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Controlled Excitation of a Cold Turbulent Swirling Free Jet

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SUMMARY

Experimental results from acoustic excitation of a cold free turbulent jet with and without swirl are presented. A flow with a swirl number of 0.35 (i.e., moderate swirl) is excited internally by plane acoustic waves at a constant sound pressure level and at various frequencies. It is observed that the cold swirling jet is excitable by plane waves, and that the instability waves grow about 50 percent less in peak rms amplitude, and saturate further upstream compared to corresponding waves in a jet without swirl having the same axial mass flux. The preferred Strouhal number based on the mass-averaged axial velocity and nozzle exit diameter for both swirling and nonswirling flows is 0.4. So far no change in the mean velocity components of the swirling jet is observed as a result of excitation.

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INTRODUCTION

Aerodynamic excitation of axisymmetric jets has been under extensive theoretical and experimental investigation over the past decade. It is already understood that acoustic excitation at the "right" Strouhal number (f · D/U) has a significant effect on the mixing characteristics of shear layers, provided that the excitation amplitude is beyond a certain minimum "threshold" level.

The idea of a preferred mode of jet instability was first introduced by Crow and Champagne (1971). They showed that the entrainment volume flow, in an axisymmetric jet, could be increased by about 32 percent by acoustic excitation at Strouhal number of 0.3 based on nozzle exit diameter. Later Zaman and Hussain (1980 and 1981) showed that turbulent mixing, in a free circular jet, is enhanced at Strouhal number between 0.2 and 0.8 and is suppressed between 2 and 4. They also concluded that enhancement or suppression of turbulent mixing not only depends on the Strouhal number, but also is affected by the nature of the nozzle boundary layer (i.e., laminar, transitional, or turbulent).

Moore (1977) and Ahuja (1982) showed that the threshold level of the excitation acoustic pressure for effective turbulent mixing and a consequential jet noise amplification can be taken to be 0.08 percent of the jet dynamic head at the "correct" Strouhal number.

The objective of the present investigation is to obtain a basic understanding of the response of cold swirling turbulent free jets to acoustic excitation. To our knowledge, this is the first attempt to study the effect of excitation on a swirling jet. As a first step, a free swirling turbulent jet, with a swirl number of 0.35 is excited internally by plane acoustic waves and the results are compared with a similar jet without swirl. The mass flux is kept constant in the two cases. Only experimental results are presented in this paper and further studies are needed to understand the mechanism of interaction.

NOMENCLATURE

D	nozzle exit diameter, 3.50 in.
f	excitation frequency, Hz
G_x	axial momentum flux, $\equiv 2\pi \int_0^\infty (\rho U^2 + (P - P_\infty))\, r\, dr$
G_ϕ	angular momentum flux, $\equiv 2\pi \int_0^\infty \rho r^2 UW\, dr$
P_∞	ambient pressure
R	nozzle exit radius, 1.75 in.
r	radial distance from the jet centerline
S	swirl number, $\left(\equiv \frac{G_\phi}{G_x \cdot R}\right)$
St	Strouhal number, $\left(\equiv \frac{f \cdot D}{U_a}\right)$
U,V,W	time-mean axial, radial and tangential velocity components
u,v,w	fluctuating axial, radial and tangential velocity components
U_a	mass-averaged axial velocity at the nozzle exit
U_m, W_m	axial and tangential velocity maximum at the nozzle exit

U_x axial velocity component along the jet centerline

U_{xo} axial velocity component at the center of the nozzle exit

u_f fundamental rms amplitude

x axial distance from the nozzle exit plane along the jet centerline

EXPERIMENTAL FACILITY

Swirl Generator

Figure 1 is a schematic diagram of the test set-up. An existing cold jet facility at NASA Lewis Research Center was modified to generate flows at a wide range of swirl numbers. The principle of combining axial and tangential streams is applied for swirl generation. Axial air is introduced through an 8 in. (20.32 cm) pipe at the end of the plenum. Tangential air enters the plenum through 54 elbow nozzles mounted on three concentric circular rings as shown in figures 1 and 2. Specially designed perforated plates, restrictors and screens are inserted into the elbow nozzles to reduce the orifice noise generation. Swirl number can be adjusted by remote control valves which vary the proportion of axial to tangential air. The flow leaving the swirl generator passes through a bellmouth and an excitation section before discharging to the test cell through a 3.50 in. (8.89 cm) diameter nozzle. For more details regarding the swirl generator and test facility see reference 6.

