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Effects of Axial Pulsing on Unconfined Vortex Breakdown

S. Khalil, K. Hourigan and M.C. Thompson

Fluid Laboratory for Aeronautical and Industrial Research (FLAIR)
Department of Mechanical Engineering PO BOX 31
Monash University, Clayton, Victoria 3800, AUSTRALIA

Abstract

The experimental investigation undertaken explores the response of low Reynolds number (300<*Re*<1000) unconfined swirling jets undergoing vortex breakdown to axial pulsing. In particular particle visualisation in conjunction with 2-D PIV has allowed a detailed examination of the effect of axial pulsing on shear-layer flow structures and vortex breakdown, as the pulsing frequency and amplitude is varied. A range of Reynolds numbers and swirl numbers is considered. Extremely promising results have been obtained revealing that pulsing at the natural shedding frequency results in substantial downstream shift of the mean breakdown position. Furthermore, application of low-level forcing at the natural frequency intensifies the shear-layer vortices considerably.

Introduction

Experimental research into vortex breakdown and vortex breakdown control techniques has been undertaken for the past 50 and 40 years respectively [2,8]. The importance of understanding this phenomenon, and how to control it, is of immense importance for applications such as heat exchangers and combustion control, but none more pronounced than in the aeronautical industry.

Studies have shown that the swirl number, defined as the ratio of azimuthal to axial velocity, is a useful parameter to determine whether vortex breakdown will occur [1]. Either slowing the azimuthal velocity or increasing the axial velocity can lower the swirl number. This can have a stabilizing effect by delaying vortex breakdown, or even lead to the recreation of the vortical core after breakdown has occurred [8]. Vortex breakdown can therefore be considered as a reversible phenomenon with respect to its ability to pass between the pre-breakdown and post-breakdown states. However, it should be kept in mind that the transition to the breakdown state is hysteretic and to re-establish the pre-breakdown state may require the swirl number to drop well below the critical value for the onset of breakdown.

Controlling this phenomenon by introducing well-defined perturbations into the flow field by implementing unsteady blowing techniques has been conducted previously on delta wings with great success. As pointed out in a review paper by [9], Werle (1954) was the first investigator to implement blowing as a means of controlling breakdown. Werle found that blowing downstream along the core delayed or eliminated breakdown, while blowing upstream caused breakdown to spontaneously occur or to move further upstream. Further studies of vortex breakdown control techniques applied to the flow over delta wings by [3,11,13] have revealed the most effective positions to implement control mechanisms are those close to the point of vortex conception and downstream of breakdown. The unsteady nature of breakdown, especially at higher Reynolds number, introduces difficulties in positioning a downstream control device; hence, in practice, the optimum control location is upstream of breakdown or at the point of conception of the vortex core.

Although both continuous and pulsed blowing or suction cause a delay in the formation of the breakdown structure, there are certain advantages displayed by the pulsed approach. [10] concluded from their investigation of continuous blowing along the core that the downside of that technique is the large amount of energy required for its effective implementation. [12,13] experimented with both steady and pulsed trailing-edge blowing and found that intermittent blowing during the upward pitching of a delta wing was the most effective means of shifting the vortex breakdown location downstream. [4] conducted several experimental investigations into control methods including tangential suction and blowing, steady suction, and alternate tangential suction and blowing, all applied along the leading edge. Although all the above-mentioned control techniques delayed breakdown, the most effective was found to be alternating blowing and suction. [5] studied the effects of oscillatory jets exiting through spanwise slots along a NACA 0015 airfoil. Their results demonstrated *"the effectiveness of pulsed blowing as a tool to increase lift and reduce drag* (by enhancing the wake profile), *especially when compared to the relative ineffectiveness of steady blowing under similar conditions*." [6] showed that pulsed blowing parallel to the leading edge was almost twice as effective in delaying vortex breakdown as continuous blowing, with the best results achieved at the natural shedding frequency of the shear layer. Further advantages of unsteady pulsing or blowing lies in the reduced energy use and the ability to maintain an unchanged mean jet momentum or mass flow as required/desired.

In this study employing unsteady pulsing to control breakdown of an effectively unconfined vortex core, an initial study of the shear layer and corresponding shedding frequency was undertaken. Subsequently, an examination of the resulting breakdown structure and its movement, both locally and globally, was carried out. The primary aim of this investigation was to uncover which frequencies and amplitudes of pulsing create the greatest movement of the vortex-breakdown (upstream) stagnation point.

