INTERACTION OF ACOUSTIC EXCITATION WITH A PASSIVE RING IN AN AXISYMMETRIC JET

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ABSTRACT

Although the application to jet flows of both acoustic excitation and passive control methods has been studied extensively, the interaction between the two however has received little attention. In this study the interaction between acoustic excitation and a passive ring is investigated experimentally in a circular jet.

Several significant acoustic excitation modes have been identified, but in this study we concentrate on two modes namely the jet column mode of stable pairing ($St_D = 0.85$) and the preferred mode ($St_D = 0.36$ for the jet facility used). The jet column mode of stable pairing has been identified as promoting the formation and subsequent pairing of vortex rings which in turn leads to an enhancement in large scale transport. The preferred mode is significant as it corresponds to the most dominant and frequently occurring large-scale structures in the unperturbed circular jet (Hussain and Zaman 1981). A thin wire ring with an outer diameter slightly less than that of the nozzle is placed concentric to and a short distance downstream of the nozzle exit is used for passive control.

The introduction of the ring reduces turbulence levels and mixing layer growth rate for both modes of excitation. The ring effectively suppresses the stable pairing mode eliminating vortex pairing and dramatically altering near field development.

INTRODUCTION

Combining active and passive control methods in jet flows is an area that has received little attention but has the potential to yield significant results in terms of both practical applications and an increased understanding of the mechanisms that govern turbulence development in jet flows.

Longmire and Duong (1996) combined axial forcing with sawtooth and stepped nozzle trailing edges to control the development of an axisymmetric jet. Through appropriate selection of trailing edge geometry, forcing frequency and amplitude a bifurcation of the jet could be obtained.

A study combining axial forcing with inclined nozzle geometry by Webster and Longmire (1997), showed that the modest increases in jet spread rate obtained, in one plane could be substantially increased by the application of axial forcing.

In this paper we investigate the effect of a thin wire ring positioned concentric to and a short distance downstream of the nozzle exit on an axisymmetric jet subject to axial forcing. The use of the thin wire ring was first presented in Tong and Warhaft (1994) and was shown to be effective in suppressing the formation and subsequent pairing of vortices in the initial region resulting in the reduced turbulence levels and spread rate. The jet column mode of stable pairing has been identified as the pairing of thick vortex rings at $x/D \approx 1.75$ (Zaman and Hussain 1980) and shown to be independent of shear layer momentum thickness or even if the initial boundary layer is laminar or turbulent. The large jet column mode structures arising from pairing produce greater large scale transports of heat, mass and momentum but produce less noise than those arising from shear layer mode structures as their larger size produces less rapid changes in the velocity of vortical fluid (Husain et al. 1987). The suppression of jet column structures has proved difficult due to their independence from initial conditions.

The use of axial forcing at the preferred mode frequency has received significant attention. Crow and Champagne (1971) identified the preferred mode for an axisymmetric jet to be obtained at $St_D = 0.3$, based on the most amplified frequency measured on the jet centreline at $x/D = 4$. Subsequent work by Zaman and Hussain (1980) used a variation of this approach identifying the preferred mode by the maximum amplification of centreline velocity fluctuations, independently of x/D. They found the preferred mode St_D to correspond closely with the results of Crow and Champagne in several jets with a variety of initial conditions and observed a tendency for St_D to increase with decreasing Re_D.

EXPERIMENTAL PROCEDURE

Experiments were carried out using a 20.5mm axisymmetric jet operating in air with an exit velocity of 10m/s ($Re_D = 13300$). Air is supplied to the nozzle from two centrifugal fans operating in parallel driven by a single D.C. motor. Varying the motor supply voltage controls jet exit velocity up to a maximum of 23m/s, allowing all hotwire calibration to be performed in the potential core of the jet.

The ring was constructed of 0.5mm diameter wire with an overall outer diameter of 20mm and was mounted on a single sting orthogonal to the measuring plane.

Hot wire measurement on the jet centreline were carried out using a 2.5μm hot wire probe with an etched length of 0.5mm operated at an overheat ratio of 1.5. Detailed mapping of the near field of the jet was performed using a 2.5μm X-wire probe with etched lengths of 0.5mm and a wire separation of 0.5mm operated at an overheat ratio of 1.5.

