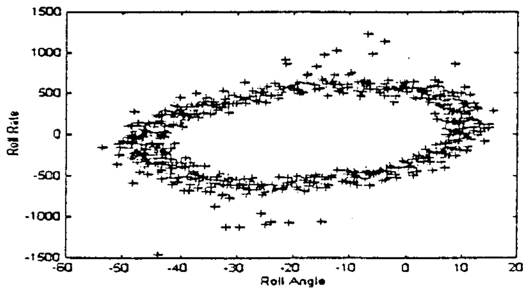

Fig. 10 Phase plane plot.

the wing rock time period of 250 ms. Hence, the time lag has been ignored.

The phase plane plot of the wing rock should ideally be a closed figure, but as seen from the data acquired during the experiments (Fig. 10), it is not so. This could be attributed to the presence of noise. Noise from the potentiometer would be due to the vibration of the sensor, due to the vibration of the tunnel itself. No effort has been made in the present exercise to eliminate the noise. The FLC is seen to be effective even in the presence of this noise.

An approximate estimate of the blowing coefficient C_μ indicated a value of 0.033. In spite of the restriction in terms of limited control available and the noisy input, the wing rock amplitude that used to be of the order of 60-deg amplitude is seen to be suppressed to the order of $\frac{1}{4}$ of the original amplitude. Further fine tuning and reduction in noise may lead to better suppression.

V. Conclusion

An FLC is presented to suppress the nonlinear wing rock phenomenon. RASB is employed for the vortex manipulation. The rules for the FLC are developed by the experience acquired during the experiments. The hardware in the loop simulation (with a delta wing in the tunnel and the controller in the personal computer) has shown encouraging results. Further experiments are being planned with improved fine tuning of the controller, proper filtering to reduce the noise, a possible increase in the blowing coefficient, and a better control over the airflow using servovalves rather than on–off valves. Vortex mapping is also planned to reason out the possible mechanism for the suppression of wing rock with the controlled blowing.

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Origin of Vortex Wandering over Delta Wings

Ismet Gursul*
University of Bath, Bath, BA2 7AY, United Kingdom
and
Wensheng Xie†
University of Cincinnati, Cincinnati, Ohio 45221-0072

Introduction

VORTEX wandering is defined as the random displacement of the vortex core. It has been observed over delta wings[1] as well as in tip vortices trailing from rectangular wings.[2–4] Several possibilities for the origin of vortex wandering were suggested previously. However, there has been no convincing explanation regarding the source of this random motion. The purpose of this Note is to present new evidence that suggests that vortex wandering may be due to the Kelvin–Helmholtz instability of the shear layer separated from the leading edge of a delta wing.

Very large swirl velocity fluctuations due to vortex wandering were observed in the vortex subcore over a delta wing[1] (in the absence of vortex breakdown) as shown in Fig. 1. The maximum rms swirl velocity, which occurs at the axis of the time-averaged vortex, increases with angle of attack and can exceed the freestream velocity. Other investigators[5–9] also observed large velocity fluctuations in the vortex cores over delta wings, model aircraft and ogive-cylinders over a wide range of Reynolds numbers. These observations are summarized in Table 1. It is seen that large velocity fluctuations in the vortex cores are common regardless of geometry and Reynolds number. Note that the amplitude of the velocity fluctuations depends on the time-averaged velocity, which is a function of particular geometry and angle of attack. Also, Gursul and Xie[10] suggested that the vortex wandering is responsible for the delta wing and fin buffeting at low angles of attack, where vortex breakdown is not observed.

It is suggested in Refs. 2 and 4 that the vortex wandering in tip vortices is due to the freestream turbulence. In Ref. 1, several possibilities including the Kelvin–Helmholtz instability in the shear layer and the unsteady turbulent flow in the wake of the wing were discussed as potential sources of vortex wandering over delta wings. It is known

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*Reader in Aerospace Engineering, Department of Mechanical Engineering.

†Graduate Student, Department of Mechanical, Industrial, and Nuclear Engineering.

