difference between the diametrically-opposed microphones; it is postulated that this change in signature is due to an additional source mechanism, associated with the shedding of vorticity from the trailing edge. (3) Preliminary results using the tailored Green's function [6, 3] show that axially-aligned quadrupoles, which are dominant sound sources at low polar angles to the jet axis, can radiate significant sound at the sideline direction due to scattering by the plate. Source models based on wave-packets, which are know to dominate the near pressure field of jets[9, 10, 4], appear thus promising to study the sideline amplification.

2 Experimental setup

The jet-wing configuration, shown in figure 1(*a*), is similar to that of Mead & Strange[7]. The flat plate is positioned parallel to the jet axis, and its trailing edge is at $x/D = 5.5$, which corresponds to the end of the potential core for the present jet without the influence of the plate. The microphone setup is shown in figure 1(*b*). The microphones are set up in this way so that the dipole signature can be easily identified. Measurements are performed over the Mach number range 0.35<M<0.6 for a range of jet-wing distances 1<r/D<2. The Mach number range corresponds to previous work on free jets[1]. Flow measurements are made using a Pitot probe and a hot wire.

(*a*) (*b*)

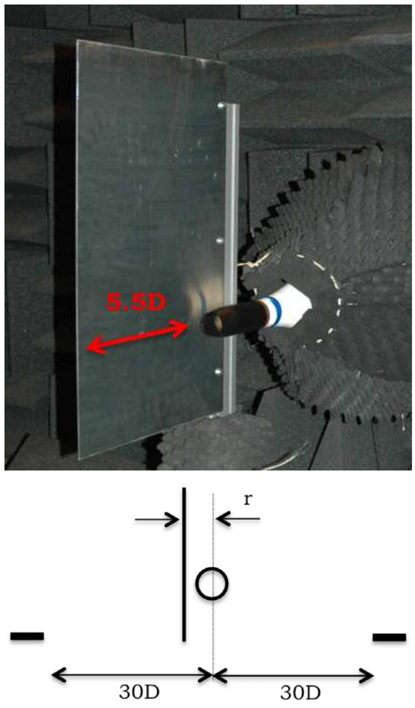

Figure 1: (*a*) Jet-wing setup; (*b*) Schema showing microphone positions

3 Aerodynamic results

Preliminary Pitot measurements have been performed in order to identify the point at which the proximity of the plate to the jet causes a deformation in the mean field of the jet. It is important to identify this position for two reasons: (1) an additional source may arise at this point, associated with the shedding of vorticity from the trailing edge of the plate; and, (2) because a stability computation can no longer be performed using an assumption of axisymmetry of the mean flow.

Velocity profiles measured along a radial traverse normal to the plate are shown in figure 2 for three Mach numbers. These show that at a distance of $r/D = 1.25$ the mean flow begins to graze the plate; at $r/D > 1.25$ no mean-field deformation is observed.

We did hot-wire measurements on the jet centerline to evaluate if the presence of the plate modifies the downstream evolution of the axisymmetric mode. Sample results are shown in figure 3 for the $M = 0.4$ jet. All curves are superposed, and thus no detectable effect on the axial

