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Interactions of a counter-rotating vortex pair at multiple offsets

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ABSTRACT

The interactions between two streamwise vortices were investigated by wind tunnel testing of two NACA0012 vanes at various lateral offsets. One vane was spaced 10 chord lengths (C) downstream of the other, with both at an angle of incidence of 8 degrees and a Reynolds number of 7×10^4. The evolution of the vortex pair was observed until 6.5C behind the downstream vane using Particle Image Velocimetry (PIV). It was found that proximity of the upstream vortex to the downstream vane had a significant effect on the rotational rate of the subsequent vortex pair, with far offset cases having little rotation, and near field cases having angle changes of 19.6 degrees per chord length travelled downstream. At the point of vortex impingement on the downstream vane, the rotational rate dropped to near zero due to a significant strength reduction of both vortices. The point of strongest interaction was found to be laterally offset from the point of closest vortex proximity to the downstream vane by -0.15C, with the vortex on the suction side of the vane. In the offset range investigated, a significant instability was observed in only the upstream vortex. These instabilities increased as the proximity between the vortices decreased, peaking where the vortex interaction was strongest.

1. Introduction

Vortex generators operating in boundary layers, turbomachinery blade interactions, wind turbines and aircraft flying in formation can all produce vortex interactions with multiple streamwise vortices in close proximity to each other [1–6]. Streamwise vortex/structure interactions have been studied considerably less than either parallel or normal vortex/structure interactions [7], particularly relating to the effects of the upstream vortex migration. Vortices of a vortex pair have been typically deployed from the same streamwise location, limiting their proximity. However, close interactions are important conditions to understand in order to provide a knowledge base for practical vortex applications, where upstream vortices may move in locations on either side of a vortex producing obstacle, such as a wing or vane.

Interacting pairs of streamwise vortices can be classified into either counter-rotating or co-rotating configurations. Counter-rotating pairs exhibit a number of instabilities when placed in close proximity to one another, including long wavelength (Crow [8]), short wavelength (elliptic [9]) and spiral [10,11]. The Crow instability is described through a solution to a linear wave system, which describes the deviations of counter-rotating vortex pairs [8]. Once the vortex cores reach a certain proximity or cutoff distance the two wakes unify into vortex rings and rapidly breakdown. Vortices that break down or dissipate in short distances and timeframes do not have a long enough duration for waves to form, and as such are not subject to the Crow instability. Using these models, it has been found that all counter-rotating pairs are inherently unstable regarding the long wave Crow instability [12–14]. For vortices of unequal strength, the Crow instability can manifest itself at much shorter wavelengths than for an equal strength case. This has been simulated numerically using Computational Fluid Dynamics (CFD), and it has been found that a medium length instability is present where the weaker vortex is drawn around the primary vortex [15].

The short wave (elliptic) instability is identified in counter and co-rotating pairs by a streamtube in the core of the vortex with a diameter approximately half that of the instabilities wavelength. This instability is caused fundamentally by a resonance of two Kelvin waves (a sinusoidal deformation) within the vortex core as driven by the strain field induced by the other vortex [16]. Like the Crow instability, it is modified by differing axial velocity components and vortex strengths. The effect of these instabilities on migration and core size in practical upstream/downstream vortex layouts is currently unknown.

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Nomenclature

$R_{0.1}$	average radius of vortex at 0.1 vorticity threshold
$A_{0.1}$	total area of vortex at 0.1 vorticity threshold
Γ	circulation
X_c	X core location
Y_c	Y core location
C	chord length
R_e	Reynolds number, based off chord length

For free flow (unbounded) inviscid cases any vortex pair will maintain a constant core separation distance due to the conservation of angular momentum [9]. For a symmetric (equal circulation), counter-rotating case, this will mean that the pair will translate along the vortex pair centre axis, while for a case with unequal circulations there will be an orbital motion [9]. These migrations have also been observed in water tunnel testing [17], where dye marker injected into the cores of a pair of counter-rotating vortices showed a near linear trend in downwards motion of an equal strength pair. This motion increases in magnitude as vortex swirl is increased through varying the angle of attack of the vortex generation blades.