Acoustic Excitation Section

Plane acoustic waves are generated by four acoustic drivers, positioned circumferentially around the adaptor ring, and operated in phase. The excitation section is located between the swirl generator and exit nozzle. Each driver is enclosed in a sealed can and vented to the nozzle inlet, to equalize pressure across the speaker diaphragm. Each driver has a rated power of 40 W over a frequency range between 500 and 20 000 Hz and is connected to an Altec Lansing 100 W power amplifier. Amplitude and frequency of the input signal to the four drivers can be selected by a Variphase tone generator.

INSTRUMENTATION

Mean-Flow Measurements

Three components of time mean velocity as well as static and total pressures are measured by a 5-hole pitot probe having a diameter of 0.125 in. (0.318 cm). The probe tip has a 45° cone angle and the pressure ports are located at the midspan of the conical surface. The 5-hole probe is self-nulling in the yaw angle, while the pitch angle, the time-mean velocity components and the pressures are computed from calibration curves.

Fluctuating Flow Measurements

The axial component of fluctuating velocity is measured along the jet centerline by standard hot-wire techniques employing linearized constant temperature anemometers. Along the jet axis, the tangential and radial velocity components are assumed to be negligible compared to axial component, and therefore the results from a single element hot-film probe are assumed to represent the actual axial velocity fluctuations. The fundamental rms amplitude at each streamwise location is obtained by analyzing the spectra of the hot film signal at the excitation frequency. Even though no cross correlation of velocity and noise fluctuation data was made, the amplitude of the fundamental wave was significantly above the background noise, which insured negligible contamination of the instability wave amplitude with the background turbulent noise. At the saturation point, for example, the amplitude of the fundamental wave was more than 10 dB above the background noise.

Sound Pressure Level Measurements

Excitation sound pressure level, at the center of the nozzle exit, is measured with a (B and K) microphone. The microphone has an outside diameter of 0.25 in. (0.635 cm) and is fitted with a nose cone. The sound pressure level in dB (re 2×10^{-5} N/m^2), at the excitation frequency, is obtained from the spectra of the microphone signal by a signal analyzer.

RESULTS

For both the swirling and nonswirling jets under investigation, the mass flow rate is held approximately constant at about 1.40 lb/sec (0.64 kg/sec). The swirling jet mass flow rate was measured with an orifice meter while that of the nonswirling jet was based on the area integral of the axial velocity profile at the nozzle exit. The Mach and Reynolds numbers based on mass-averaged axial velocity at the nozzle exit are 0.26 and 5.8×10^5 respectively. The swirling jet has a swirl number of 0.35 (see Nomenclature for swirl number definition).

The radial distributions of the time-mean axial velocity, measured at $x = 0.06$ D, for the swirling and nonswirling jets is plotted in figure 3. The form of the profile for the swirling jet deviates from the flat-top shape of the nonswirling jet as expected. The rapid expansion of the swirling jet is also noticeable in this figure. The time-mean tangential velocity distribution at $x = 0.06$ D for the swirling jet is shown in figure 4. The distribution is in the form of a Rankine-type vortex (combined free and forced vortex). The geometrical and the jet axis coincide from $x/D \approx 1.0$. The decay of time-mean axial velocity component along the jet centerline for both flows is plotted in figure 5. The length of potential core is about 4 diameters for the nonswirling jet. In the case of the swirling jet, the decay of the time-mean axial velocity starts from the nozzle exit.