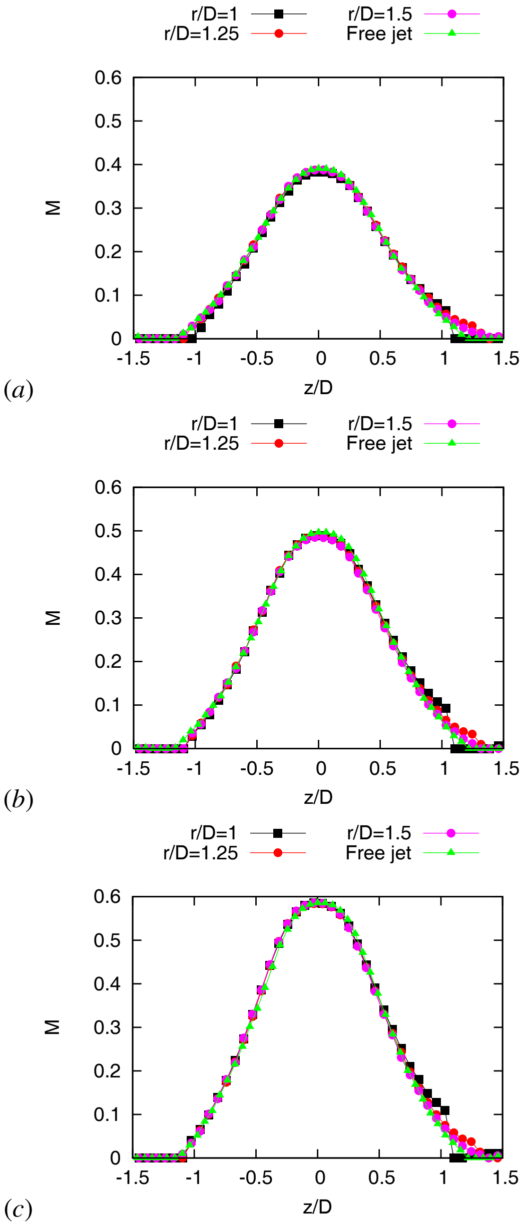

Figure 2: Mean velocity profiles at $x/D = 5.6$ for the $M = 0.4$ (a), $M = 0.5$ (b) and $M = 0.6$ (c) jets

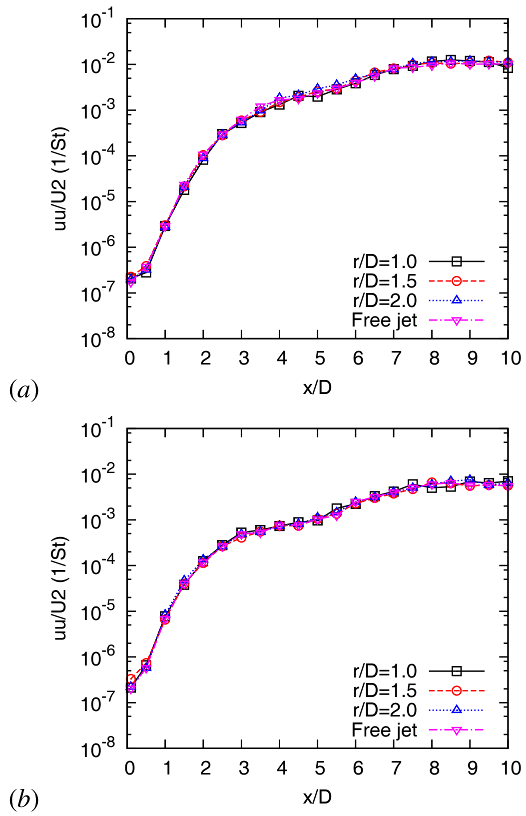

Figure 3: Evolution of velocity fluctuations on the jet centerline for $M = 0.4$ and St = 0.4 (a) and St = 0.6 (a).

evolution of the velocity fluctuations was observed. The same is true for other Mach and Strouhal numbers, which are not shown here. Although this is not a comprehensive evaluation, since only the jet centerline was used, the present results suggest that a single source model could be used for sound generation, the only change being the tailored Green's function that accounts for the geometry and the position of the plate.

4 Acoustics results

4.1 Increase of sound radiation due to the flat plate

Figures 4 and 5 shows sound spectra measured by the two microphones for different jet-wing distances and exit Mach numbers. A low-frequency amplification can be observed, similar to that observed by Mead & Strange [7] and Lawrence et al. [5], for both the shielded and unshielded microphones and for all Mach numbers. The shielding effect of the wing is observed only in the higher frequencies (at He > 0.2): the pressure field incident on the plate at these frequencies is purely acoustic. The amplified part of the spectra scale better when plotted as a function of Helmholtz number, showing that the associated mechanism is associated with the ratio between the characteristic length of the problem and the acoustic wavelength, rather than with some change in the turbulence of the jet. Another result obtained from this figure is the velocity scaling of the spectra: while the high-frequency part of the spectra scale with a velocity exponent of about 7.5, the low-frequency part scales with an exponent that varies between 3 and 6 depending on the frequency considered. Lower velocity scalings are expected for the scattered field[3].