Experimental Setup

The swirling flows generated in this experiment were created by a similar method to that of [1,15], and consisted of a pressure-driven swirling water jet which discharges into a large tank. The swirl is imparted by means of an electric servomotor, which rotates a honeycomb within a settling chamber. A schematic of the apparatus is shown in Figure 1.

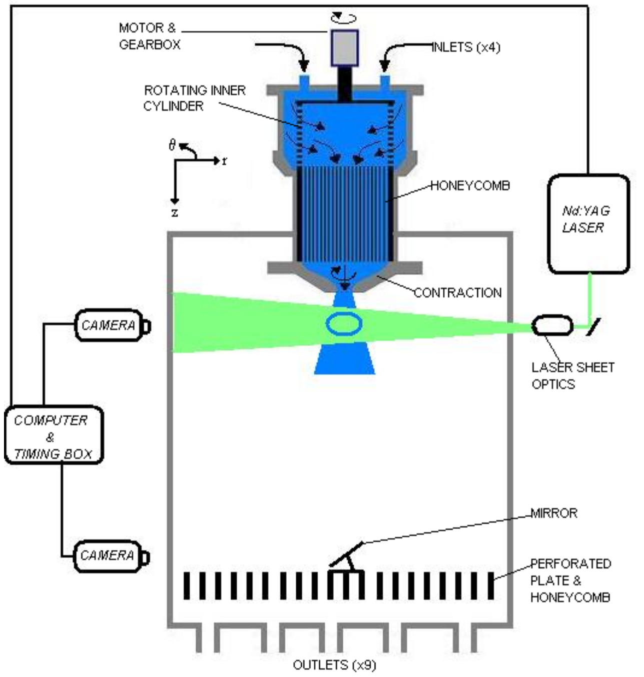

Figure 1: Experimental setup. Note: Laser sheet is rotated for both horizontal and vertical plane cross-sections.

A smooth axial velocity is generated by a laminar pulse-less disc pump, creating a closed circuit with accurate control of axial flow rates. It also enables a more realistic simulation of a pulsing mechanism, which could be used in combustion chambers or in flight. Pulsing is achieved via an inline computer-controlled proportional-lift solenoid valve. Previous studies (see [9]) have examined steady and unsteady suction and blowing of separate flows, which join the vortical structure somewhere along its path to control vortex breakdown. This experiment is novel in that it pulses the actual vortical structure in the axial direction at the point of generation. The flow rate, which in turn determines the axial Reynolds number, is controlled to within ± 1% by a frequency inverter connected to the disc pump and an electronic flow meter.

The azimuthal velocity component is imparted to the flow via the vortex generator. The vortex generator consists of a motor and two concentric cylinders, similar to that used by [1]. The underlying principle is to set the axially flowing fluid into a solid body rotation before passing through a contraction. The fluid in the outer cylinder passes through the upper part of inner cylinder through an arrangement of holes. In order to set the flow into laminar solid-body rotation, (i.e. a Rankine vortex), the flow is then passed through a honeycomb located in the lower part of the rotating inner cylinder. The swirling jet then passes through a smooth converging nozzle, which is attached to the outer cylinder and is fixed, i.e. non-rotating. In order to avoid flow separation, the contraction zone is designed according to Mikhail (1979)'s optimum contraction design method. The exit diameter of the contraction zone is $D = 2R = 39.5$mm. A frequency inverter and servomotor control the frequency of rotation to within ± 0.5 %.

The vortex generator is partly submerged in a square cross-section (650mm x 650mm x 1500mm) transparent Perspex tank into which the swirling jet is discharged. Such a configuration allows the simulation of an almost unconfined vortex due to the large ratio of tank to jet area (~345). Recirculation currents were found to be almost non-existent in all cases.

An intercooler setup was also incorporated to ensure minimal temperature gradients within the tank to avoid thermal convection currents. The intercooler involved passing the cooler outflow over the warmer inflow via an intercooler core. In order to ensure slow-moving outlet flow, and to minimise pressure gradients caused by the outlet pipes, a perforated plate, acting as a honeycomb, is placed at the bottom of the test tank. This also had the advantage of retarding any whirlpool effect from occurring. Water consistency and temperature uniformity was vigilantly monitored with highly sensitive thermometers at specified locations around the whole circuit. The maximum temperature difference between the swirling jet and fluid within the test tank was found to be 0.5°C.

