action of this pair of vortices, a significant ejection of the jet air into the ambient air was observed at all downstream locations. Similar to previous work,[2] this favorable pumping action of mushroom-type vortices resulted in a continuous increase in mixing as shown in Fig. 3a. As in the previous experiments,[2] nozzle RS, which generates a kidney-type pair of streamwise vortices, showed better mixing in the near field, whereas nozzle RC, which generates a mushroom-type pair of streamwise vortices, showed better mixing at locations farther downstream, as shown in Fig. 3a.

Ideally Expanded Case ($M_j = 2.0$)

Significant jet cross-sectional development is observed for this flow condition by the cutout on the contoured nozzle block. With this nozzle configuration, the jet cross-sectional developments with downstream location for nozzles RS and RC are similar to those in the underexpanded flow regime of $M_j = 2.2$ with similar cutouts as in previous experiments. This is expected because the ratio of the static pressure at the beginning of the cutout to the ambient pressure is 2.4, in comparison with 1.0 in the previous cases with cutouts on the splitter plate or on the nozzle extension. This underexpansion generates a surface pressure gradient around the cutout, which is a necessary condition for streamwise vorticity generation. The two pairs of counter-rotating streamwise vortices are similar to those in the $M_j = 2.5$ case, although not strong enough to deform the jet cross section dramatically.

Mixing areas at $x/D_{eq} = 2$ and 8 increased about 20% when they are compared with those for nozzles with similar cutouts on the splitter plate.[1] Nozzle RS shows better mixing in the near field as in the $M_j = 2.5$ case.

Overexpanded Case ($M_j = 1.75$)

With the cutout on the contoured nozzle block, the jet cross-sectional development is significantly altered for locations far downstream. The jet cross sections of nozzle RS and RC show an axis switching, as in the baseline nozzle, by the $x/D_{eq} = 8$ location for the present cases. On the other hand, only the baseline nozzle showed an axis switching by this location in the previous cases.[1] From the instantaneous images, the degree of flapping motion of mixing layers can be inferred.[4] In the previous cases,[2,4] most of the cutouts significantly reduced the flapping motion. However, the present cutout did not significantly change the flapping motion. The unaltered flapping motion is most likely responsible for the enhanced mixing.

Nozzle RS shows approximately 60% increased mixing at $x/D_{eq} = 8$ when compared with that of a nozzle with a similar cutout on the splitter plate,[1] although it shows a little reduced mixing at $x/D_{eq} = 2$. Nozzle RC shows a reduced mixing level at $x/D_{eq} = 2$ and about the same mixing level at $x/D_{eq} = 8$ when it is compared with that of a nozzle with a similar cutout on the splitter plate.[1] Contrary to the previous cases, the growth rates of mixing area for both nozzles RS and RC are positive all the way up to $x/D_{eq} = 8$. As mentioned earlier, the unaltered jet flapping motion is most likely related to the enhanced mixing.

Conclusions

A rectangular nozzle with a cutout on the contoured nozzle block showed higher mixing levels than previous experiments with the cutouts either on the splitter plate in a half nozzle or on the extension plates in a full nozzle. Except for the increased mixing level, the overall development of jet cross sections with downstream locations and the role of streamwise vortices remained similar to those of previous experiments with the cutouts on a splitter plate or a nozzle extension plate. The role of streamwise vortices in the jet development of the ideally expanded case seemed to be similar to those in the underexpanded case.

In the overexpanded flow regime, the present nozzle with a cutout on a contoured nozzle block showed about the same level of flapping motion as the baseline nozzle, whereas nozzles with cutouts on the splitter or on the extension in the previous experiments showed reduced flapping. The unaltered flapping motion of nozzles with a cutout resulted in positive growth rates all the way up to $x/D_{eq} = 8$, whereas the growth rates of nozzles with cutouts on nozzle extensions were negative at locations far downstream. Therefore, a nozzle with a cutout on a contoured nozzle block would perform better in mixing at all flow conditions. Note that in the previous experiments with the cutouts either on the splitter plate in a half nozzle or on the nozzle extension in a full nozzle, there was no thrust loss associated with the cutouts. However, no thrust measurements were performed for the present cutouts.