Figure 6 compares the unshielded spectra, for r/D=1, 1.5 & 2, with that of the free jet. The fact that the high frequency part of the former does not perfectly match that of the free jet with an additional 3dB (to account for uncorrelated reflection of the sound field) is believed to be due to the fact that the plate dimensions are finite (3dB would result from reflection by an infinite plane). Also of note in this figure is the dependence of the amplified part of the spectrum on the jet-wing distance: variation of the SPL with r/D is exponential, suggesting that the fluctuations driving the amplified part of the sound field are those of the hydrodynamic jet nearfield, whose radial decay is also exponential (cf. Crighton & Huerre[2], Suzuki & Colonius [9]).

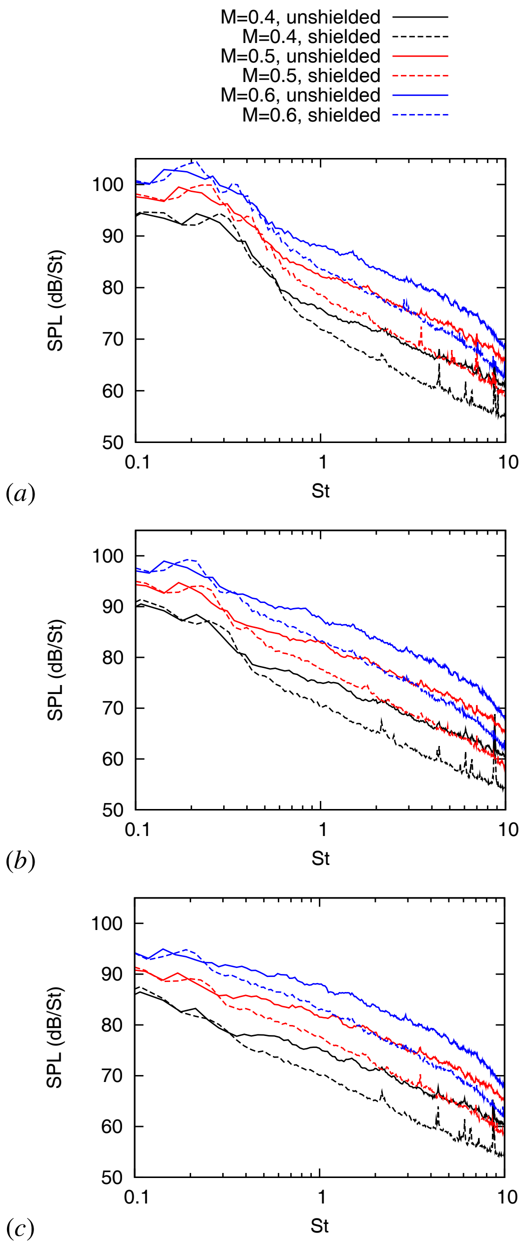

Figure 4: Sound spectra as a function of Strouhal number measured by the shielded and unshielded microphones for $r/D = 1$ (a), $r/D = 1.5$ (b) and $r/D = 2$ (c)