In order to characterise this experiment the following non-dimensional variables were used based on a cylindrical (r, θ, z) coordinate system. The swirl number S provides a measure for the ratio of azimuthal velocity U_θ and axial velocity U_z.

$$S = \frac{2U_{\theta max}}{U_{zmax}} = \frac{2U_\theta(r = R/2)}{U_z(r = 0)}. \quad (1)$$

At the critical swirl number, S_c ~1.3, vortex breakdown is found to occur independent of the Reynolds number and nozzle diameter [1]. The Reynolds number characterises the axial flow component, and is based on the jet diameter $D = 2R$ and average axial velocity $\overline{U}_z$ which is extracted from the mean mass flow rate $\overline{m}$.

$$R_e = \frac{2\overline{U}_z R}{\upsilon}. \quad (2)$$

Furthermore, the Strouhal number non-dimensionalises the frequency of pulsing, f,

$$St = \frac{2fR}{\overline{U}_z}. \quad (3)$$

The sinusoidal variation in mass flow during pulsing is characterised by the *Peak Mass Flow Variation* (PMFV).

$$m_v = \frac{\overline{m} - m_{\min}}{\overline{m}} = \frac{m_{\max} - \overline{m}}{\overline{m}}. \quad (4)$$

Here, $m_{\min}$ and $m_{\max}$ are the minimum and maximum mass flow rates, respectively.

Data Acquisition

For both visualisation and PIV measurements, the water was seeded with spherical polyethylene (25μm) particles with an SG of 0.9. In order to create minimal disturbance to the flow the particles were continuously feed into the flow as far upstream as possible. The injection rate was controlled via a piston-controlled injection chamber and a gravity-feed device. Particles were illuminated via a combination of stage lights and lasers. For PIV, the particles were illuminated using a laser sheet generated by a frequency doubled Nd:YAG laser at 532nm and 400mJ in 5ns bursts.

Flow visualisations were conducted using a 5 mega-pixel Minolta digital camera and a Kodak ES4 CCD 4 mega-pixel camera, which was also used to acquire the raw PIV images. The ES4 CCD camera was used at both 30hz (1024 x 1024 pixels) and double shutter mode at 5ms and an 8Hz sequence between image pairs. PIV was used for quantitative measurements of axial and swirl profiles in order to obtain the swirl number.

PIV was performed using a cross-correlation type analysis, with the dynamic range enhanced using an iterative approach to select the Sample Window Size (SWS) by starting at 128 x 128 to a final window size of 16 x 16 with a an overlap of 50%. By performing the analysis in this fashion the largest displacement vectors are determined by using a large SWS. The accuracy and spatial resolution is increased by then reducing the SWS and offsetting successive pairs of sample windows by the displacement calculated from the previous iteration. Erroneous vectors are rejected by comparing them to a local fit of the data (in an absolute sense) and any vector which deviates from that fit (by more then 2 pixels in this case) are rejected and replaced by the local fit. Vorticity is calculated using a second-order least-squares fit in X and Y (6 terms) and then analytically differentiating this equation to obtain the derivatives i.e. the vorticity.

Results & Discussion

An examination of the (helical) vortex structures forming at the edge of the unforced swirling jet was conducted by using long exposure (0.5sec) images spanning a period of 120 seconds. A sample frame is shown in Figure 2.

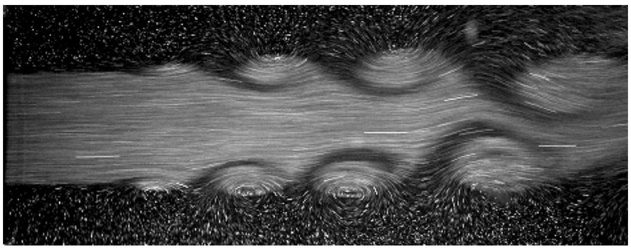

Figure 2: Shear layer shedding of a swirling Jet at R_e=900, S=0.3.

A spectral analysis of the data revealed that the shear-layer Strouhal number is independent of the swirl number, in agreement with [7]. Furthermore, over the Reynolds number range tested, the Strouhal number is independent of Reynolds number to within two standard deviations of the mean and is fixed at $St = St_n = 0.78 \pm 0.01$, as shown in Figure 3. The shear layer first sheds at approximately one to two nozzle diameter downstream in all cases and appeared to periodically shed in small bursts with durations and delays of the same order as the natural shedding frequency of the structure.