Probe positioning was accomplished using an automated XY traverse under computer control with a minimum step size of 0.02 mm. Excitation waveforms were generated using a PC30 A to D card and software developed in-house. Amplification of the excitation signal to obtain the required amplitude and power was accomplished using an audio amplifier.

Simultaneous sampling of hot wire signals as well as excitation voltage was performed to allow the use of phase locked averaging techniques to decompose velocity signals into coherent and incoherent components as well as identify coherent structures in the initial jet region. Where vortex pairing was present, the signal from an additional single wire probe at a fixed position downstream of the pairing location was also recorded and used in the phase locked averaging calculations.

Initial measurements were performed on the jet facility to establish the relationship between excitation frequency and voltage and the resulting level of velocity fluctuations. The excitation level used throughout this study is 2% i.e. $u'/\overline{U} = 0.02$.

RESULTS AND DISCUSSION

Centreline development

The effect on centreline development of the introduction of the ring in the absence of excitation is shown in Figure 1 for comparison with the excited cases. The introduction of the ring leads to a reduction in the peak value of u' by 22% and a downstream shift in the location of the peak value from x/D = 7 to x/D = 9. From the distribution of U_C it is clear that the presence of the passive ring also results in an extension of the jet potential core.

For the preferred mode case (Figure 2) introducing the ring reduces the peak value of u' by 35%. The double peak characteristic in u' is still evident but the upstream peak is reduced by the full 35% whereas its location (x/D = 3) was unaltered. The downstream peak in u' shows only a small reduction in magnitude (14%). Its location is however shifted downstream from x/D = 7.5 to x/D = 8.

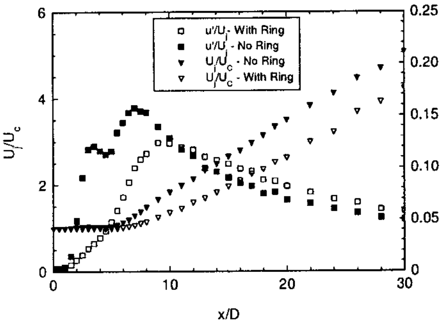

Figure 1 Centreline distribution of u' and U_C, with and without ring. No excitation.

Phase lock averaging techniques were used to quantify the contribution of the coherent ($\tilde{u}$) and incoherent ($\hat{u}$) components of turbulence on the jet centreline with (Figure 4) and without the ring (Figure 3). It is clear that with or without the ring the upstream peak in the turbulence intensity is dominated by the contribution of the coherent fluctuations, at the excitation frequency, and the contribution of the incoherent fluctuations dominates the downstream peak. The contribution of the coherent fluctuations declines more rapidly after the upstream peak in the absence of the ring than with the ring present. All these trends for the coherent component of turbulence are in good agreement with those observed from the spectra. As in the case of the spectra, the phase locked averages revealed no significant contribution from the sub-harmonic (i.e. f/2) at any location on the jet centreline for the preferred mode. Spectra at various x/D locations (Figure 5) reveal that with or without the ring the dominant frequency present near the upstream peak is the excitation frequency ($St_D = 0.36$) and at the downstream peak no dominant frequency is evident. It is also clear from the spectra that, while the maximum contribution of the excitation frequency to turbulence levels is greatly reduced by the introduction of the ring, its contribution is sustained further downstream when the is ring present.

These results tend to indicate that the presence of the passive ring weakens the coherent structures formed at the preferred mode frequency although the influence of these structures persists further downstream.

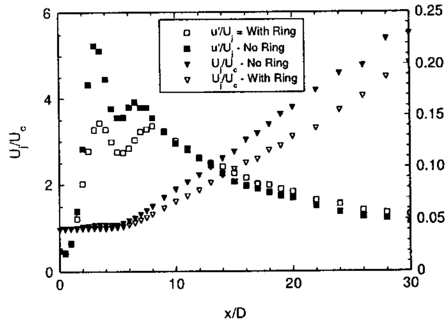

Figure 2 Centreline distribution of u' and U, with and without ring. 2% excitation at $St_D = 0.36$.