To examine the effect of excitation on the swirling jet, and compare with the excited nonswirling jet, both flows are excited internally by plane acoustic waves upstream of the nozzle inlet. To isolate the effect of excitation frequency, the sound pressure level is kept constant at 126 dB for both jets at all excitation frequencies, measured at the center of the nozzle exit.

Figures 6 and 7 illustrate the growth of the instability waves triggered at different excitation frequencies for the nonswirling and swirling jets respectively. It is observed that the swirling jet under investigation as well as the nonswirling jet are excitable by plane acoustic waves. At equal excitation frequencies, the instability waves grow about 50 percent less in peak rms amplitude in the swirling jet as compared to the nonswirling jet. This difference is not unexpected as linear instability theory states that the stability of the free shear layers depends upon the detailed velocity distributions. Here we are dealing with two jets which are entirely different as far as velocity and pressure distributions are concerned. It is also expected that the growth of the instability waves should also depend upon the swirl number which affects the velocity and pressure distributions.

For the nonswirling jet, the location of the maximum growth of the instability waves is approximately at the end of the potential core ($x = 4.0$ D). This is in agreement with the observation in the literature that the axisymmetric disturbances achieve their peak amplitude near the end of the potential core (e.g. Ref. 4). For the swirling jet, the potential core does not exist and the maximum growth occurs at about $x = 2.5$ D. This location should also depend on swirl number.

The variation of the peak rms amplitude of the axial velocity fluctuations on the jet axis versus the Strouhal number ($St = f \cdot D/U_a$) is plotted in figure 8. From this figure it is observed that the maximum growth of the instability wave is measured at a Strouhal number of 0.4, based on mass-averaged axial velocity at the nozzle exit for both cases. This is in agreement with the results quoted in the literature for the nonswirling axisymmetric jets (ref. 7). For the swirling jets, the effect of swirl strength on the preferred Strouhal number requires further investigation.

Even though significant improvement in jet mixing, as a result of excitation, is measured in our facility for nonswirling jets (ref. 5), no change is observed in the mean velocity components of the swirling jet due to excitation. Two plausible explanations may be forwarded, namely: (1) the presence of strong static pressure gradients in the near field of a swirling jet (with moderate to strong swirl) overwhelms the turbulence-induced shear layer growth and (2) higher initial turbulence level of the swirling jet as compared to its nonswirling counterpart dampens the growth of the shear layer instability wave. The effect of core turbulence intensity on the mixing and excitability of an axisymmetric, nonswirling cold free jet is examined by Raman et al. (ref. 9) which supports our argument. External excitation by helical waves with a more powerful excitation device may be beneficial.

It should be noted that, as the swirl number exceeds the critical value of 0.60, a recirculating zone starts to develop and therefore a drastic change in the response due to excitation is expected.

CONCLUSIONS

The cold turbulent swirling free jet under investigation ($S = 0.35$) is found to be excitable by plane acoustic waves. At a constant excitation sound pressure level of 126 dB, the growth of the shear layer instability waves depends on the excitation frequency. These waves grow about 50 percent less in peak rms amplitude, and the downstream location of their maximum growth is further upstream for the swirling jet under investigation, compared to a non-swirling jet with the same axial mass flux. Maximum growth of instability waves is observed at Strouhal number of 0.4 for both swirling and nonswirling jets (based on mass-averaged axial velocity). In spite of the growth of instability waves, so far no change in the mixing of the swirling jet, as a result of excitation has been observed.

RECOMMENDATIONS FOR FUTURE WORK

From the results of this experiment, it seems that even though the instability waves grow in the swirling jet under investigation, no effect on jet mixing is noticed. The following improvements in the experimental facility may be beneficial:

(1) Moving the location of the acoustic drivers to the downstream of the nozzle exit (external excitation) which results in higher excitation amplitude and also allows helical mode of excitation.