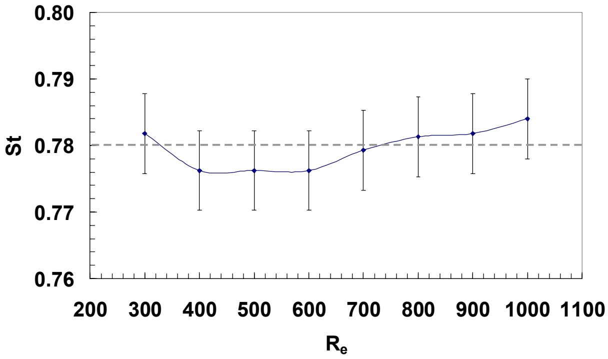

Figure 3: Shear-layer Strouhal number as a function of Reynolds number. S_{tn} is shown by a dashed line.

By sinusoidally pulsing the swirling jet mass flow rate *m*, in the form $m = \overline{m} + (m_{\max} - \overline{m})\sin(2\pi f\, t)$, it is possible to alter the vorticity within the shear layer (see Figure 4), hence altering the vortex-shedding frequency at the point of its conception.

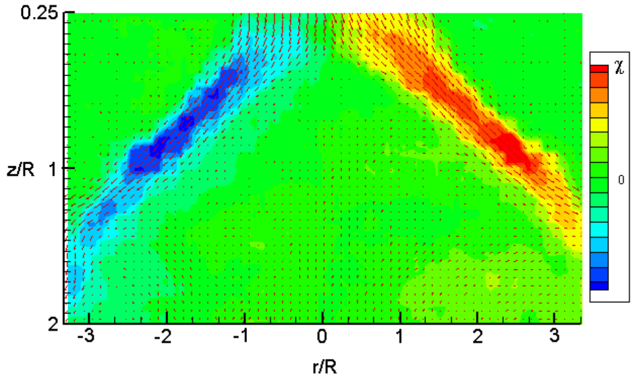

Figure 4: Vorticity χ plot of a swirling jet undergoing breakdown with no pulsing (m_υ=0) at Re=600 S=1.36.

The vortex shedding frequency was easily controlled when pulsing was conducted at S_t<2S_{tn}. The shedding frequency of the swirling jet was found to lock onto low frequencies up to approximately twice the un-pulsed or natural frequency of shedding. Above this critical value, the flow below the stagnation point where the shedding becomes apparent is unresponsive to the imposed perturbation and the jet sheds at its natural frequency independent of the amplitude of the perturbation. As is the case with most stability problems, the shear layer is unreceptive when pulsing is conducted far from that of the natural frequency.

The effect of pulsing at various Strouhal numbers on breakdown was determined by flow visualisation. The breakdown stagnation point Z_b was found to move further downstream as the pulsing Strouhal number approached the natural Strouhal shedding frequency (see Figure 5) in agreement with the experiments conducted by [6] using delta wings. To obtain significant downstream movement of the breakdown position, pulsing must be conducted at $St = St_n \pm 10\%$.

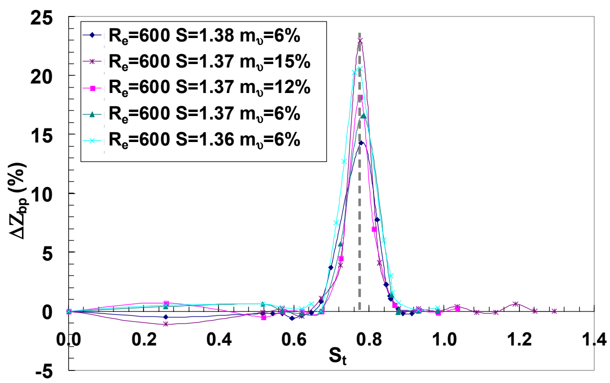

Figure 5: Pulsed breakdown position Z_{bp} as a percentage of the un-pulsed breakdown position Z_b (where: ΔZ_{bp}= (Z_{bp}-Z_b)/Z_b) for various Swirl and PMFV values at R_e=600. Similar results occur for the other Reynolds numbers tested.