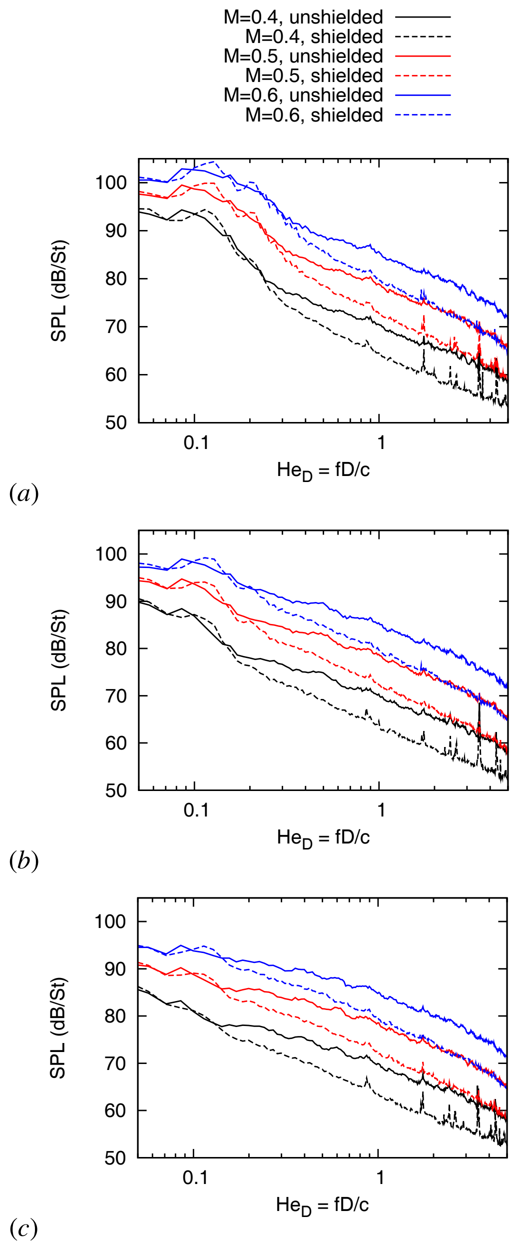

Figure 5: Sound spectra as a function of Helmholtz number measured by the shielded and unshielded microphones for $r/D = 1$ (a), $r/D = 1.5$ (b) and $r/D = 2$ (c)

4.2 Evaluation of dipolar radiation

The mechanisms reponsible for the low-frequency amplification was postulated by Mead & Strange to be due to the scattering of the jet by the trailing edge. While the above observations support this hypothesis, further verification can be obtained by considering the coherence between the two diametrically-opposed microphones. As the scattering mechanism corresponds to a compact edge dipole, the two microphones should be highly correlated at the scattered frequencies, and, furthermore, a particular phase relationship should exist.

The coherence between the microphones is shown in figure 7 for different jet-wing distances and Mach numbers. The coherence is consistently high (varying from 0.6 to 0.9) in the frequency range corresponding to the sideline amplification.

Since the microphones are centered on the jet axis, for a distance r between the plate and the axis the phase difference between the microphones, for a compact dipole, is given as

$$\Delta\psi = -\pi + 4\pi \mathrm{St} M \frac{r}{D}. \qquad (1)$$

This phase characteristic is compared with the experimentally-determined phase in figure 8. The straight dashed lines show the model. For $r/D = 1.5$ and $r/D = 2$ the result is as one would expect: close agreement is observed between the modelled and measured phase over a frequency range that corresponds to the sideline amplification. A curious result is obtained for $r/D = 1$ however: the agreement extends to St=1.5. On closer examination of the coherence (figure 7) it can be seen that while the coherence is very low over this frequency range, in the case of $r/D = 1$ it is not exactly zero. Our working hypothesis with regard to this result is as follows. As seen above, in figure 2, at $r/D = 1$ the jet grazes the plate. This means that a boundary layer is created over a limited plate span, and vorticity is consequently shed from the trailing edge. While the range