(2) Using more powerful excitation devices.

The above improvements are being implemented in our jet facility and another series of excitation experiments will be conducted shortly.

We also intend to implement the following measurements in order to assess the swirling jet excitability more thoroughly:

(1) The rms amplitude based on <u>total</u> fluctuating velocity will be measured.

(2) Hot wire spectra to indicate the effect of excitation on broadband turbulence will be studied.

Of course, high initial turbulence levels, in the case of swirling jet, is another factor which reduces the effectiveness of excitation in improving the mixing rate. This problem remains unsolved because any attempt to reduce the turbulence level automatically reduces the swirl number as well.

REFERENCES

1. Ahuja, K.K., Lepicovsky, J., Tam, C.K.W., Morris, P.J. and Burrin, R.H., "Tone-Excited Jet, Theory and Experiments," NASA-CR 3538, 1982.

2. Crow, S.C. and Champagne, F.H., "Orderly Structure in Jet Turbulence," <u>Journal of Fluid Mechanics</u>, Vol. 48, Part 3, Aug. 16, 1971, pp. 547-591.

3. Moore, C.J., "The Role of Shear-Layer Instability Waves in Jet Exhaust Noise," <u>Journal of Fluid Mechanics</u>, Vol. 80, Part 2, Apr. 25, 1977, pp. 321-367.

4. Petersen, R.A. and Samet, M.M., "On the Preferred Mode of Jet Instability," to appear in Journal of Fluid Mechanics.

5. Raman, G., "Enhanced Mixing of an Axisymmetric Jet by Aerodynamic Excitation," NASA CR-175059, 1986.

6. Taghavi, R., "Experimental Investigation of Swirling Turbulent Jets," Ph.D. Thesis, University of Kansas, Oct. 1987.

7. Zaman, K.B.M.Q. and Hussain, A.K.M.F., "Vortex Pairing in a Circular Jet Under Controlled Excitation, General Jet Response," Journal of Fluid Mechanics, Vol. 101, Part 3, Dec. 11, 1980, pp. 449-491.

8. Zaman, K.B.M.Q. and Hussain, A.K.M.F., "Turbulence Suppression in Free Shear Flows by Controlled Excitation," Journal of Fluid Mechanics, Vol. 103, Feb. 1981, pp. 133-159.

9. Raman, G., Zaman, K.B.M.Q. and Rice, E.J., "Initial Turbulence Effect on Jet Evolution With and Without Tonal Excitation," AIAA Paper 87-2725, Oct. 1987.

