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The behaviour of excited plane jets

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Abstract. A plane subsonic jet can be excited to entrain more fluid from its surroundings by subjecting it to antisymmetric periodic disturbances. The essential feature in this phenomenon is the rolling-up motion of an initially flapping jet to form large vortices which are responsible for greater entrainment. Several methods developed to impart oscillations to the flow at the nozzle, such as the acoustic pressure oscillator, the vibration of a single vane in the potential core region, the reciprocating lip system and the twin vane exciter, are described in this article. A minimum threshold in amplitude is necessary for exciting the flow. However, the frequency of oscillation is much less than that predicted by stability considerations.

Keywords. Jet; unsteady flows; vortex dynamics; jet excitation.

1. Introduction

The fluid dynamics of steady jets, plane as well as axisymmetric, has been the subject of intense study for the past few decades on account of its direct influence in the aerospace industry (Hinze 1981; Wygnanski & Fiedler 1969; Crow & Champagne 1971; Hussain & Clark 1977). One of the significant characteristics of a turbulent jet is its ability to entrain more fluid from its surroundings due to the shear inherently present in the flow. The induced flow even in the case of a steady jet is not smooth and continuous but is indented with large turbulence structures (figure 1) which exhibit a wavy motion along the outer edge of the flow (Townsend 1976). Though these large eddies are formed in a random fashion, they do follow a well-defined statistical pattern which enables us to describe the overall characteristics of the flow using a minimum number of parameters such as a velocity and a length scale for a given nozzle flow.

Crow & Champagne (1971) observed that the large eddies in a round jet could be energized in a selective manner by imposing disturbances at some definite frequencies. Their pioneering work initiated further activity in jet excitation. Since the eddies play a major role in the production of noise, selective modification of the large-scale turbulence structures can be usefully employed for altering the radiating noise pattern. Recently, this subject has evoked further interest due to its

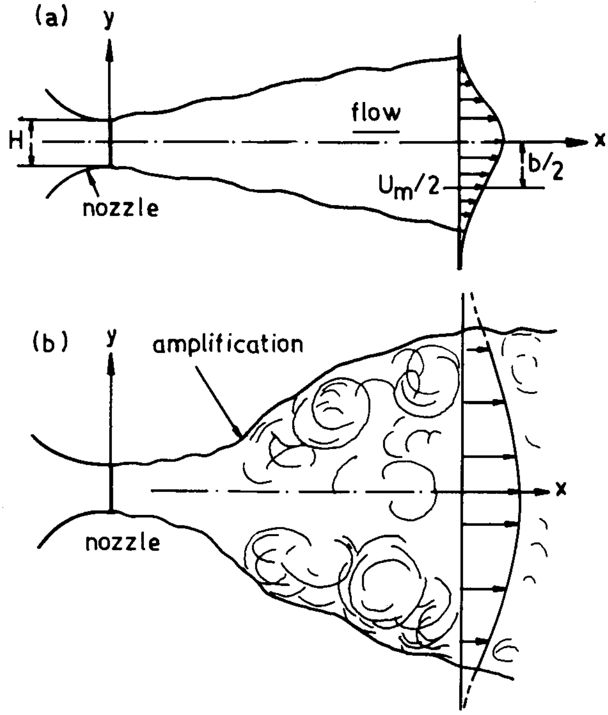


Figure 1. (a) Steady, and (b) excited jet.

application to V/STOL aircraft propulsion, which requires efficient thrust augmenting ejectors (Bevilaqua 1984; Braden *et al* 1982). In this system, the induced flow plays a major role. An excited jet which has a higher mixing capability could satisfy the above requirement.

The oscillations for exciting the jet can be categorized as: (a) pulsating the flow which produces periodic fluctuations in mass flow, and (b) the flapping of the jet. It is not always necessary that the application of such disturbances should induce excitation. The criterion for excitation is still under exploration and the available information on this subject indicates that the configuration of the jet, the strength of the imposed disturbance, and the mode of applying it, influence the process in a selective manner. For instance, a plane jet and a round jet exhibit entirely different behaviour when subjected to the same disturbance. The former can be excited only by antisymmetric oscillations whereas a round jet is sensitive to many modes (Rockwell & Niccolls 1985; Bernal & Sarohia 1984). A round jet gets excited through the dynamics of vortex rings, but the process involved in a plane jet is still under speculation. This article is mainly concerned with the excitation of a plane jet, a field in which the author has been actively engaged for the past few years.