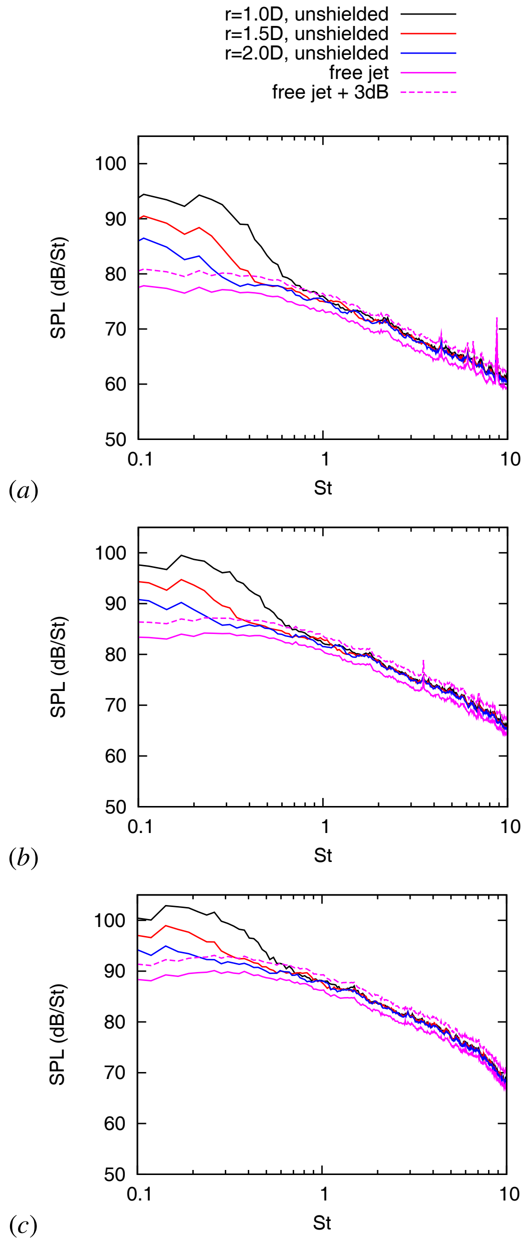

Figure 6: Effect of distance between the plate and the jet centerline on sound radiation for the $M = 0.4$ (*a*), $M = 0.5$ (*b*) and $M = 0.6$ (*c*) jets

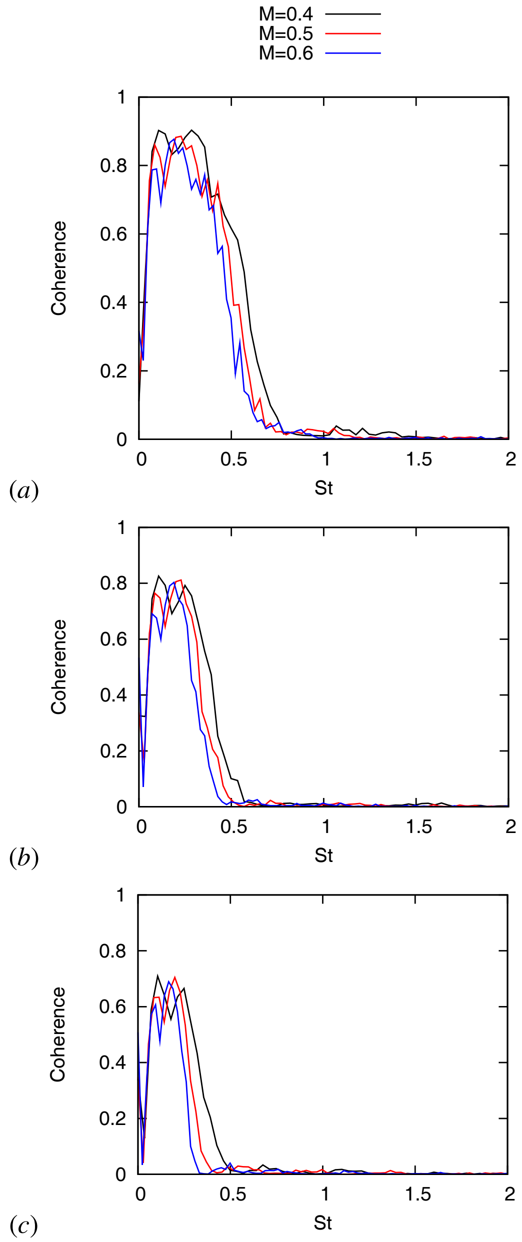

Figure 7: Coherence between the two diametrically-opposed microphones for $r/D = 1$ (*a*), $r/D = 1.5$ (*b*) & $r/D = 2$ (*c*).

of flow scales implicated in the scattering of the irrotational, hydrodynamic nearfield by the plate is limited because only the lowest frequencies find themselves within a wavelength of the plate, the boundary layer that results when the jet grazes the plate will comprise a broad range of turbulence scales: a weak broadband edge dipole will therefore result when these are scattered by the trailing edge, leading to the phase signature observed in figure 8.

5 A model for sound radiation by a jet close to a flat plate

Finally, the sound field is studied theoretically by means of a tailored Green's function accounting for scattering by a semi-infinite plate of vanishing thickness (Macdonald[6], Ffowcs Williams & Hall[3]). At present some preliminary computations have been performed using a compact, axially-aligned quadrupole located at $x/D = 5.5$, $r/D = 1$. The results, shown in figure 9, show how large sideline amplification results when the quadrupole is scattered by the trailing edge. Modelling of the sound source as wavepackets, which were detected previously in free jets and were seen to drive the near pressure field[9, 4] appears thus promising. Further modelling work based on wave-packet models developped for the free-jet case[1, 8], but with the tailored Green's function to account for scattering by the plate, is underway.