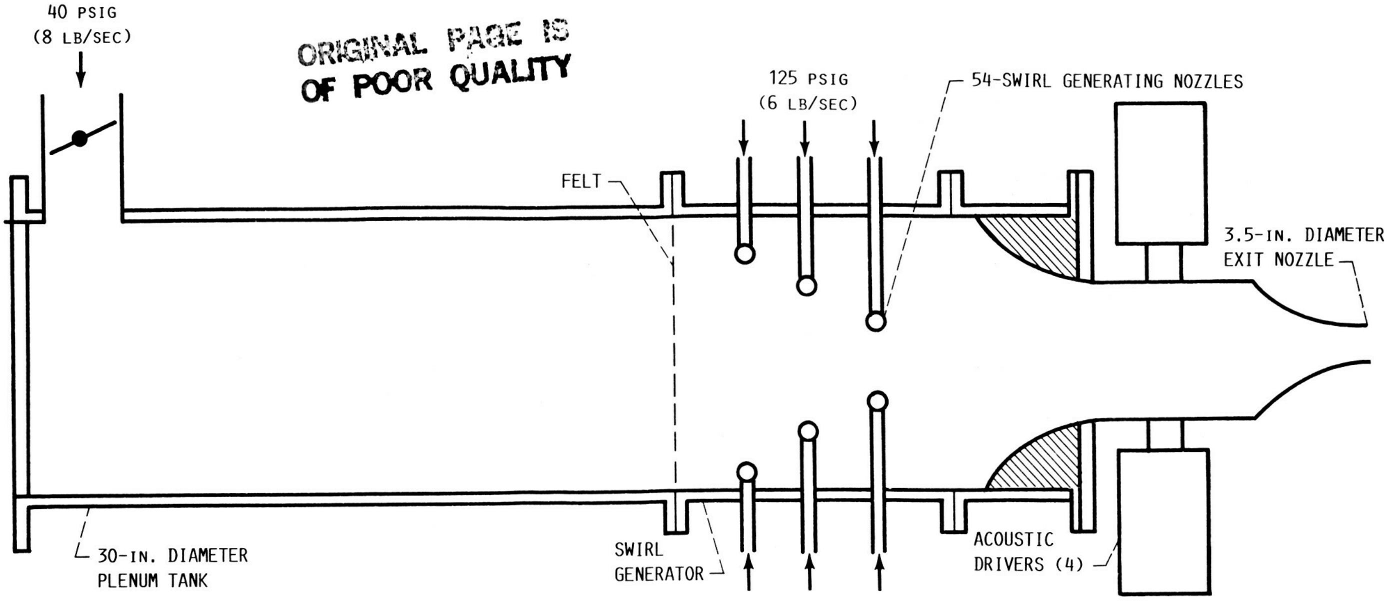

FIGURE 1. - SCHEMATIC DIAGRAM OF THE JET FACILITY.

