111-02

25616
P-8

NASA Technical Memorandum 104483

Control of an Axisymmetric Turbulent Jet by Multi-Modal Excitation

Ganesh Raman
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

Edward J. Rice
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

and

Eli Reshotko
Case Western Reserve University
Cleveland, Ohio

Prepared for the
Eighth Symposium on Turbulent Shear Flows
sponsored by the Turbulent Shear Flow Committee
Munich, Germany, September 9-11, 1991

111 02
25616
P-8

NASA Technical Memorandum 104483

Control of an Axisymmetric Turbulent Jet by Multi-Modal Excitation

Ganesh Raman
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

Edward J. Rice
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

and

Eli Reshotko
Case Western Reserve University
Cleveland, Ohio

Prepared for the
Eighth Symposium on Turbulent Shear Flows
sponsored by the Turbulent Shear Flow Committee
Munich, Germany, September 9-11, 1991

NASA

CONTROL OF AN AXISYMMETRIC TURBULENT JET BY MULTI-MODAL EXCITATION

Ganesh Raman
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Edward J. Rice
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Eli Reshotko
Case Western Reserve University
Cleveland, Ohio 44106

ABSTRACT

Experimental measurements of naturally occurring instability modes in the axisymmetric shear layer of a high Reynolds number turbulent jet are presented. The region up to the end of the potential core was dominated by the axisymmetric mode. The azimuthal modes dominated only downstream of the potential core region. The energy content of the higher order modes ($m > 1$) was significantly lower than that of the axisymmetric and $m = \pm 1$ modes. Under optimum conditions, two-frequency excitation (both at $m = 0$) was more effective than single frequency excitation (at $m = 0$) for jet spreading enhancement. An extended region of the jet was controlled by forcing combinations of both axisymmetric ($m = 0$) and helical modes ($m = \pm 1$). Higher spreading rates were obtained when multi-modal forcing was applied.

INTRODUCTION

The study of the fundamental aspects of natural jets as well as their excitability and control is of great practical importance and shows promise for enhancing mixing, controlling separation and reducing jet noise.

Although a vast body of data exists, most of the observations have been made in idealized "clean" jet flows. There is a need for studying these phenomena in jets that are more representative of industrial applications, i.e., high Reynolds number, fully turbulent initial condition, and high core turbulence. In addition, the focus needs to be at and beyond the potential core. Such an understanding is essential if any further progress is to be made in the application of these techniques to technologically relevant situations.

In a jet excited by naturally occurring disturbances, the large scale coherent structures occur over a band of frequencies and over various azimuthal mode numbers. The nature of these structures has frequently been characterized using correlation functions (Drubka, 1981; Sreenivasan, 1984; Chan, 1977; Gutmark et al., 1988). Correlations of streamwise velocity with circumferential separation can indicate the relative dominance of the axisymmetric or the azimuthal waves. For example, the correlations are independent of circumferential separation if the flow consists of circular vortex rings. If the correlations show a circumferential dependence, they may be due to azimuthal waves developing on the circular vortex rings, or by a transverse flapping of the jet. The modal spectrum representation provides the capability of resolving the naturally occurring axisymmetric and azimuthal modes over a range of frequencies.

Sample mode spectra have been reported previously (Petersen et al., 1987) but have not been used to characterize the evolution of the various instability modes triggered by natural disturbances. Drubka (1981) examined the evolution of modes in an unexcited jet for both laminar and turbulent exit conditions at various levels of core turbulence. However, most of the measurements reported were for $x/D < 1$ at a Reynolds number of 42,000. From the standpoint of practical applications there is a need to study the evolution of modes over an extended region of the jet and at more representative Reynolds numbers.

There have been several other investigations of instability modes in jets (Kusek et al., 1989; Corke et al., 1991). In these studies, a very low level of excitation was used to organize shear layer instabilities and to raise the large scale coherent structures over the background levels, in addition to providing a phase reference for the measurements. Even though the levels of excitation were of the same order as the naturally occurring fluctuations, the jet displayed different characteristics. For example, in the work of Corke et al., 1991, low amplitude acoustic excitation of the jet at the natural fundamental frequency of the axisymmetric mode suppressed the occurrence of the helical modes observed by Drubka, 1981, in the same jet facility. For this reason, it is necessary to document the evolution of natural instability modes without any acoustic excitation.