2. Plane jet excitation

It is now well-established that a plane jet cannot be excited by mass fluctuations in the nozzle flow or by any other symmetric disturbances. Only antisymmetric oscillations are effective. The early experiment on plane jet excitation was

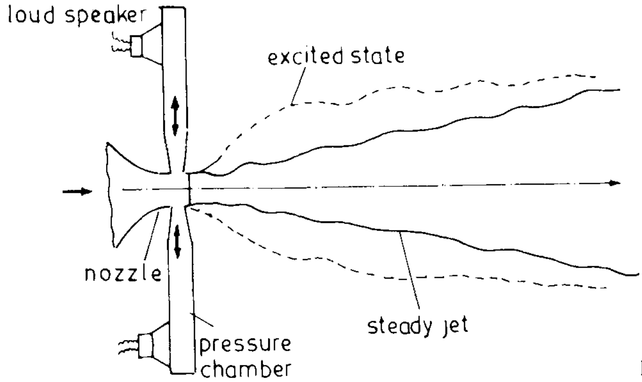


Figure 2. Pressure driven exciter.

performed by Fiedler & Korschelt (1979) using periodic pressure pulses generated by a pair of loud speakers at the exit of the nozzle (figure 2). Only when the two speakers were operating in an out-of-phase mode did the jet exhibit a tendency to a greater spread. It was observed that a perceptible amplification set in only after a threshold of driving amplitude; beyond a certain level of excitation, there was little effect on the overall flow condition. At low frequencies, the jet was only flapping from one side to another, without any increase in the overall entrainment. With an increase in frequency, the flapping mode ceased and the flow generated alternate vortices spanning the entire width of the jet. At higher frequencies, the vortices could not be distinctly identified. The entrainment enhanced only when the flapping mode changed to the vortex mode. Fiedler & Korschelt (1979) also noticed that the onset of amplification occurred only at some distance downstream of the nozzle, and this (distance) depended on the imposed frequency. Since the disturbances in their experiments were generated by loud speakers, the intensity of the pressure fluctuations was small and restricted the amplification to only a short distance downstream of the nozzle. The possibility that there might be a critical Strouhal number associated with the excitation process was also suggested by them.

For industrial applications, more practical methods are required to excite the jet. To achieve this, simple mechanical devices were tried (Lai & Simmons 1985; Badri Narayanan & Platzer 1986; Badri Narayanan 1987) to increase the strength of the imposed oscillations. The first attempt was the introduction of a tiny vane placed across the jet in the potential core region and subjected to periodic pitching oscillations by an external mechanism (figure 3). This technique was quite successful and the entrainment ratio of the jet could be increased significantly. The stationary vane kept at a zero angle of attack had negligible effect on the flow. Several investigators have examined this flow under different conditions (Lai & Simmons 1985; Badri Narayanan & Raghu 1983; Collins *et al* 1984). All the experiments carried out on this vane system were mainly confined to mean and turbulent velocity measurements by varying the amplitude and frequency of the vane oscillations. No attempts were made to examine the flow patterns. However it was speculated that the entrainment could be associated with the formation of vortices. The major conclusion arrived at was that, for a given exit velocity, the amplitude as well as the frequency influence entrainment. Some typical experimental results obtained by Badri Narayanan & Raghu (1983) are shown in

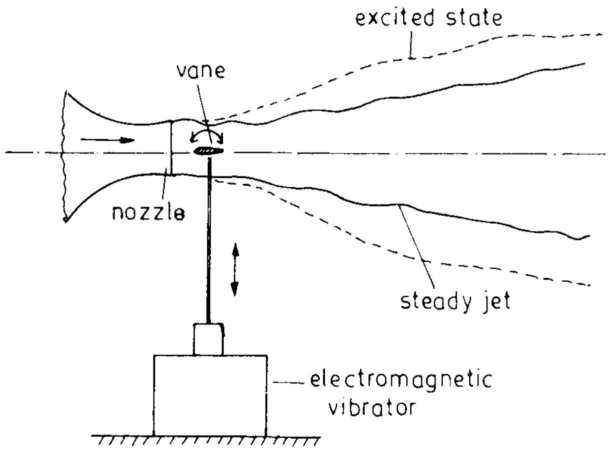


Figure 3. Single vane exciter.

figure 4. None of the investigators established a Strouhal number for excitation for this arrangement.