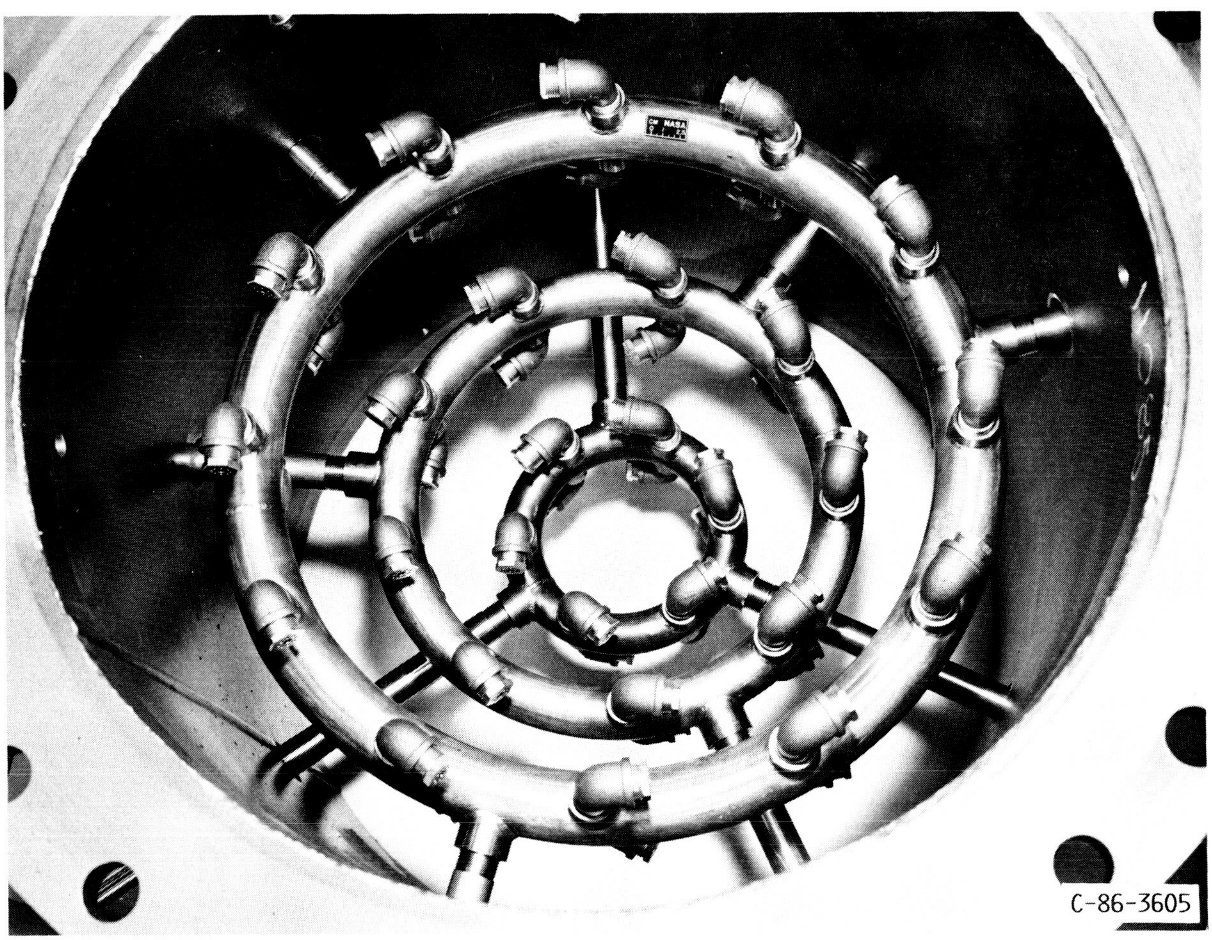

FIGURE 2. - SWIRL GENERATOR.

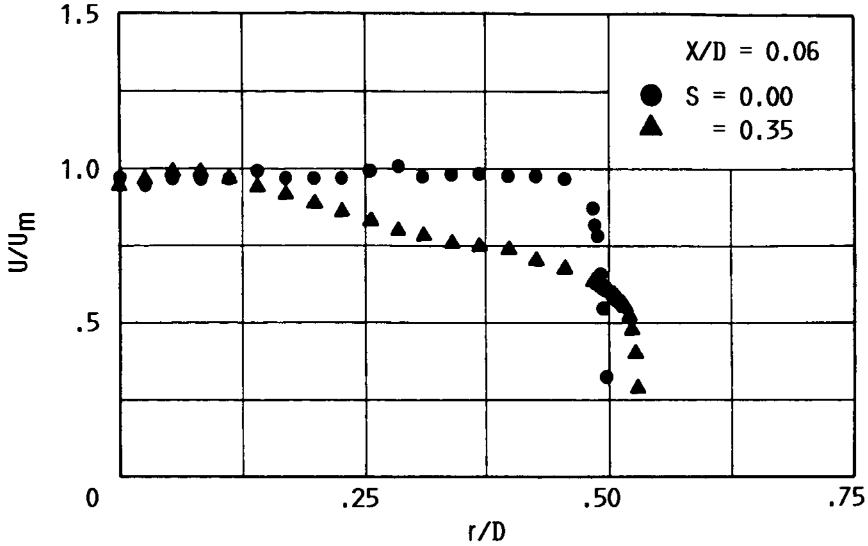

FIGURE 3. - RADIAL DISTRIBUTIONS OF MEAN AXIAL VELOCITIES.