Cohen and Wygnanski (1987-a) calculated the natural evolution of disturbances in the axisymmetric mixing layer. Linear stability analysis was applied to a family of mean velocity profiles for the first seven azimuthal modes after assuming that the flow is inviscid and quasi-parallel. These calculations showed that at $x/D = 0.125$ the amplification rates of the first four azimuthal modes are almost indistinguishable from one another. As the mixing layer widens the relative importance of the azimuthal modes diminishes and at the end of the potential core, only the $m = 1$ and the $m = 0$ modes remain amplified. Their calculations reveal that at the end of the potential core, mode 1 emerged as the dominant instability. This was also predicted by Michalke and Hermann (1982) and Batchelor and Gill (1962), and reported by Mattingly and Chang (1974) and Zaman and Hussain (1984). It is suggested, therefore, that the $m = 1$ azimuthal mode is prevalent at the end of the potential core, and one expects this mode to control the evolution of the fully developed jet. However, the experimental evidence for the existence of spinning modes in high Reynolds number jets has been rather sketchy. Direct proof, through detailed measurements, has yet to substantiate these findings.

The degree of jet spreading offered by single frequency plane wave excitation may not seem attractive enough to pursue for practical applications. However, when the "preferred mode" frequency becomes neutrally stable, its subharmonic, which is then amplifying near its maximum rate, can be used to cause further mixing enhancement. The development of a subharmonic in a free shear layer has been observed by several researchers. An analysis was presented by Kelly (1967) which showed that there exists a mechanism for the generation of a subharmonic wave in the case of a flow with a hyperbolic tangent velocity profile. It was fer function associated with the system (amplifiers, cables, acoustic drivers, and tubes) caused the input phases and amplitudes to be different from those measured at the jet exit. The radial traversing ring is used to traverse 8 single or x-wires simultaneously in the radial direction.

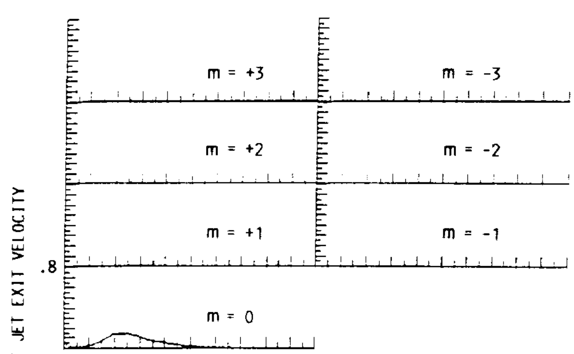
DISCUSSION OF RESULTS

Naturally Occurring Modes in a Jet

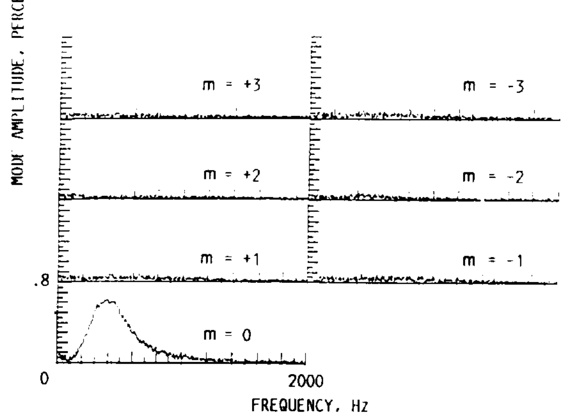
The modal decomposition representation at a discrete frequency of the spectrum can be used to characterize the flow as consisting of various modes of motion of the vortical structures at that frequency. The modal spectrum was determined by measuring the unsteady streamwise velocity using 8 hot-wires positioned at intervals of 45° about the circumference of the jet cross-section. Linearized signals from the hot-wires were input to a spectrum analyzer to obtain cross-spectra. The cross-spectra are randomly triggered ensemble averages over a long time interval. Using the signal from hot-wire number 1 as reference, 7 cross-spectrum magnitudes and phases were evaluated at each frequency with the 7 cross-spectra (magnitudes and phases) as input the magnitude and phase of the first 3 modes in the clockwise direction and the first 3 modes in the counter-clockwise direction were determined, by solving the 7 simultaneous complex equations. To generate the modal spectrum, the decomposition is performed at every frequency in the chosen range. The modal spectrum then consists of the amplitude of the mode plotted as a function of the frequency. The modal decomposition was performed at every 5 Hz up to 2000 Hz using 8 circumferential measurements providing the magnitude of modes $m = 0$, ±1, ±2, ±3 as a function of frequency.