Table 1 Maximum velocity fluctuations in vortex cores over different geometries

Reference	Model	$Re_x = U_\infty x / \nu$	Velocity fluctuations
Menke and Gursul[1]	Delta wing, $\Lambda = 75$ deg, $\alpha = 20$–42 deg	9.43×10^3–3.28×10^4	$v_{rms}/U_\infty = 0.38$–1.10
McCormick[5]	Delta wing, $\Lambda = 70$ deg, $\alpha = 30$ deg	3×10^4	$v_{rms}/U_\infty = 0.54$
Kommallein and Hummel[6]	Delta wing, $\Lambda = 66.6$ deg, $\alpha = 16.5$ deg	4.5×10^5	$\sqrt{[\frac{1}{2}(u^2_{rms} + v^2_{rms})]}/U_\infty = 0.44$
Cornelius[7]	Model aircraft, $\alpha = 21$ deg	5.75×10^5–6.625×10^5	$\sqrt{[\frac{1}{3}(u^2_{rms} + v^2_{rms} + w^2_{rms})]}/U_\infty = 0.40$–$0.42$
Schmucker and Gersten[8]	Delta wing, $\Lambda = 63.4$ deg, $\alpha = 16$ deg	5×10^5	$v_{rms}/U_\infty = 0.62$, $u_{rms}/U_\infty = 0.45$
Degani[9]	Ogive-cylinder, $\alpha = 40$ deg	2.6×10^5	$u_{rms}/U_\infty = 0.225$

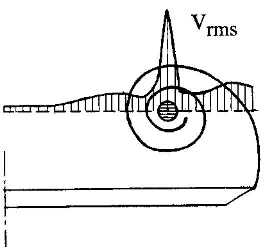
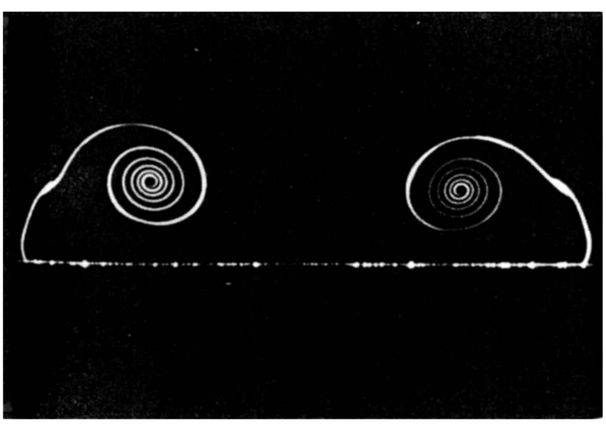
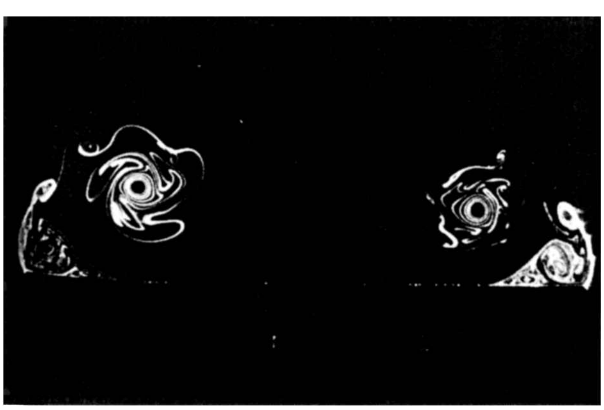


Fig. 1 Variation of rms swirl velocity across the vortex core (adapted from Menke and Gursul[1]).



a) $Re \approx 7 \times 10^3$



b) $Re \approx 2.3 \times 10^4$

Fig. 2 Flow visualization of shear layer (Lowson[12]).

that the shear layer vortices due to the Kelvin–Helmholtz instability exist in the separated shear layer, as demonstrated by Gad-el-Hak and Blackwelder.[11] However, as can be seen from Fig. 1, the swirl velocity fluctuations rapidly decrease with the radial distance from the centerline of the time-averaged vortex, and the fluctuations in the shear layer are not as energetic. Whether these weak fluctuations in the shear layer can induce very large fluctuations in the vortex core is not clear. The purpose of this Note is to clarify this issue.