The single vane system described above has its own drawbacks when considered for aircraft applications. Since the vane is placed in the centre of a high speed jet, aeroelastic problems do arise and the penalty is more severe if the jet is hot. Hence better techniques were sought, as a result of which, a reciprocating lip device was developed (Badri Narayanan & Platzer 1986, 1987). The novel feature of this oscillating mechanism is the incorporation of two small segments in the exit region of the jet, spanning the entire length of the nozzle (figure 5). These segments, which form the lips of the nozzle, reciprocate in opposite directions at the required frequency by a gear-cam arrangement coupled to a variable speed motor. The maximum movement of the segments (L) was controlled by the eccentricity of the cam. Some experiments were conducted with this system at an exit velocity of 120 m/s. Using cams with different eccentricities, the movement of the segments was varied in steps of 0·25, 0·50, 0·75 and 1·0 cm. Mean velocity profiles were measured in this investigation using a hot-wire anemometer. Flow patterns were observed with smoke filaments. Initial experiments indicated that at low frequencies, the jet was flapping up and down for all values of L. As the frequency was increased, formation of vortices could be clearly seen only for $L = 0{\cdot}75$ and 1·0 cm. For $L = 0{\cdot}50$ cm, vortices could be observed only at a considerable distance away from the nozzle but not distinctly. There was no rolling-up motion at all for $L = 0{\cdot}25$ cm, a trend clearly suggesting that a minimum disturbance is essential for excitation of the jet. Detailed velocity measurements were therefore carried out only for $L = 0{\cdot}75$ cm, for which the entrainment was enhanced. Entrainment higher than that of the single vane system was achieved by this oscillator. The spread of the jet and the entrainment ratio with and without excitation are shown in figure 6.

Flow visualisation clearly indicated that the initial vortex formation occurred at a certain distance downstream of the nozzle exit and this distance was influenced by the exit velocity as well as by the frequency. For a given exit velocity, the vortex moved towards the nozzle as frequency was increased, while for a fixed frequency, the distance increased with the exit velocity. Since flow visualisation using smoke