Results will be shown for one case at $M = 0.2$ ($Re(D) = 400,000$), with a core turbulence intensity of 0.1% and a turbulent nozzle exit boundary layer. The data in Figure 2(a-d) show that the energy content of the higher order modes ($m > 1$) was significantly lower than the $m = 0$ and $m = \pm1$ modes. The initial region of the jet is dominated by the axisymmetric mode, whereas the region downstream of the potential core is dominated by helical modes. Drubka (1981) found that when the disturbance level in his laminar exit boundary layer was of the order of 5% the probability of finding either mode (0 or 1) was 0.5, near the nozzle exit ($x/D < 1$). The present work (Figure 2) shows that the axisymmetric mode is dominant in the initial region. But beyond the end of the potential core ($x/D \sim 6$) the helical modes dominate. The damping of the axisymmetric mode beyond the potential core is in agreement with the predictions of Batchelor and Gill (1962) and Morris (1976).

The stability analysis of Strange and Crighton (1983) predicted that helical waves would be more amplified than axisymmetric waves at the preferred frequency. Even though the helical modes have a higher growth rate (Raman (1991)), the initial region of the jet is dominated by the axisymmetric mode. This result is attributed to the type of natural disturbances occurring at the jet lip. For the 8.89 cm nozzle used, the cutoff frequency for all nonaxisymmetric modes was 2270 Hz (Skudrzyk (1971), page 431). Therefore, acoustic disturbances in the frequency range of 0 - 1000 Hz arriving at the jet lip through the nozzle are axisymmetric. Some of these disturbances are of a relatively high amplitude (due to plenum resonances) and they couple

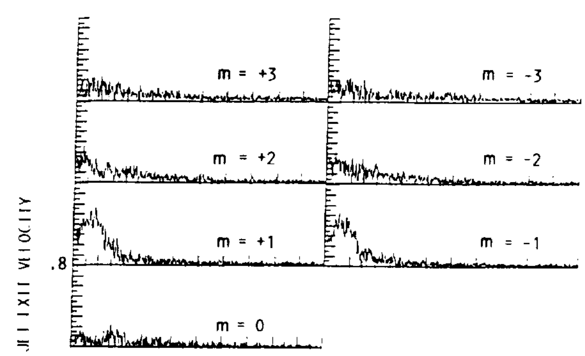


(a) x/D = 2.

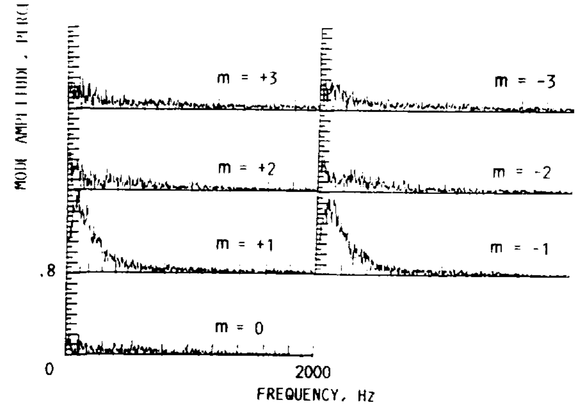


(b) x/D = 4.