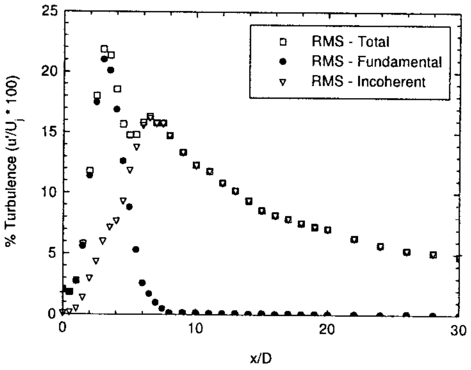

Figure 3 Phase lock averaged turbulence intensity on jet centreline, with 2% excitation at $St_D = 0.36$ (without passive ring)

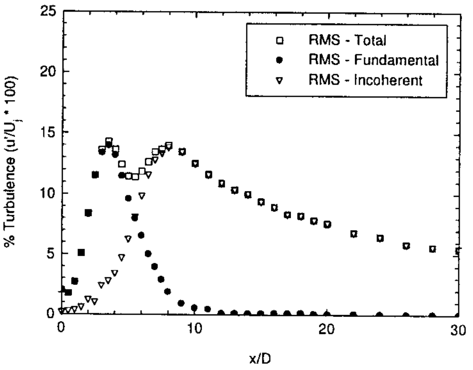

Figure 4 Phase lock averaged turbulence intensity on jet centreline, with 2% excitation at $St_D = 0.36$ (with passive ring)

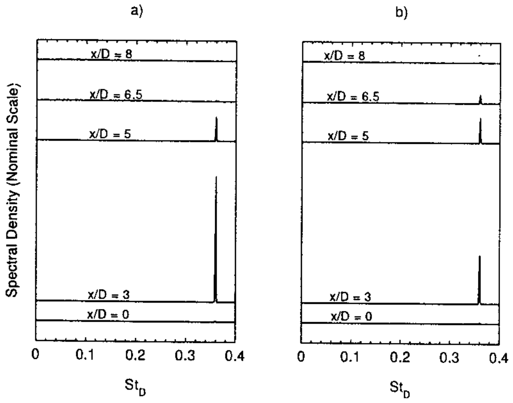

Figure 5 Spectral density on jet centreline a) without ring and b) with ring, with 2% excitation at $St_D = 0.36$.

For the jet column mode of stable pairing ($St_D = 0.85$), the introduction of the ring has a far more dramatic effect on the distribution of turbulence intensity (Figure 6) than was the case for the preferred mode. The upstream peak in the distribution is completely eliminated with a reduction in turbulence intensity at this location (x/D = 2.5) of 84%. The magnitude of the downstream peak is also reduced, though only by 10 %, and it location shifted slightly upstream from x/D = 8.0 to x/D = 7.5.

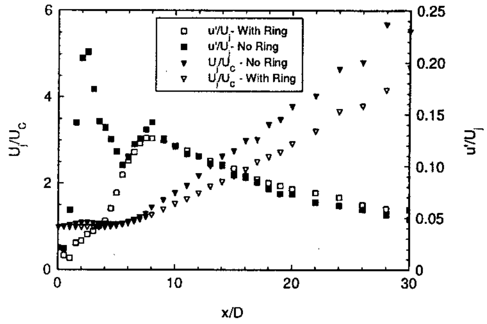

Figure 6 Centreline turbulence intensity distribution, with and without ring, with 2% excitation at $St_D = 0.85$.

Phase locked averaging of turbulent fluctuations reveals that in the absence of the passive ring (Figure 7) the upstream peak in turbulence intensity is dominated by the first sub-harmonic of the excitation frequency, with only a small contribution from fluctuations at the excitation frequency which peaks slightly upstream of both the peaks at the sub-harmonic frequency and the overall turbulence intensity.

The introduction of the passive ring dramatically alters the nature of the velocity fluctuations (Figure 8) with the disappearance of the upstream peak in overall turbulence intensity corresponding to the absence of fluctuations at the first sub-harmonic of the excitation frequency.