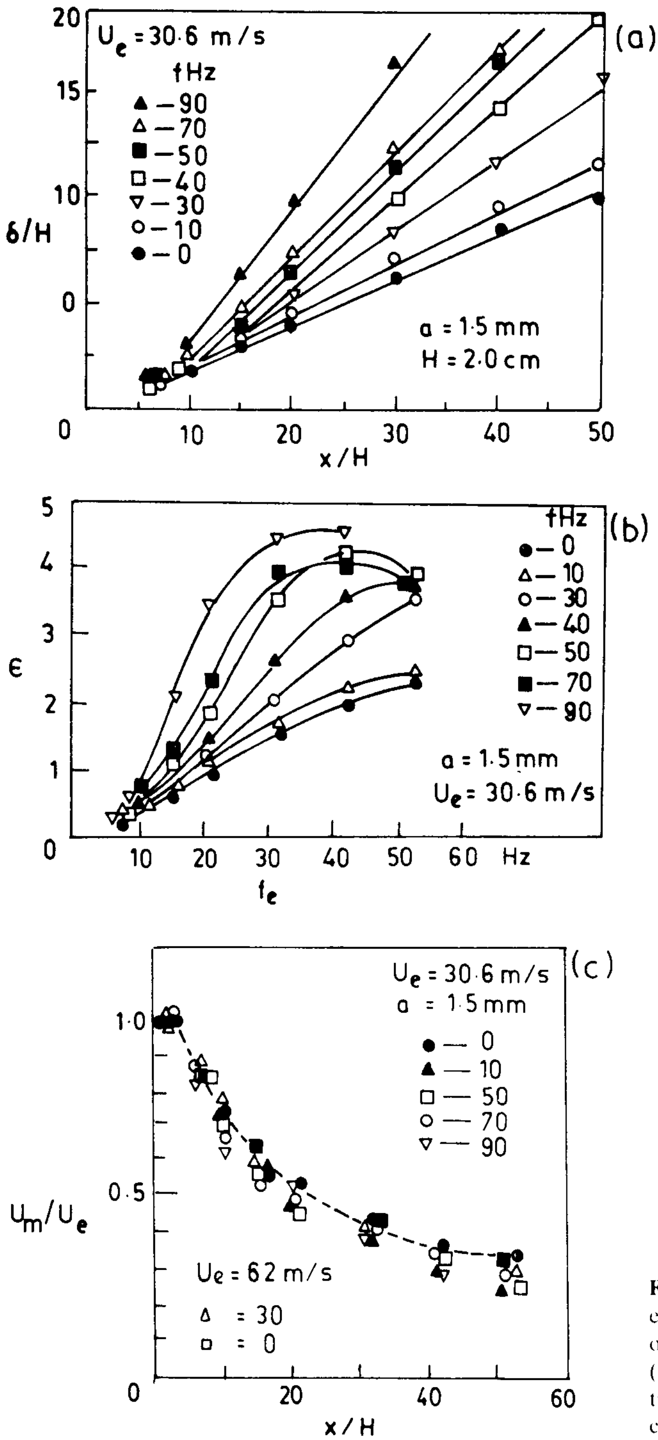


Figure 4. The effect of single vane excitation on the jet. (**a**) Growth of the jet due to excitation, (**b**) entrainment ratio, (**c**) variation of mean velocity along the centre line.

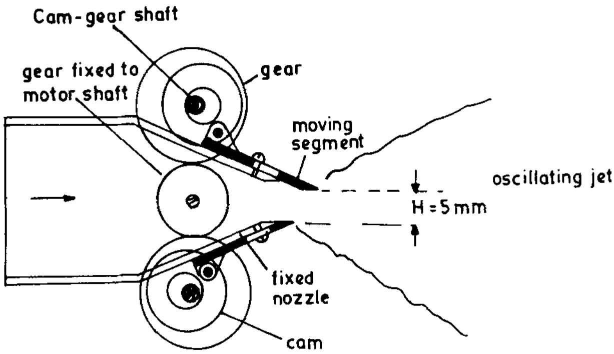


Figure 5. Reciprocating lip mechanism.

filaments could not be successfully used beyond an exit velocity of 20 m/s, attempts were made to identify the change-over from the flapping motion of the jet into the excited state using hot-wire traces. Near the vicinity of the nozzle, the velocity fluctuations exhibited a large swing reaching zero value for a considerable period at every stroke of the moving lip, clearly indicating flapping motion. As the hot-wire was shifted downstream, the velocity, though fluctuating periodically, did not reach zero value but was found to ride over a non-zero base velocity. This modification in the flow pattern was rapid and clearly distinguishable in the hot-wire traces especially in the outer part of the jet. The criterion for the above condition was examined for different values of exit velocity and excitation frequency, and the results suggested a critical Strouhal number ($St_c = f\delta/U_m$) associated with this process. St_c was about 0·067, based on the excitation frequency, the width, and the centre-line velocity of the steady jet. Overall, the reciprocating lip jet did clearly reveal that the excitation is associated with the formation of large periodic vortices which are responsible for inducing additional mass flow into the jet.

Very recently another technique was developed (Badri Narayanan 1987) for imparting oscillations to the jet, which seems to be superior in many respects to the earlier methods. It is a twin-vane system. A pair of vanes is employed (instead of a single one), located in the outer edges of the jet as shown in figure 7. The vanes are rigidly attached to each other so that their movements are in phase. Preliminary experiments were carried out with the vanes oscillating in the transverse push-pull mode (Badri Narayanan 1987). The oscillations generated vortices on both sides of

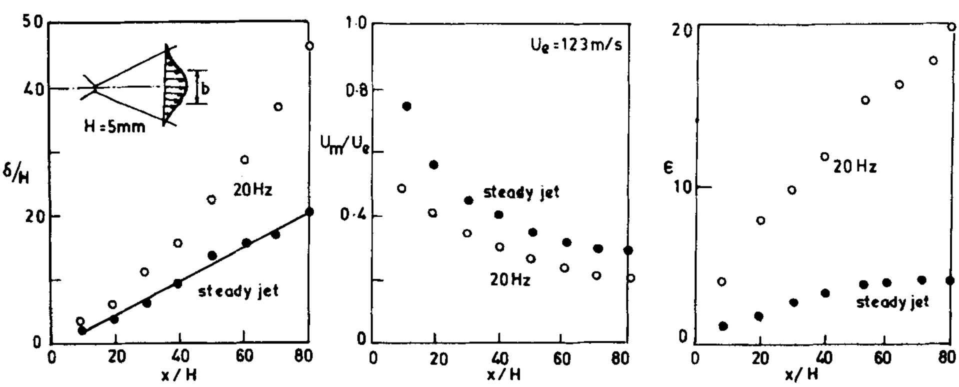


Figure 6. Characteristics of the jet excited by reciprocating lips.