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Insensitivity of Unsteady Vortex Interactions to Reynolds Number

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Introduction

SEVERAL investigations have revealed that the vortex breakdown location over delta wings exhibits quasi-periodic oscillations along the axis of the vortices due to an interaction between the two leading-edge vortices. These observations were made by flow visualization in water-tunnel facilities at low Reynolds numbers, and the issue arises as to whether this is a low-Reynolds-number phenomenon. In this Note, by using two-point unsteady surface pressure measurements in a wind tunnel, it is shown that this phenomenon exists at much higher Reynolds numbers.

The antisymmetric motion of breakdown locations for left and right vortices (Fig. 1) can be demonstrated by studying the difference between the breakdown locations $(X_{left} - X_{right})/c$ and the average breakdown location $(X_{left} + X_{right})/2c$. The spectra of these are shown in Fig. 2 for $\Lambda = 75$ deg and $\alpha = 42$ deg (taken from Ref. 1). It is seen that most of the energy is concentrated in the difference and that there is a dominant peak corresponding to the quasi-periodic antisymmetric oscillations. Experiments on the nature and source of these oscillations as well as the effect of angle of attack and sweep angle are reported in detail in Ref. 2. Similar observations of the quasi-periodic oscillations of breakdown location were also made by others[3–7] by using flow visualization in water tunnels. The range of Reynolds number in these water-tunnel experiments and the frequency of the organized motion are shown in Table 1. Note that these oscillations were observed at Reynolds

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Table 1 Water-tunnel observations of the quasi-periodic oscillations of breakdown locations over stationary delta wings

Reference	Reynolds number Re	Dimensionless frequency fc/U_∞
Ayoub and McLachlan[3]	2.25×10^3	0.10–0.17
Portnoy[4]	3.8×10^3–4.96×10^4	0.04–0.10
Helin and Watry[5]	1.16×10^4	0.10
Gursul and Yang[6]	5.0×10^4	0.06–0.12
Johari et al.[7]	1.0×10^5	Not given
Menke et al.[2]	4.1×10^4–5.4×10^4	0.04–0.12

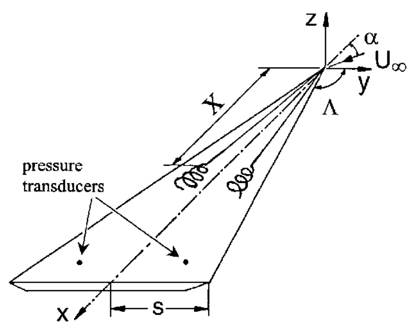

Fig. 1 Schematic of delta wing with flush-mounted pressure transducers.

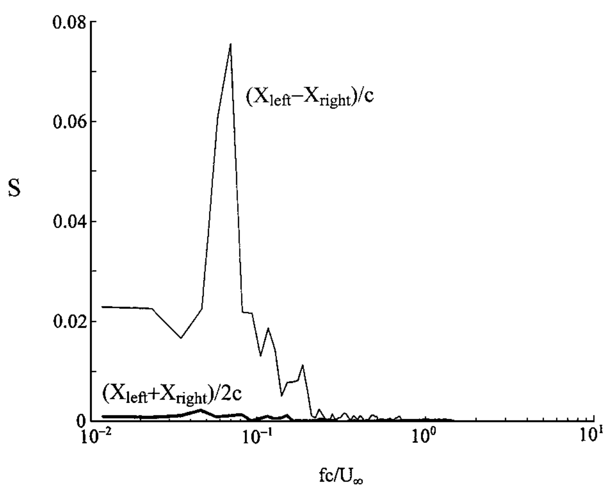

Fig. 2 Spectra of difference and average of breakdown locations, $\alpha = 42$ deg, $\Lambda = 75$ deg, and $Re = 4.1 \times 10^4$ (from Ref. 1).

numbers as low as $Re = 2.25 \times 10^3$. Examination of Table 1 shows that a similar range of dominant frequencies has been observed in all water-tunnel experiments. Recently, Mitchell et al.[8] carried out smoke flow visualization in a wind tunnel at $Re = 9.75 \times 10^5$–2.6×10^6, and reported a similar range of dominant frequencies of oscillations of breakdown location (although they did not present any spectra). In this Note, we present further and quantitative evidence of oscillations of breakdown location at $Re = 1.6 \times 10^6$ by using two-point surface pressure measurements rather than relying on flow visualization.