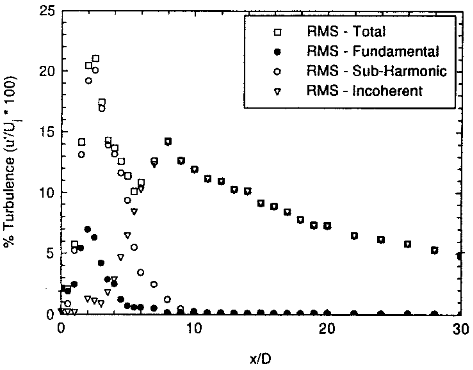

Figure 7 Phase lock averaged turbulence intensity on jet centreline, with 2% excitation at $St_D = 0.85$ (without passive ring)

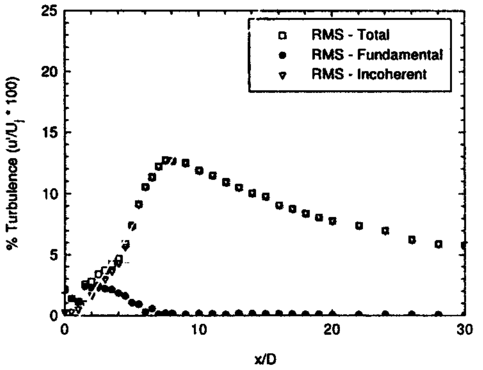

Figure 8 Centreline turbulence intensity distribution, with and without ring, with 2% excitation at St_D = 0.85.

Observations of spectra at various locations along the jet centreline confirm that, in the absence of the ring the dominant frequency in the upstream peak is the first sub-harmonic of the excitation frequency (f/2). There is a much smaller, though still significant, contribution at the excitation frequency. The introduction of the ring leads to a dramatic change in the evolution of the spectra, with no significant contribution at any sub-harmonic of the excitation frequency anywhere on the axis.

These results indicate that while excitation at this frequency still produces coherent structures with the passive ring in place, these structures are weaker and do not undergo pairing which normally characterises this mode of excitation.

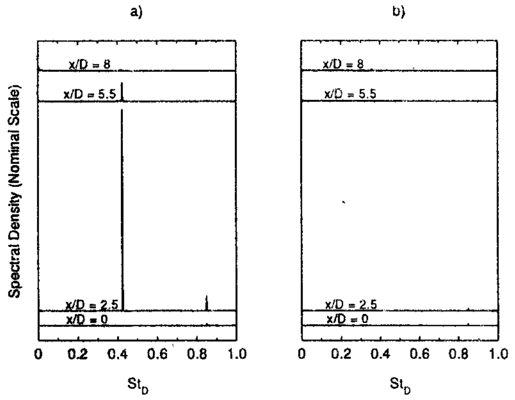

Figure 9 Spectral density on jet centreline a) without ring and b) with ring, with 2% excitation at St_D = 0.85.

Mixing Layer Development

Figure 10 shows the effect of introducing the ring to the flow when excited in the stable pairing mode. The upper profiles show the development of mean velocity in the absence of the passive ring and it is apparent that the presence of pairing events results in a non-linear mixing layer growth. With the introduction of the ring the mixing layer growth becomes much more linear.

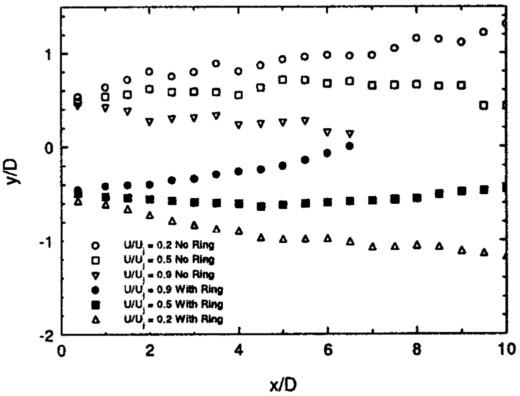

Figure 10 Mean U profiles, with (bottom) and without (top) passive ring, 2% excitation at St_D = 0.85

Excitation at St_D = 0.85 without the ring results in stable pairing of vortices, occurring at approx x/D ≈ 2. Figures 11–14 show the evolution of vorticity through two excitation cycles. Figure 15 shows a typical vorticity distribution for the same excitation conditions with the ring in place. It is clear that the presence of the ring results in a reduction in the strength of vortices and an absence of pairing. These distributions were derived from phase lock averaged velocity distributions measured using an X-wire probe on a grid of 744 points covering the plotted area. The phase angles (θ) shown are relative to the last positive zero crossing of the excitation signal prior to the start of the sequence, which repeats every two excitation cycles (720^0). The vorticity contours used in Figure 11figures 11-15 are 1500, 2000, 3000, 4000, 5000 and 6000.