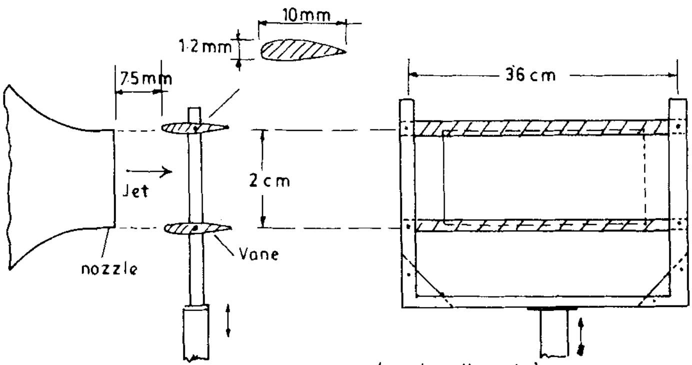


Figure 7. Twin vane exciter in the push-pull mode.

the jet some distance downstream of the nozzle and they grew rapidly in size giving a bloom-like appearance when observed with smoke filaments (figure 8). As in the case of the reciprocating lip system, the amplification distance (x_c) depended on the exit velocity and the frequency of oscillation. In this mode of operation, the jet did not exhibit a tendency to flap. On the other hand, vortices were formed at the edges of the jet in the same fashion as observed in the case of free shear layers (Wygnanski *et al* 1979). They grew rapidly in an individual manner and at some distance downstream (x_c) the vortices from both sides interacted with each other. The distance x_c moved towards the nozzle as the frequency was increased and reached a minimum close to the potential core region. x_c was insensitive to the amplitude of excitation beyond a minimum threshold level. Since the vortices formed in this technique are different in nature from those formed by the reciprocating lip method, the possibility that two separate mechanisms are involved in the formation of the vortices cannot be ruled out.

When the twin vanes were oscillated with a rotary motion around a pivot as illustrated in figure 9, which is termed as pitching mode in this report hereafter, the vortex formation was different from that of the push-pull mode, but similar to that of the reciprocating lip oscillator described earlier (Badri Narayanan & Platzer 1987). The jet initially exhibited a flapping motion which rolled up as the frequency was increased (figure 10). As in the case of other techniques, the movement of the amplification region varied with the imposed frequency and exit velocity. Mixing in this case was more predominant than in the push-pull mode. For low exit velocity and frequency operations, a critical Strouhal number around 0.05 could be identified for this system. Since the detailed velocity measurements in the pitching mode were carried out at high blowing pressures for an ejector application, the entrainment ratio and the spread of the jet cannot be directly compared with those of other systems which were operated at low exit velocities.

The twin-vane system oscillating in the pitching mode seems to be more suitable for practical applications. The thrust of the jet measured with and without the vanes showed a loss of about 3% even when the vanes were oscillating. In addition, the vanes, being placed at the edges of the jet, will not bear the burnt of the gas temperature if the issuing jet is hot. It is the opinion of the author that the two-vane oscillator operating in the pitching mode is a more practical system for existing a plane jet when compared to other systems described earlier.