Experimental Setup

Surface pressure measurements were carried out over a delta wing. The experiments were conducted in the 2.1×1.5 m low-speed wind tunnel at the University of Bath. The delta wing model had a sweep angle of $\Lambda = 80$ deg and a chord length of $c = 750$ mm. This particular sweep angle was chosen because of previous observations, which revealed that vortex interactions intensify as the sweep angle is increased. The lee surface of the model was flat, whereas the leading edges were beveled at 45 deg on the windward side. The thickness of the wing was 12 mm, giving a thickness-to-chord ratio of 1.6%, and the blockage ratio was 4.7% at an angle of attack $\alpha = 50$ deg. The experiments were carried out at a freestream velocity $U_\infty = 30$ m/s, and the Reynolds number based on the chord length was $Re = 1.6 \times 10^6$. The model was sting mounted on a high-α test rig. The angle of attack could be easily adjusted from outside the tunnel, and a pantograph arrangement kept the model in the center of the cross section of the tunnel.

Unsteady surface pressure measurements were made by two miniature pressure transducers (Entran, EPE-C1), which are suitable for low-pressure measurements with high sensitivity (150 mV/psi). The pressure transducers were installed within the model delta wing due to their small size and were used for simultaneous measurement of pressure fluctuations at two different locations. The flush-mounted transducers eliminated the need for calibration and correction for the amplitude attenuation and phase distortion due to transmission lines, while the size of pressure sensing area (less than 2 mm^2) was still acceptable. The measurements were taken at a streamwise station of $x/c = 0.90$. The two pressure transducers were positioned symmetrically about the plane of symmetry of the model and underneath the vortices as shown schematically in Fig. 1. The spanwise locations of the vortices ($y_v/s = \pm 0.63$) were estimated by using the experimental database given in Ref. 9. The measurement uncertainty for the rms of the pressure fluctuations was estimated as 4%. A more complete description of the model support system, delta wing, instrumentation, data acquisition, and reduction may be obtained from Ref. 10.

Results and Discussion

The angle of attack was set at $\alpha = 50$ deg for which vortex breakdown location was well over the wing.[11] The vortex breakdown location was not visualized in this work; however, it is estimated to be located at approximately 30% of the chord length from the wing apex based on the reported breakdown locations from the literature.[11] The measurement station ($x/c = 0.90$) for surface pressure was well downstream of breakdown location. Therefore, measurements of pressure fluctuations could detect the oscillations of breakdown location. It has been previously shown that velocity measurements taken well downstream of breakdown location could reveal the oscillations of the breakdown location.[12] The dominant frequency of the fluctuations in vortex breakdown location obtained from flow visualization experiments was also found in the spectra of the velocity fluctuations measured well downstream of breakdown. Therefore, it is expected that surface pressure fluctuations beneath the vortex downstream of the breakdown could detect the oscillations of the breakdown location in addition to other inherent instabilities such as the helical mode instability. Because the antisymmetric motion of breakdown locations was demonstrated by studying the difference between the breakdown locations and the average breakdown location (Fig. 2), we considered the difference between the surface pressures at $y/s = \pm 0.63$ and -0.63 and the average surface pressure. Note that the rms of surface pressure fluctuations at $y/s = \pm 0.63$ were very close to each other, $Cp_{\rm rms} = 0.29$ and 0.30. The spectra of the difference ($p_{\rm left} - p_{\rm right}$) and the average $(p_{\rm left} + p_{\rm right})/2$ are shown in Fig. 3. It is seen that most of the energy is concentrated in

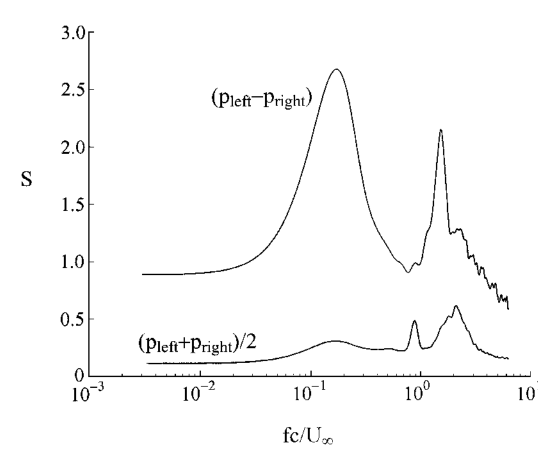

Fig. 3 Spectra of difference and average of pressure fluctuations, $\alpha = 50$ deg and $\Lambda = 80$ deg.