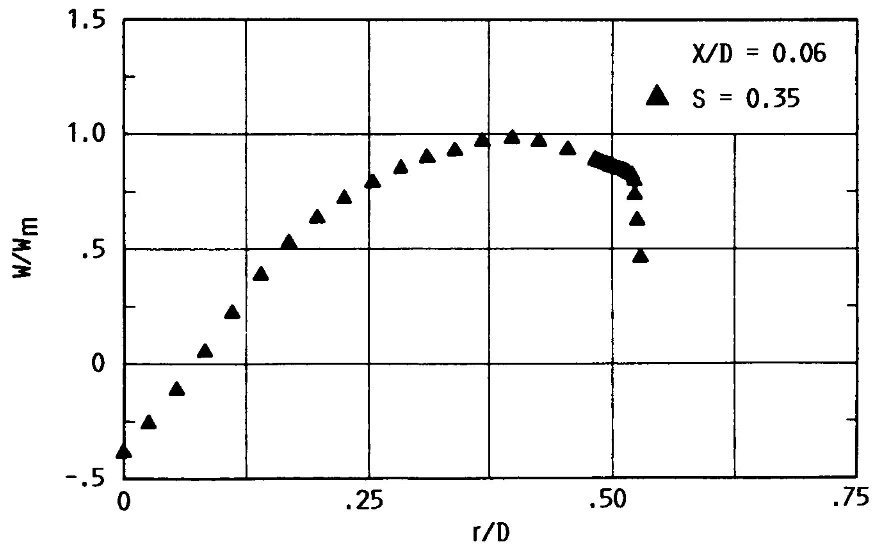

FIGURE 4. - RADIAL DISTRIBUTION OF MEAN TANGENTIAL VELOCITY.

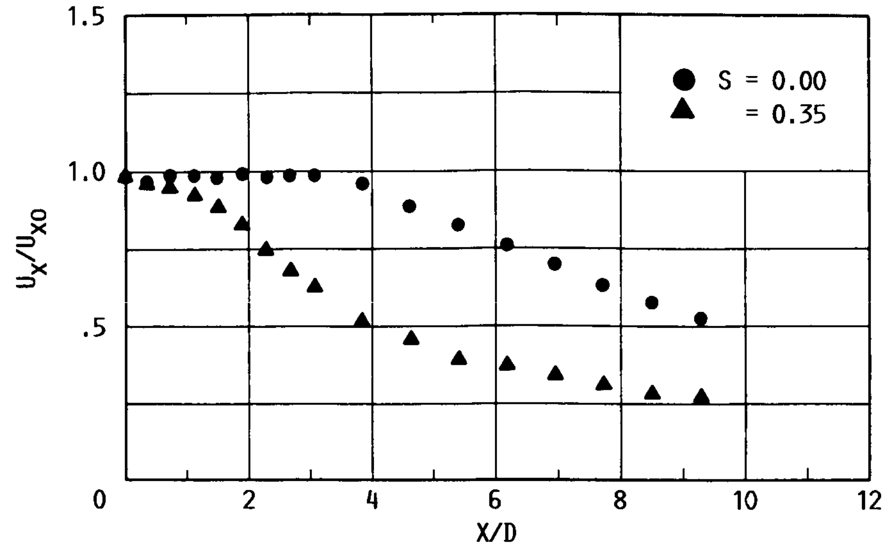

FIGURE 5. - DECAY OF MEAN AXIAL VELOCITIES ALONG THE JET AXIS.

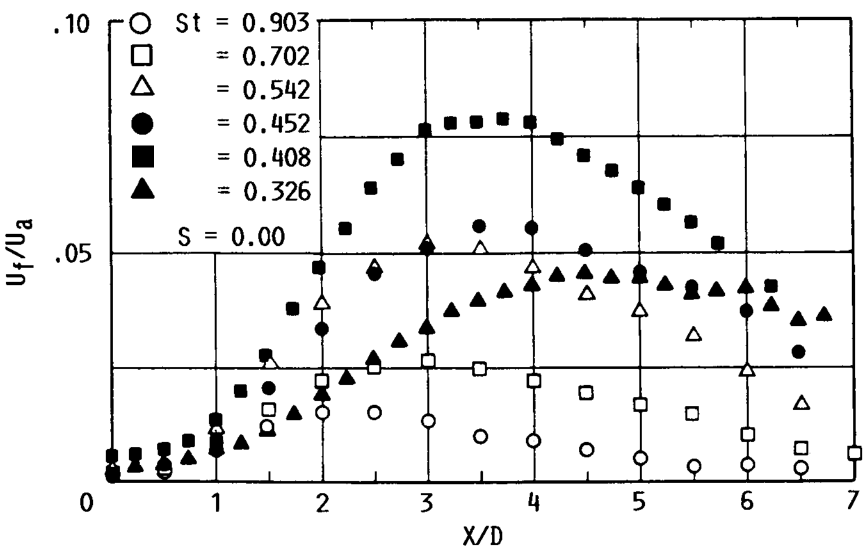

FIGURE 6. - VARIATION OF FUNDAMENTAL RMS AMPLITUDE ALONG THE JET AXIS.