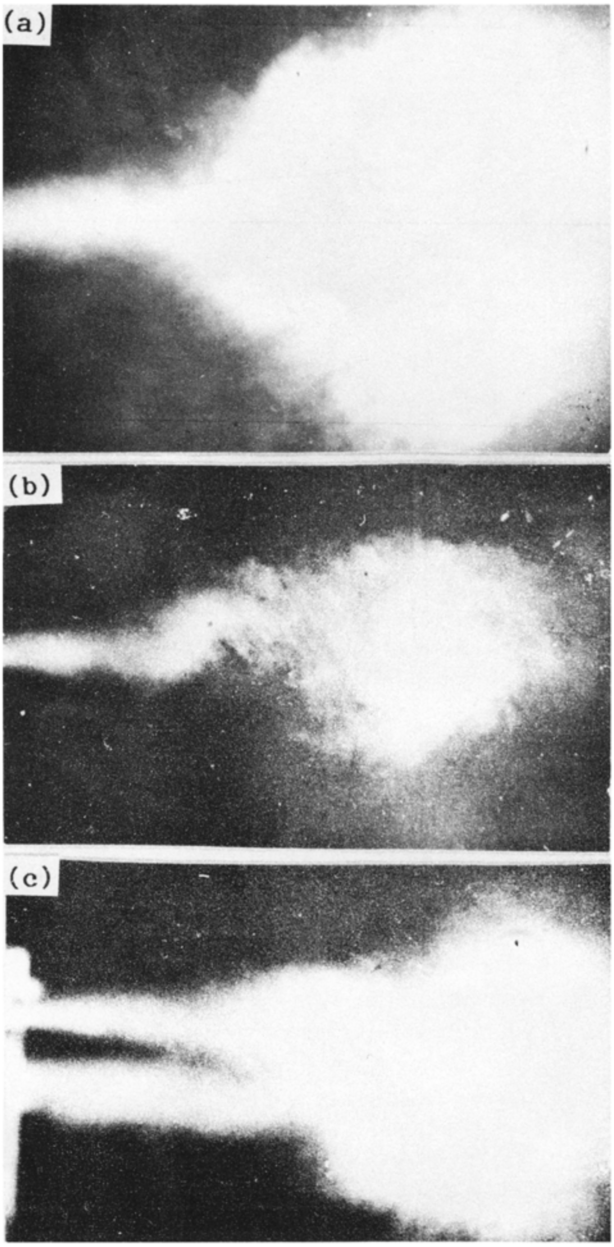


Figure 8. Flow patterns observed with twin vane exciter in the push-pull mode. (**a**) Excited jet, long exposure without strobe. (**b**) and (**c**) with strobe light, smoke injected on one vane and on both vanes, respectively.

3. Discussions

All the investigations on excited turbulent plane jets converge to the conclusion that the initially present flapping motion produces large vortices on either side of the flow which are primarily responsible for entrainment of additional mass into the system. The amplitude of the imposed oscillations do not affect the location of the amplification; however, it has an influence on the size of the vortex. It was also

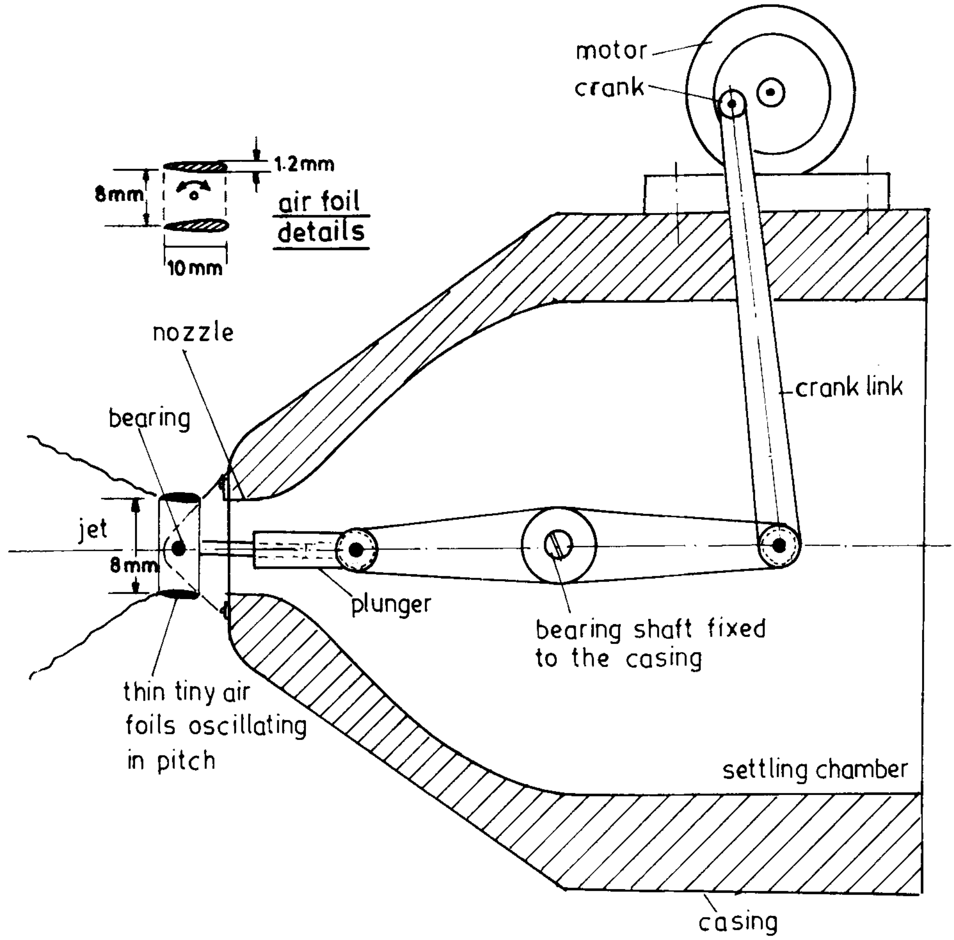
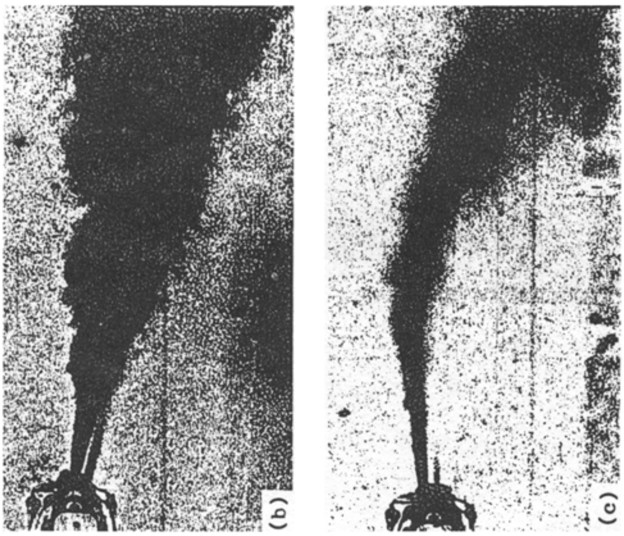