The interactions of a streamwise vortex with a wingtip at close range have also been computationally investigated [7,11]. By aligning an incident vortex with the tip of a downstream vane, the energy of the vortex system is increased in the near range, however more rapid energy attenuation occurs downstream. When the vortex is positioned inboard of the tip, it reduces the tip vortex size and strength, while placing it outboard of the wingtip enhances the wingtip vortex [7]. Reducing the distance of the incident vortex to the wingtip has been found to increase the magnitude of the turbulence production from the resultant vortex interaction [11]. It has experimentally been found that a counter-rotating wing configuration with a 2.5C streamwise wing spacing can substantially improve rear wing L/D by up to 24% at an overlap of 5% of the wingspan [18]. Such a configuration causes migration of the rear vortex towards the root of the rear wing, however the downstream consequences of these interactions have not been characterised for more than one chord length downstream. These effects have also not been evaluated at different vortex distances from the suction and pressure sides of the downstream vane.

Adverse pressure gradients produced by downstream geometries can interact with and disrupt the path of an existing vortex. A significant obstruction in the path of a vortex will cause the vortex to transition into either a spiral or bubble breakdown mode [19]. This vortex breakdown location is dependent on the swirl number (controlled by the angle of incidence of the upstream vane) and the adverse pressure gradient. If the adverse pressure gradient is not sufficient to cause breakdown, only slow diffusion of the core through viscous mechanisms will occur.

Due to the swirling nature of vortices, they act as pressure gradient amplifiers in the sense that an induced pressure gradient in the freestream will be substantially increased at the vortex core [20]. A probe placed near a vortex causes substantial upstream migration of the breakdown location [21]. As such, either Laser Doppler Anemometry (LDA) or Particle Image Velocimetry (PIV) must be used for accurate experimental results for steady vortices. However averaging point measurements can result in errors of up to 35% in tangential velocity in meandering vortex cases, emphasising the importance of a global measurement technique for meandering or unstable vortex analysis [22,23].

The work described in this paper investigates the near field interactions of a vortex produced by an upstream vortex with a downstream vane. PIV analyses have been performed for a wide variety of vane offsets at multiple downstream locations, allowing inspection of both the paths of the vortices and the meandering of the vortex pairs. Characterisation of near-field counter-rotating vortex interactions has been achieved, and the effects of generating a vortex in a flow field with a pre-existing vortex structure are found.

2. Experimental setup

The present study considers the interaction of two streamwise vortices produced by two NACA 0012 vanes. One vane was located 10 chord lengths (C) downstream of the other, as can be seen in Fig. 1. This configuration was chosen as it allows interactions between vortices to occur at extremely close proximities that cannot be observed if the vortices are deployed at the same locations. This is also representative of the effects of a pre-existing vortex in a flow interacting with a vortex producing device. An angle of attack of 8 degrees on each vane has been used for all cases, with a square-edged tip. Higher angles of attack decreased the vortex stability, with unsteady breakdown becoming observable for a single vortex case at 12 degrees. Multiple offsets were tested from −0.6C to 0.5C in increments of 0.1C, with a finer spacing of 0.05C between −0.4C and 0C.

The x-axis is in the direction of the flow, with positive downstream, the Y axis is across the tunnel and the Z axis is in the vertical direction. As such, the rear vane quarter chord was located at $X = 10C$, with the vane root at $Z = -1.5C$.

Planar slices of the flowfield were captured using PIV at 0.5C intervals from 1.5C back from the quarter chord of the trailing vane to 7C back. These correspond to 11.5C and 17C from the leading vane respectively. The laser sheet was not moved closer than 11.5C as the reflections from the vanes began to distort the results. The experiment was performed at a Reynolds number of approximately 7×10^4 based on chord length. At 7×10^4 the vortex shedding from a NACA0012 airfoil at 8 degrees angle of attack is within the supercritical region [24] and therefore any Reynolds number lower than 6×10^4 at this angle of attack will result in a shedding regime that is not indicative of higher Reynolds number scenarios. Running the tunnel as slow as possible within the acceptable Reynolds number range minimised vibration of the diffuser expansion, camera mounting and test section caused by the operation of the fan, thus minimising imaging errors.

2.1. Wind tunnel

Experiments were performed in the Macquarie University open return, closed section wind tunnel. This tunnel has a 610 × 610 mm (24 × 24 in.) octagonal test section with a 1900 mm (6′ 3″) length. Optical access is through a glass window on the top of the test section and removable windows on the side. The test section was characterised using a Turbulent Flow Instrumentation 100 Series Cobra probe, giving a peak turbulence intensity of 0.35% and average of 0.25%. Velocity uniformity was measured as better than 1% variance, and flow angularity was found to vary by 1 degree across the test section inlet. The wind tunnel speed was electronically controlled through a National Instruments MyRIO, with the pressure sensors calibrated against a temperature