the difference, which confirms that pressure fluctuations are mostly out of phase. The same conclusion could be reached by examining the amplitude and phase of the cross spectrum of left and right pressure signals as shown in Ref. 10.

There are two dominant frequencies in the spectrum of the difference. The lower dominant frequency ($fc/U_\infty \cong 0.15$) is in the same range as the frequencies of the water-tunnel observations of the quasi-periodic oscillations of breakdown locations shown in Table 1. The out-of-phase pressure fluctuations are due to the antisymmetric motion of breakdown locations. Hence, quantitative evidence of vortex interactions at higher Reynolds numbers is presented. Also, the numerical values of the dominant frequencies seem insensitive to the variations in Reynolds number. For example, a dimensionless frequency of $fc/U_\infty = 0.17$ was reported for $\Lambda = 76$ deg and $\alpha = 50$ deg in Ref. 3 when the Reynolds number was $Re = 2.25 \times 10^3$. In this present study, we found $fc/U_\infty = 0.15$ for $\Lambda = 80$ deg at the same angle of attack when the Reynolds number was $Re = 1.6 \times 10^6$.

It is known that Reynolds number has little effect on the time-averaged quantities such as vortex breakdown location[13,14] and aerodynamic forces.[15] There is now growing evidence that unsteady phenomena in vortex flows are also insensitive to Reynolds number. This Note (as well as Ref. 8) presents evidence for the quasi-periodic oscillations of breakdown locations. Other unsteady phenomena such as the helical mode instability and vortex shedding were also found insensitive to Reynolds number when water-tunnel and wind-tunnel results were compared.[12] Review of investigations of surface pressure fluctuations on fins[16] also revealed that the helical mode instability, which is the main source of fin buffeting, is driven by predominantly inviscid mechanisms.

Returning to Fig. 3, the larger dominant frequency in the spectrum of the pressure difference is believed to be due to the helical mode instability. It is shown in Ref. 10 that individual spectrum of pressure fluctuations (p_{left} and p_{right}) revealed relatively broad peaks that covered between $fc/U_\infty = 1$ and 3, with individual maximums at $fc/U_\infty \approx 1.5$ and 2. These broad peaks agree well with earlier measurements of the helical mode instability detected in velocity[12] and pressure[17] fluctuations that revealed dominant frequencies between $fc/U_\infty = 1$ and 2 for a variety of delta wings with different sweep angles placed at different angles of attack. The different dominant frequencies ($fc/U_\infty \approx 1.5$ and 2) of the helical mode instability, which may be due to a slight asymmetry in the time-averaged breakdown locations, explain the peak at $fc/U_\infty \approx 1.5$ and the smaller peak at $fc/U_\infty \approx 2$ observed in the spectrum of ($p_{\text{left}} - p_{\text{right}}$). Note that the helical mode instabilities for the left and right breakdowns do not have to be in phase. Possible asymmetry in the time-averaged breakdown locations will introduce a phase lag between the two instabilities. Consequently, the broad peak with a maximum at about $fc/U_\infty \approx 2$ also appears in the spectrum of the average pressure fluctuations. Finally, the dominant peak at $fc/U_\infty = 0.87$ in the spectrum of the average of pressure fluctuations was traced to the fan blade passage frequency after further experiments.[10]

Summary

There have been several low-Reynolds-number investigations in water tunnels that have revealed the antisymmetric and quasi-periodic motion of vortex breakdown locations over delta wings. In this Note, we show that this interaction also exists at much higher Reynolds numbers. This was quantitatively demonstrated by using two-point unsteady surface pressure measurements in a wind tunnel. Evidence indicates that the vortex interactions as well as other unsteady phenomena over delta wings are insensitive to Reynolds number.

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