Figure 9. Twin vane oscillator in the pitching mode.

noticed that the extent of amplification is restricted to a certain distance depending on the strength of excitation. Since the amplification distance depends only on the frequency and the exit velocity and not on the amplitude of oscillation, it is possible to construct a critical Strouhal number for amplification. This could be considered as the criterion for the conversion of the flapping mode to the rolling motion. At low exit velocities and low frequencies, the vortex formation can be distinctly observed by flow visualisation, which enables the location of the excitation distance (x_c). For this condition, the estimated critical Strouhal number is around 0.05 ± 0.01.

A steady turbulent jet is also known to be associated with a reasonably well-defined Strouhal number equal to 0.22 for its self-generated large eddies for which the frequency was obtained from auto correlation of the velocity fluctuations (Cervantes & Goldschmidt 1980). The frequency varies along the jet in such a manner that the Strouhal number is constant at all longitudinal stations, a result which gave rise to the speculation that the jet has an inherent flapping tendency in a stochastic sense. Whether flapping or not, the steady jet does generate smaller



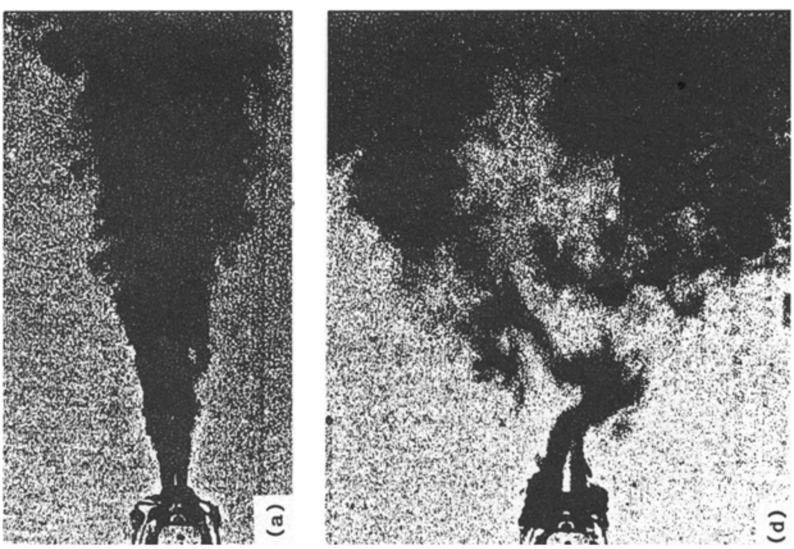


Figure 10. Flow patterns observed with smoke injection twin vane in pitching mode. **(a)** Steady jet; **(b)** steady jet-vanes in extreme position; **(c)** $f = 5$ Hz; **(d)** $f = 60$ Hz. The exit velocities in **(a)** - **(d)** are the same.

vortices which grow in size as they are convected downstream. These vortices are entirely different from the large periodic ones generated by the flapping motion.