The evolution of vortical structures with excitation at the preferred mode exhibits a far less dramatic modification due to the introduction of the ring. As was the case with the stable pairing mode, the vortices formed at the fundamental frequency are less intense. As vortices formed under this excitation regime do not undergo pairing the introduction of the ring does not change the underlying nature of their development unlike the case of the stable pairing mode.

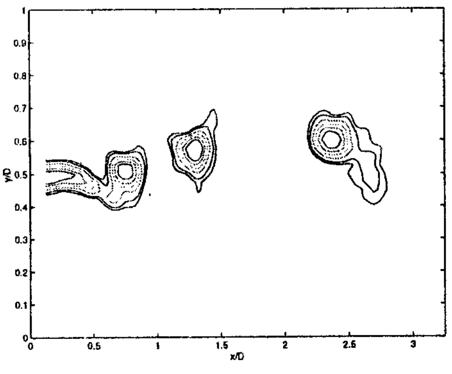

Figure 11. Mixing layer vorticity, 2% excitation at St_D = 0.85, No ring, θ = 83^0

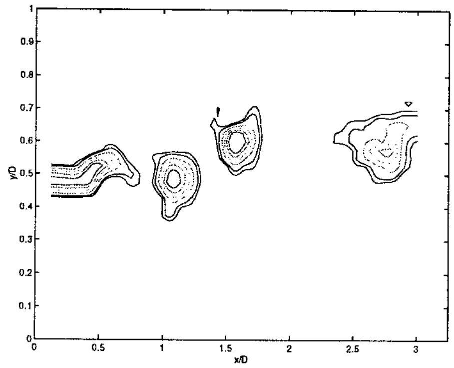

Figure 12. Mixing layer vorticity, 2% excitation at St_D = 0.85, No ring, $\theta = 263^0$

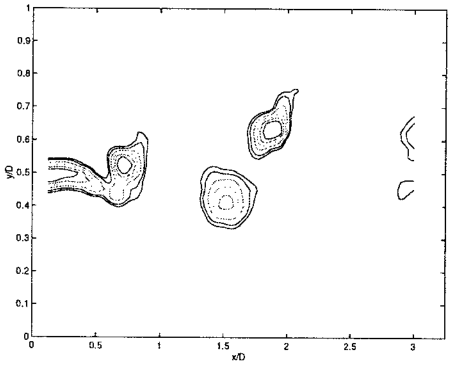

Figure 13. Mixing layer vorticity, 2% excitation at St_D = 0.85, No ring, $\theta = 443^0$

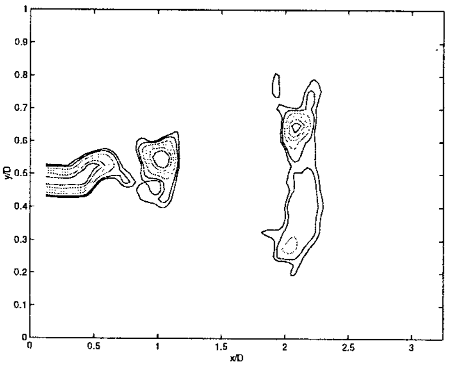

Figure 14. Mixing layer vorticity, 2% excitation at St_D = 0.85, No ring, $\theta = 623^0$

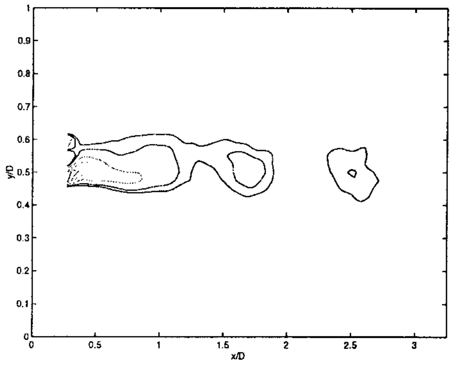

Figure 15. Mixing layer vorticity, 2% excitation at St_D = 0.85, with ring

Figures 16 and 17 show the effect of introducing the ring on the evolution of mean velocity in the mixing layer for the jet column mode of stable pairing and the preferred mode respectively. In both cases the ring produces an initial increase in mixing layer thickness but a reduced rate of growth particularly on the high-speed side of the layer. This is consistent with the increase in the length of the potential core that is apparent in the distribution of centreline velocity. The sudden increase in mixing layer thickness associated with vortex pairing in the stable pairing mode disappears with the introduction of the passive ring.

