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Technical Notes

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Unsteady Pressures Under Impinging Jets in Crossflows

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I. Introduction

THE in-ground effect of the flowfield surrounding jet-lift V/STOL aircraft provides many problems for the aircraft designer and operator.[1] High pressure ratio jets striking the ground are a well-known source of noise and jet instability[2]; with two jets an unsteady fountain (or upwash) is formed between the jets by the collision of the two opposing wall jets. In the presence of a crossflow the ground jet sheet formed from the impingement region separates and rolls up to form a ground vortex.[1] The ground vortex is one source of hot gas ingestion (HGI) as well as influencing airframe airloads; the fountain is another important source of HGI and can lead to airframe fatigue problems. Both of these sources of HGI are known to be highly unsteady.[1] It has been argued by Williams[3] that the statistical extrema of the flowfield conditions are as important as the mean, from the point of view of safe engine operations. What is not clear is the nature and origin of this unsteady behavior.

Single impinging jets have long received attention from the research community for a variety of reasons, including the generation of impingement tones (e.g., Refs. 2 and 4). These tones appear to be due to a feedback mechanism between the impingement plane and the nozzle lip. There has been some experimental disagreement about the precise feedback route—either outside the jet or through the jet shear layer, although the latter seems to be more likely.[4] Little experimental work has been published on twin impinging jets, particularly from the point of view of aeroacoustics.

The unsteadiness of the ground vortex surrounding a single, low-pressure-ratio, normally impinging jet in crossflow has been investigated experimentally by Cimbala et al.[5] They used hot-wire anemometer measurements in and around the jet, in the crossflow, and in the ground vortex region to try to characterize the vortex unsteadiness and identify its origin. Are such low pressure ratio tests representative of underexpanded-jet flowfield fluctuations?

This paper reports measurements of ground plane pressure fluctuations, both near the impinging jet(s) and under the ground vortex and fountain for a range of nozzle pressure ratios (pr_n = 1.05–4.0), nozzle heights above the ground (h/d_n = 2–8) and crossflow velocities (V_∞ = 0–20 ms^{-1}).

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II. Experimentation

The basic facility has been described earlier by Knowles and Bray.[6] The nozzles used for these tests were of conical, convergent design, having an exit diameter (d_n) of 0.5 in. (12.7 mm). Ground plane static pressures were measured using a miniature (0.080 in. diam, 0.25 in. long), diffused silicon diaphragm, strain gauge type, differential transducer (Entran EPIL-080-2). The reference pressure was ambient static. This transducer could be mounted in different positions along the centerline of the ground board. For the single jet tests this was the plane of symmetry of the horseshoe vortex; with twin nozzles this lies under the fountain formed between the two jets (which were spaced six diameters apart).

The Entran transducer had a range of 2 psig and a flat frequency response to 30 kHz. The output signal from it was amplified and put through a low-pass filter (Kemo UBF/8), typically set at half the sampling rate or less to avoid aliasing. This signal was digitized and then logged by an Analogic Data 6000. Samples were normally taken at a rate of 1 kHz.

To analyze the pressure signal, typically 10^4 samples were stored and divided into up to 10 records. Fourier transforms were taken (using the Analogic with a cosine window) of each of these records and then averaged. In an attempt to identify the presence of any periodic events within the flowfield, pressure amplitude distributions were calculated from the original pressure-time histories and autocorrelation functions have been obtained.

III. Results and Discussion

Typical spectra for a single, choked nozzle wall jet are shown in Fig. 1. In this case, the ground vortex core is upstream of y/d_n = 12. These reveal no dominant single frequency components. From their hot-wire anemometer measurements (at a velocity ratio of 10, with a 45.7-ms^{-1} jet and a nozzle height of $3d_n$), Cimbala et al.[5] found that the wall jet flow was characterized by a broadband low-frequency hump whose center frequency decreased from about 100 Hz near the jet impingement region to about 4 Hz under the vortex. The results of Fig. 1 are for a similar height with about twice the crossflow velocity, but the jet is nearly sonic (pr_n = 1.8) and the nozzle is 1/6th the diameter of Cimbala's. There is evidence of a slight broadband hump in the pressure spectrum at $y = 6d_n$, with a center frequency of about 120 Hz. In the region of the vortex (y = 12, $14d_n$) there is a more pronounced hump with a center frequency in the region of 5–10 Hz. This tends to support Cim-

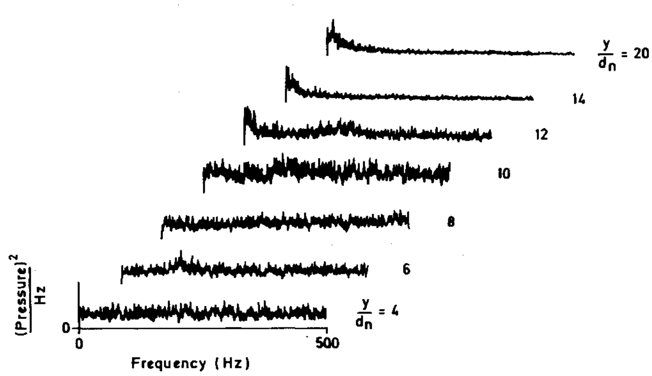
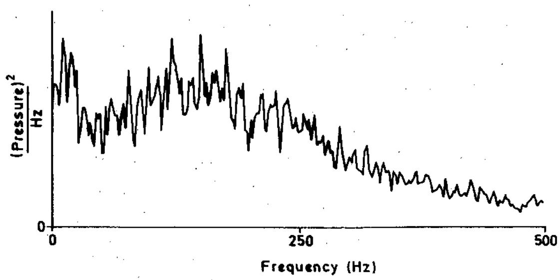


Fig. 1 Comparative spectra at various streamwise positions under the wall jet and ground vortex: single nozzle, h/d_n = 4, pr_n = 1.8, and V_∞ = 10.3 ms^{-1}; arbitrary pressure scale; y measured upstream from nozzle centerline.