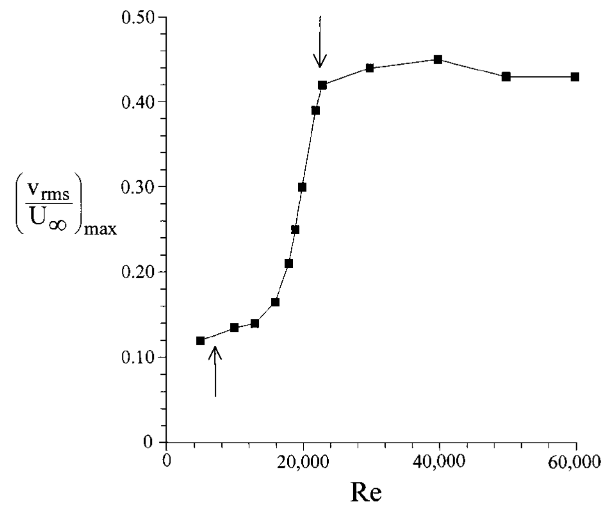


Fig. 3 Variation of maximum rms swirl velocity as a function of Reynolds number.

If velocity fluctuations in the absence and presence of the Kelvin–Helmholtz instability could be compared, the issue might be clarified. Recently, Lowson[12] carried out experiments at low Reynolds numbers and demonstrated the effect of Reynolds number on separated shear layer. The sweep angle of the delta wing used by Lowson in flow visualization experiments was $\Lambda = 70$ deg. At low freestream velocity, the flow is laminar and the separated shear layer is steady (Fig. 2a). As speed is increased, the flow becomes unsteady and vortical structures appear within the separated free shear layer (Fig. 2b). Approximate values of Reynolds number are given for each flow visualization in Fig. 2. It was decided that the effect of Reynolds number could clarify the role of the Kelvin–Helmholtz instability on vortex wandering. For this purpose, the rms swirl velocity was measured over a delta wing as a function of Reynolds number.

Experimental Setup

Experiments were carried out over a delta wing in a water tunnel with a cross-sectional area of 61 × 61 cm. The delta wing model had a sweep angle of $\Lambda = 75$ deg and a chord length of $c = 203$ mm. The velocity was measured with a single component laser Doppler velocimetry with frequency shift. The uncertainty for the rms swirl velocity was estimated as 3%. Further information on the tunnel, delta wing model, and instrumentation can be found in Ref. 1.

The angle of attack was set at $\alpha = 20$ deg, and the measurements were performed at a streamwise station of $x/c = 0.7$. The freestream velocity was varied and the maximum rms swirl velocity was measured by traversing across the vortex core.

Results and Discussion

The maximum rms swirl velocity, which gives a measure of vortex wandering, is normalized by the freestream velocity. The variation of the maximum value of v_{rms}/U_∞ is shown in Fig. 3 as a function of Reynolds number $Re = U_\infty c/\nu$. The two arrows in Fig. 3 indicate the corresponding Reynolds numbers of the flow visualizations in Fig. 2. As expected, the transition takes place between the two Reynolds numbers. Also it is seen that the transition process is very rapid. For low Reynolds numbers ($Re \leq 1.6 \times 10^4$), the magnitude of vortex wandering is small. For Reynolds numbers $Re \geq 2.3 \times 10^4$, the magnitude of the vortex wandering becomes relatively larger. Therefore, a definite correlation between the vortex wandering and the presence of the Kelvin–Helmholtz instability was demonstrated.