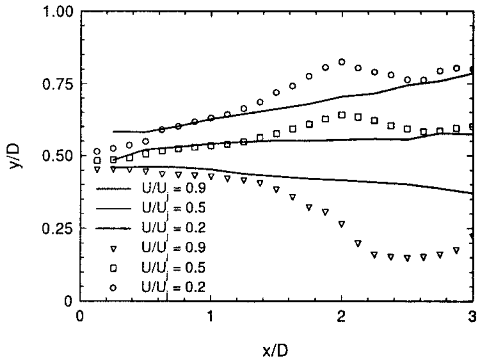

Figure 16. Mixing layer mean velocity (U) distribution, 2% excitation at St_D = 0.85, with ring (solid lines) without ring (symbols)

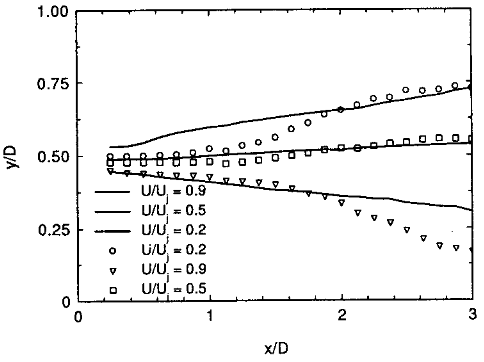

Figure 17. Mixing layer mean velocity (U) distribution, 2% excitation at St_D = 0.36, with ring (solid lines) without ring (symbols)

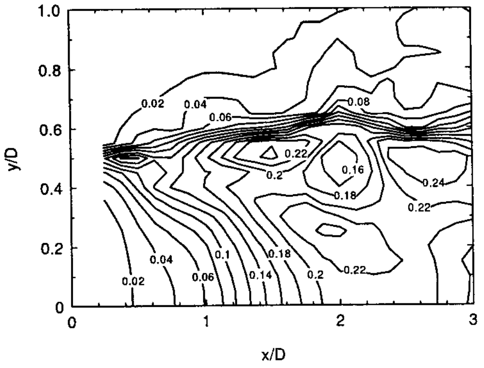

Figure 18. Distribution of u' /Uj 2% excitation at St_D = 0.85, no passive ring

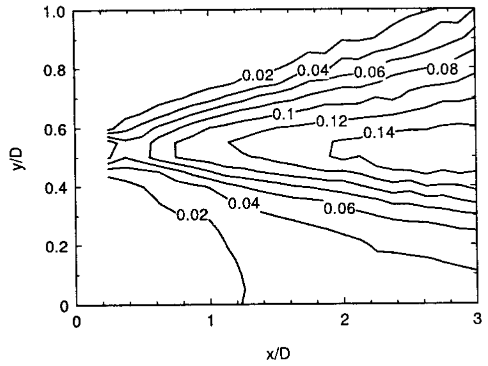

Figure 19 Distribution of u' /Uj 2% excitation at St_D = 0.85, with passive ring

Figure 18 shows the distribution of u'/Uj in the mixing layer when the jet is excited in the stable pairing mode in the absence of the ring. Figure 19 shows the distribution of u'/Uj for the same excitation conditions with the passive ring in place. It is clear that the introduction of the ring leads to a substantial decrease in the levels of turbulence at almost all locations in the mixing layer as the nature of the distribution is quite different for the two cases.

For the preferred mode case substantial decreases in turbulence levels are also obtained but the nature of the distribution is not altered significantly.

CONCLUSIONS

The results indicate that there is a strong interaction between the ring and the acoustic excitation at the jet column mode of stable pairing. The ring reduces the intensity of vortices produced at the fundamental frequency and eliminates the previously stable pairing of these vortices. This produces a dramatic reduction in mixing layer turbulence intensity and growth rate. The ring effectively suppresses this mode of coherent structures .The interaction between the ring and excitation at the jet preferred mode does not produce a dramatic change in the nature of the evolution of vortices in the mixing layer but significantly reduces the intensity of these structures which results in reduced levels of turbulence and mixing layer growth rate.

These results suggest that the passive ring is an effective tool in suppressing the formation of large coherent structures and could find useful applications in the suppression of noise generated by structures in these and possibly other modes.

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