Figure 2.—Axial evolution of the natural modes in a circular jet, turbulent initial boundary layer, velocity measurement at $U/U_{CL} = 0.8$, $M = 0.2$, $Re(D) = 400\ 000$.



(c) x/D = 6.



(d) x/D = 8.

Figure 2.—Concluded.

Multi-Modal Forcing

Based on the results presented thus far, plane wave ($m = 0$) excitation would be expected to be effective mainly in the region up to the end of the potential core, since beyond this point, the axisymmetric mode is damped. Control of the region beyond the potential core could be accomplished via the forcing of the helical modes. Hence, a combination of both plane wave and helical mode forcing would be expected to be even more effective for controlling the jet than either excitation applied alone. Results will be shown for one case at a Reynolds number of 400,000, with a core turbulence intensity of 0.1% and having a turbulent nozzle exit boundary layer.

Figure 5 shows the evolution of modes f or a forcing case: $m = \pm 1$ at $St(D) = 0.15$, and $m = 0$ at $St(D) = 0.6$. The forcing here is in the range of the naturally preferred frequencies determined from the modal spectrum for the unforced jet. The forcing levels measured at $U/U_C = 0.8$, $x/D = 0$ were $(\tilde{u}_0/U)_{St(D)=0.6,m=0} = 0.06$ and $(\tilde{u}_0/U)_{St(D)=0.15,m=\pm 1} = 0.02$. The modal decomposition technique used for generating these results is the same as that for the unexcited case. However, only the coherent part of the signal at the excitation frequency was used.

In the initial region, the axisymmetric mode ($m = 0$) grows to about 9 percent of the jet exit velocity. Note that the modes in Figure 5(a) are evolving in the presence of each other. Figure 5(a) shows that the $m = 0$ mode is amplified and saturates in the initial region of the jet. As the $m = 0$ mode becomes damped, the $m = \pm 1$ (combined and denoted by a single curve) grow and peak around $x/D = 6$, beyond which they are damped. Figure 5(b) shows the momentum thickness plotted versus axial distance.

Curves are shown for the following cases: unexcited, plane wave ($m = 0$ at $St(D) = 0.6$); helical modes ($m = \pm 1$, at $St(D) = 0.15$); and the multi-modal case ($m = 0$ at $St(D) = 0.6$ and $m = \pm 1$ at $St(D) = 0.15$). The last two cases are represented by bands bounded by $\theta_{\max}$ and $\theta_{\min}$ since θ varies azimuthally. Comparing Figures 5(a) and (b) one observes that the local regions of higher spreading rate (steeper curves in Figure 5(b) for x/D between 0 and 2, 4 and 6) correspond to regions of wave amplification in Figure 5(a), and local regions of lower spreading rate (flattening of curves in Figure 5(b), for x/D between 2 and 4, greater than 6) correspond to regions where the waves are damped. The jet's spreading rate is enhanced in a 2-step process. In step 1, due to $m = 0$ (x/D between 0 and 2), and in step 2, due to $m = \pm 1$ (x/D between 4 and 6). The above interpretation is also supported by the theory of Mankbadi and Liu (1981).

The low frequency helical modes along with the axisymmetric mode of the multi-modal case (Figure 5) are more effective in producing higher spreading rates in the downstream region ($5 < x/D < 10$). Therefore, the choice of the forcing frequencies would vary depending on the region over which maximum control is desired. From Figure 5 it is clear that the combination of a plane wave and two opposing helical modes provides a higher degree of control over the spreading rate of the jet than either excitation applied alone. The plane wave enhances spreading up to the end of the potential core, and helical modes ($m = \pm 1$) cause the jet to flap beyond the potential core.