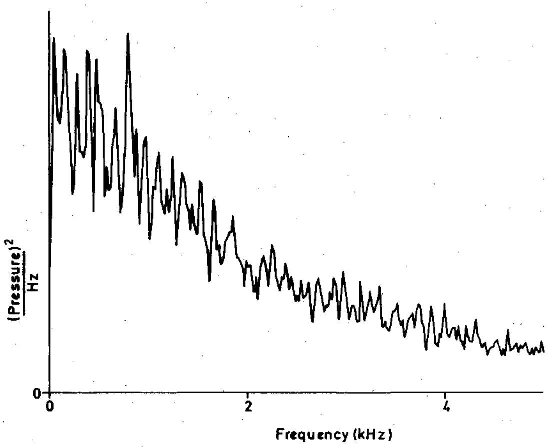
bala's view that the vortex unsteadiness is characterized by a low-frequency "puffing."

Increasing the nozzle pressure ratio to highly underexpanded ($pr_n = 4$) emphasizes the broadband hump under the wall jet (Fig. 2a). The center frequency, however, has not changed significantly from that identified earlier. It should be emphasized that the spectrum of Fig. 2a is an average of eight separate spectra; these individual spectra can vary significantly.

The peak level of pressure fluctuation can be identified from the pressure-time traces and then plotted against streamwise position. Figure 3 shows such plots for three different crossflow velocities at one nozzle pressure ratio close to choking and for a twin jet case. This emphasizes the high levels of pressure fluctuation close to the jet. The plot also reveals, however, further lower peaks. These seem to be either side of the vortex core position. In these positions the local static pressure is changing rapidly with streamwise position and so any axial movement of the ground vortex (as identified by Cimbala[5]) will cause a large fluctuation in surface pressure.



a) Under wall jet, showing broadband hump: single nozzle, $pr_n = 4$, $V_\infty = 10.8$ ms^{-1}, $y/d_n = 16.0$, arbitrary pressure scale



b) Under twin jet fountain; $pr_n = 4$, $V_\infty = 10.8$ ms^{-1}, $y/d_n = 8.0$, arbitrary pressure scale

Fig. 2 Spectral content of pressure signals.

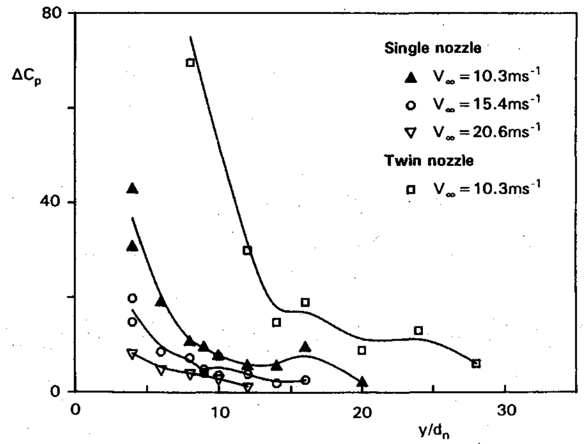


Fig. 3 Variation of peak pressure fluctuation amplitude (ΔC_p) with position for various conditions: $pr_n = 1.8$ and $h/d_n = 4$.

With twin jets we have previously observed the ground vortex to be even more unsteady than with a single jet.[6] Ground plane pressure measurements under the fountain flow reveal high fluctuation levels (Fig. 3) and generally no identifiable low-frequency broadband spectral hump (Fig. 2b). A pressure amplitude distribution under the fountain reveals a slightly skewed probability. This is typical of the kind of velocity distribution associated with an inhomogeneous turbulent flow.[7] Similarly, an autocorrelation function is close to that for an entirely random signal, although there may be signs of a small periodic component.

Regarding the question of impinging jet oscillations feeding the unsteadiness in the ground vortex or fountain, the following points should be made. Impingement tone frequencies depend on nozzle height but if an average frequency is considered, as in Tam and Ahuja,[4] then we would expect an impingement tone frequency of at least 7 kHz for our experiment. We have not yet seen any dominant signals at such frequencies. Indeed, the ground vortex and the fountain are both characterized by very low-frequency oscillations, of the order of a few Hertz.

IV. Conclusions

Pressures have been measured on the ground plane upstream of single and twin impinging jets in crossflows. The following points are noted.

1) The ground vortex is characterized by very low-frequency, broadband oscillations, with a center frequency in the 5–10 Hz range. This does not reflect frequencies seen elsewhere in the flowfield. The fountain is not obviously characterized by a low-frequency broadband hump.

2) The wall jet near the impingement region is characterized by a rather higher frequency broadband hump, centered around 120 Hz.

3) The peak amplitude of pressure oscillations under the wall jet and vortex is greatest near to the jet impingement region but with further peaks around the vortex core. These peak oscillation amplitudes near the vortex are consistent with the vortex changing in size and/or position.

4) The fluctuation levels with twin jets are higher than for a single jet and are consistent with inhomogeneous turbulence.

Overall there is no evidence that the vortex or fountain fluctuations are driven by impinging jet instabilities. Indeed, there are no signs of any dominant single frequency characteristics in these fluctuations.

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