The significant process in the excited jet is the conversion of the flapping motion into rolling motion. This could be due to a simple mechanical process, without involving viscosity, an analogy of rotation due to a crank and wheel mechanism. A flapping motion does produce a transverse flow, periodically changing its direction in tune with the imposed oscillations. When the longitudinal and the transverse velocities become comparable, a circular motion is possible which is one of the preferred modes of a vortex. This hypothesis supports the dependence on the location of amplification by the excitation frequency and the exit velocity. Further experiments on the instantaneous velocity components are required to verify this suggestion. Of course, the viscous forces will eventually play a role in breaking up of the large eddies into smaller ones.

The mechanism involved in the entrainment process is also not clear. Measurements do indicate large entrainment, which does not increase suddenly in one step but continuously, the jet engulfing more fluid as the flow moves downstream. Flow visualisation reveals large turbulence-free potential flow from outside ingested into the jet. This pattern suggests the possibility of some other mechanism being involved in the entrainment process. It has been noticed that the flapping jet generates large pressure fluctuations on either side of the flow (Badri Narayanan & Platzer 1987). They are out of phase during flapping motion but seem to become in-phase (Badri Narayanan 1987) at the onset of amplification. Therefore, the possibilty that pressure fluctuations may play a significant role in the entrainment of fluid into the system requires consideration.

4. **Practical applications**

The main characteristic of an excited jet is to entrain more mass flow by mixing. An ejector system whose efficiency depends on jet mixing can take advantage of excitation. Another possible use is to accelerate convective cooling. The possibility that excitation could be employed to improve combustion efficiency is yet to be explored. So far, investigation on plane jet excitation is mainly confined to the development of a suitable oscillating mechanism which is practical and suitable for the aircraft industry.

The installation of ejectors in a wing to produce lift for vertical take-off is under consideration by the aircraft industry (Braden *et al* 1982). However, the designers are looking for higher ejector thrust. In practice, a thrust augmentation ratio (ϕ) of nearly 1·4 could be achieved with a diffuser duct ejector shroud even though higher values are theoretically possible. The main limitation is due to separation of the flow in the diffuser especially at higher blowing pressures. In an aircraft system, short wide angle diffusers are required to satisfy the design conditions. An excited jet seems to suppress diffuser stall on account of its additional mixing characteristics. Laboratory experiments indicate that an excited jet can increase the ejector thrust by nearly 20% even at high blowing pressures (Badri Narayanan & Platzer 1987). These tests are preliminary in nature and it is envisaged that the shape of the duct could be optimized to increase the ejector thrust further.

5. Concluding remarks

A plane turbulent jet can be excited only by subjecting it to antisymmetric oscillations. The jet which is initially in the flapping mode rolls up forming vortices, initiating amplification. During excitation, the entrainment increases appreciably from that of the steady counterpart, due to enhanced mixing. A critical Strouhal number seems to be associated with amplification. The conversion of flapping motion into a vortex mode seems to be a fundamental phenomenon of unsteady flows and further investigations are necessary to understand this process. Similarly, the mechanism involved in the ingestion of fluid into the jet is not clear. The role played by the large pressure fluctuations during excitation needs further study.

List of symbols

a	maximum amplitude of vane oscillation;
f_e	oscillating frequency;
H	height of the nozzle;
Q_0	mass flow at the nozzle exit;
Q	mass flow in the jet at any x station;
St	Strouhal number $= f_e\delta/U_m$;
T_1, T_2	thrust of the jet and ejector, respectively;
U	mean velocity;
U_e	exit velocity;
U_m	mean velocity along the centre line of the jet;
x_c	distance between the nozzle exit and the region of amplification;
x	coordinate along the longitudinal axis;
y	coordinate along the width of the jet;
δ	width of the jet based on half the centre velocity $(U_m/2)$;
ε	entrainment ratio $= (Q-Q_0)/Q_0$;
ϕ	thrust augmentation ratio $= (T_1 + T_2)/T_1$.

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