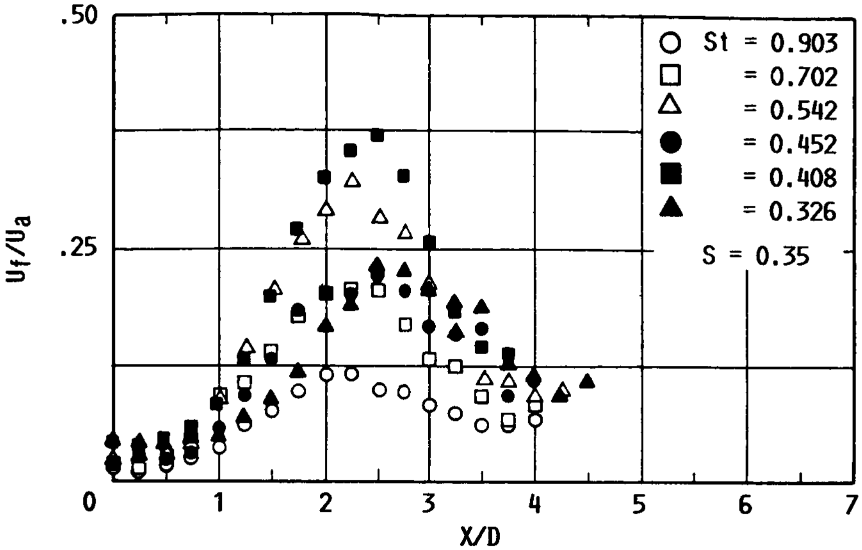

FIGURE 7. - VARIATION OF FUNDAMENTAL RMS AMPLITUDE ALONG THE JET AXIS.

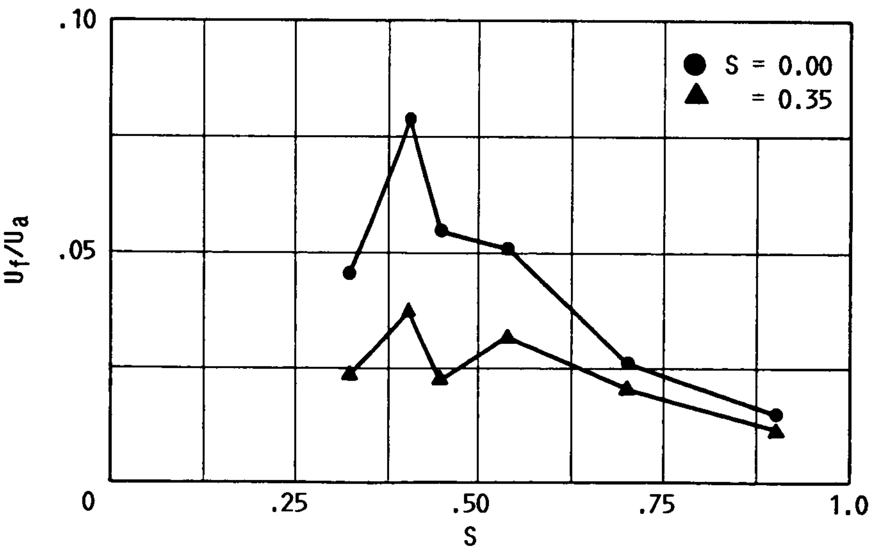

FIGURE 8. - VARIATION OF PEAK RMS AMPLITUDE OF THE FUNDAMENTAL WITH EXCITATION STROUHAL NUMBER.

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15. Supplementary Notes

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16. Abstract

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