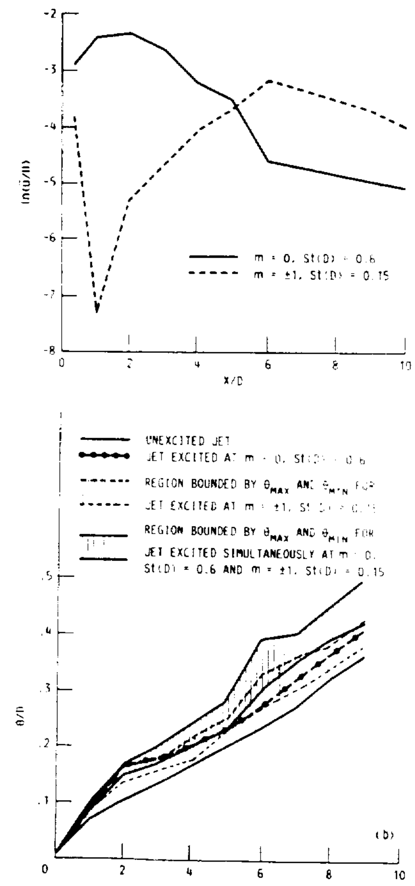


Figure 5.—Multi-modal excitation results (forcing levels, $\tilde{u}_0/U = 0.06$, ($St(D) = 0.6$, $m = 0$) ($\tilde{u}_0/U = 0.02$, ($St(D) = 0.15$, $m = \pm 1$)).

SUMMARY AND CONCLUSIONS

The overall objective was to study natural as well as excited jets under conditions more representative of practical applications, i.e. high Reynolds number and fully turbulent initial condition, with a focus at and beyond the potential core. The conclusions are as follows:

(1) The evolution of instabilities resulting from naturally occurring disturbances at the jet lip was studied using the modal frequency spectrum. The region up to the end of the potential core was dominated by the axisymmetric mode. The azimuthal modes grew rapidly but dominated only after the potential core region. For the jet excited by natural disturbances the energy content of the higher order modes ($m > 1$) was significantly lower than the axisymmetric and $m = \pm 1$ modes.

(2) Based on the results from the naturally occurring jet instability mode experiments, target modes for efficient excitation of the jet were determined. The effect of exciting a high Reynolds number, initially turbulent jet simultaneously at fundamental and subharmonic frequencies was studied. The initial phase difference between the two waves was varied in steps of 45°. The effect of varying the initial forcing levels was also studied. It was found that at high amplitudes of fundamental and subharmonic forcing levels, the subharmonic augmentation and the axial location of the peak are independent of the initial phase difference. This finding will have a very favorable impact on the design of practical excitation devices. Two-frequency excitation is indeed more effective than single frequency excitation in jet spreading enhancement. The spreading is quantified by:

ORIGINAL PAGE IS OF POOR QUALITY

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-104483	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Control of an Axisymmetric Turbulent Jet by Multi-Modal Excitation		5. Report Date
		6. Performing Organization Code
7. Author(s) Ganesh Raman, Edward J. Rice, and Eli Reshotko		8. Performing Organization Report No. E-6243
		10. Work Unit No. 505-62-52
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the Eighth Symposium on Turbulent Shear Flows sponsored by the Turbulent Shear Flow Committee, Munich, Germany, September 9-11, 1991. Ganesh Raman, Sverdrup Technology, Inc. Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142; Edward J. Rice, NASA Lewis Research Center; Eli Reshotko, Case Western Reserve University, Cleveland, Ohio 44106. Responsible person, Ganesh Raman, (216) 826-2277.

16. Abstract

Experimental measurements of naturally occurring instability modes in the axisymmetric shear layer of a high Reynolds number turbulent jet are presented. The region up to the end of the potential core was dominated by the axisymmetric mode. The azimuthal modes dominated only downstream of the potential core region. The energy content of the higher order modes ($m > 1$) was significantly lower than that of the axisymmetric and $m = \pm 1$ modes. Under optimum conditions, two-frequency excitation (both at $m = 0$) was more effective than single frequency excitation (at $m = 0$) for jet spreading enhancement. An extended region of the jet was controlled by forcing combinations of both axisymmetric ($m = 0$) and helical modes ($m = \pm 1$). Higher spreading rates were obtained when multi-modal forcing was applied.

17. Key Words (Suggested by Author(s)) Turbulent jets; Stability; Acoustic excitation	18. Distribution Statement Unclassified - Unlimited; Subject Category 02

19. Security Classif. (of the report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161