Some key findings are that axial pulsing within the hysteretic range at which breakdown exists has the ability to revert the core to the non-breakdown state, with PMFV values as low as m_υ=6-12%. An established breakdown moves downstream as PMFV values increase, however, the shift begins to plateau at m_υ>30-40%. For higher amplitudes, large fluctuations in the stagnation point position are observed. It is not uncommon to experience relative shifts of up to ΔZ_{bp} = 50% at $S = S_c$ and St= 0.78, with higher swirl stabilizing the structure, in agreement with [7], and lowering ΔZ_{bp}. Flow visualisations at St = 0.78 (Figure 6) shows that axially pulsing the breakdown at this frequency increases the concentrations of vorticity within the shear layer and excites the shear-layer resonance.

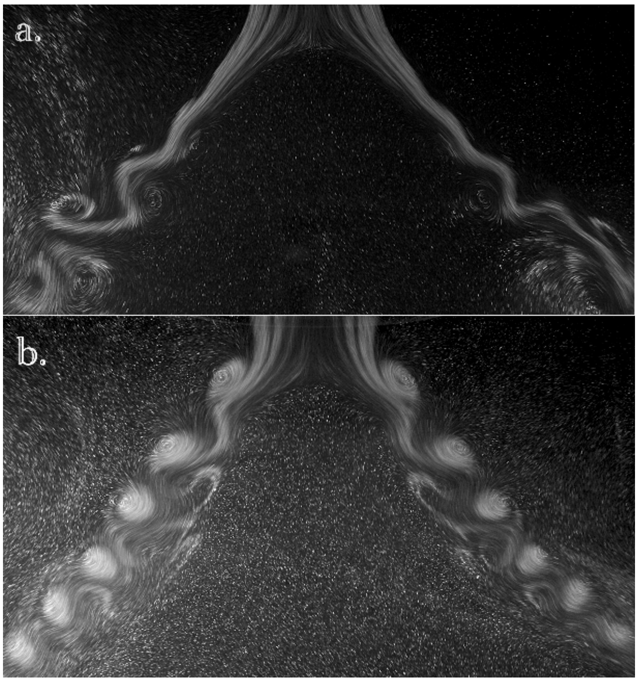

Figure 6: (a) Unpulsed breakdown m_υ=0 at R_e=600, S=1.41; (b) pulsed breakdown m_υ=6%, St=0.78 at R_e=600, S=1.41 clearly showing increased vorticity concentrations in the shear layer resulting in increased ΔZ_{bp}.

The modifications to the shear layer structure and the highly periodic shedding at St = 0.78 ± 10% has the effect of forcing the stagnation point further downstream. From observations it was also interesting to see that the stagnation point without pulsing was consistently further upstream than the axial position at which the shear layer begins to shed. Whereas when axial pulsing was applied at St = 0.78 ± 10%, the axial location at which shedding begins moved further upstream closer to the jet outlet consistently higher then the stagnation point which moved downstream. The reason for the stagnation point movement downstream could be that the shear layer vorticity concentrations effectively modify the mean axial and azimuthal velocity profiles so that breakdown is delayed. This hypothesis is still under investigation.

Conclusions

The application of axially pulsing to swirling jets undergoing vortex breakdown can have some profound effects on the resulting structure. The following can be concluded from this preliminary experimental investigation:

1. For an unforced swirling jet, the Strouhal number of shedding is independent of Reynolds number and swirl number, and is fixed at $St = St_n$ (= 0.78).
2. For the forced case, the shedding frequency of the swirling jet was found to lock onto low frequencies up to approximately $2St_n$. Above this critical value, the flow below the stagnation point is not receptive to the higher frequency pulsing and the jet sheds at its natural frequency, independent of the amplitude of the forcing.
3. To obtain significant downstream movement of the breakdown position, pulsing must be conducted close to the natural frequency, i.e., at $St = St_n$ ± 10%.
4. Axial pulsing within the hysteretic range over which breakdown exists has the ability to destroy the breakdown structure all together with PMFV values as low as m_υ=6-12%. It is possible to shift the breakdown structure by up to 50% at $S = S_c$ and St = 0.78.
5. The increased vorticity concentrations within the shear layer and the highly periodic shedding at St =0.78 ± 10% has the effect of forcing the stagnation point further downstream, delaying breakdown as shedding now occurs closer to the nozzle exit.

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