6 Conclusion and perspectives

Experiments have been performed to explore the mechanisms involved in sound generation when a turbulent jet is situated in close proximity to a flat plate. The experiment constitutes a simplified representation of jet-wing interaction of concern to aircraft manufacturers. Preliminary results support the hypothesis that large sideline

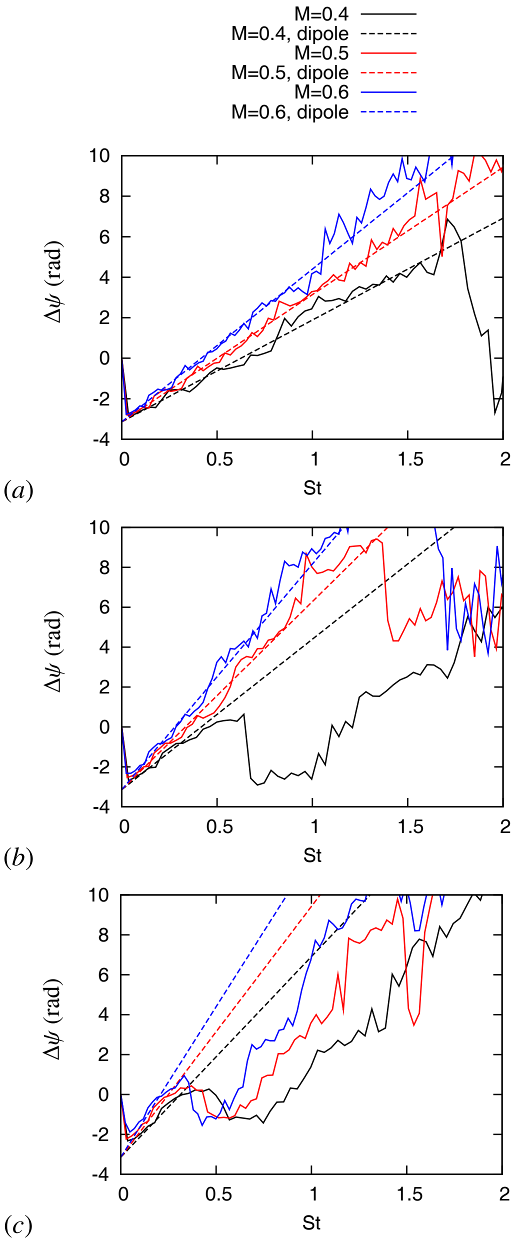

Figure 8: Phase difference between the two microphones for $r/D = 1$ (a), $r/D = 1.5$ (b) and $r/D = 2$ (c).

amplifications are essentially due to the scattering of the irrotational, hydrodynamic nearfield of the jet by the trailing edge. The signature of a further mechanism, which we postulate to be associated with the shedding of vorticity from the edge when the jet grazes the plate is observed. A model, based on the tailored Green's function for a semi-infinite plate, predicts the sideline amplifications. Since wave-packets of low azimuthal modes are known to dominate the near pressure field of free jets, further modelling work to study scattering of wave-packet sources appears thus promising.

Acknowledgments

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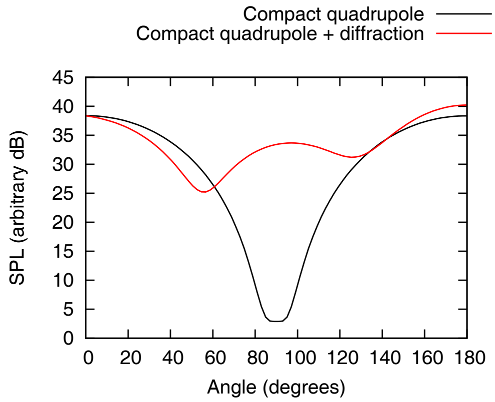

Figure 9: Sound radiation by a compact quadrupole at free space and in the presence of a semi-infinite flat plate.

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