This can be understood by considering the interaction of shear layer vortices and the primary vortex. The small-scale vortices due to the Kelvin–Helmholtz instability form in the shear layer and are convected around the primary vortex.[13] During this process, these small vortices displace the primary vortex via the Biot–Savart induction. The presence of several small-scale vortices and their nonlinear interaction with each other and the primary vortex cause the random displacements of the core of the primary vortex. In a theoretical model of the oscillations of a side-edge vortex, Sen[14] showed that the trajectory of the primary vortex became chaotic due to interaction with a small vortex.

The unsteady Kelvin–Helmholtz (K–H) instability was observed by flow visualization,[11,12] by hot-wire velocity measurements,[15] and by particle image velocimetry measurements,[16,17] as well as by numerical simulations.[13] Riley and Lowson[18] suggested that the appearance of the unsteady K–H instability is due to extraneous inputs peculiar to the particular wind/water tunnel and that this unsteady instability is not a generic part of the flow. They reported that the appearance of the unsteady instability was dependent on a certain range of tunnel velocities. Also, Lowson[12] found that the shear layer was forced by vibrational inputs of the tunnel motor cooling fan running at a constant speed of 50 Hz. (Note that both Gad-el-Hak and Blackwelder[11] and Lowson[19] reported that the frequency of the unsteady instability varies with the freestream velocity.) It is well known that disturbances in individual facilities may cause large scatter of dominant frequencies for two-dimensional shear layers[20,21] becuase the shear layer is unstable to a wide range of frequencies. However, in the absence of any discrete disturbances, the instability will develop at the most unstable frequency. This is the case in the numerical simulations[13] in which no deliberate forcing of the shear layer is applied. In both experiments[17] and computations,[13] the observed frequencies were found to agree with the predictions from the linear stability analysis of the crossflow shear layer. Therefore, the unsteady K–H instability over delta wings is a generic part of the flow as much as it is for two-dimensional shear layers. In fact, it is so generic that the unsteady K–H instability was identified to be one of the main sources of flap-edge noise,[22] where a streamwise vortex is formed by the rollup of the separated shear layer. Also, both experimental[23] and computational[9] studies of unsteady forebody flows showed the existence of the unsteady K–H instability in the separated shear layer.

Another important feature of the unsteady K–H instability is that it exists in both laminar and turbulent mixing layers.[21] Likewise, these vortical stuructures were detected over delta wings by hot-wire measurements[15] at Reynolds numbers much higher than those corresponding to flow visualization experiments. The existence of the K–H instability, once generated, at higher Reynolds numbers is the required source of unsteadiness to induce vortex wandering. Finally, several researchers[18,24] revealed the existence of stationary small-scale vortices around the primary vortex. This steady instability cannot be responsible for an unsteady flow phenomena such as vortex wandering because it does not travel around the shear layer, unlike the unsteady K–H instability.

The results shown in Fig. 3 also have an implication regarding the low Reynolds number experiments performed usually at water tunnel facilities, but also occasionally in wind tunnels. Experiments performed at Reynolds numbers less than 2.3×10^4 may be sensitive to Reynolds number and may not be representative of high Reynolds number flows. For Reynolds numbers $Re \geq 2.3 \times 10^4$, the normalized rms swirl velocity is roughly constant, suggesting that the effect of Reynolds number is negligible. However, this critical Reynolds number may be strongly dependent on angle of attack and sweep angle.

Conclusions

This Note investigates the origin of the vortex wandering over delta wings. The rms swirl velocity in the vortex core is small when the shear layer does not exhibit the K–H instability at low Reynolds numbers. However, the shear layer is dominated by the vortical structures due to the K–H instability for Reynolds numbers larger than a critical value ($Re \approx 2.3 \times 10^4$). The corresponding rms swirl velocity in the vortex core becomes much larger, confirming much increased levels of vortex wandering. The present results demonstrate that the vortex wandering is directly related to the presence of the vortical structures in the shear layer due to the K–H instability. This is explained by the Biot–Savart induction of the small-scale vortices, which displace the primary vortex. Nonlinear interactions of small vortices and the primary vortex lead to the random displacements of the primary vortex core.

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