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The Generation and Suppression of Vortex Breakdown by Upstream Swirl Perturbations

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Abstract

While a mechanism for vortex breakdown has not yet been comprehensively described, efforts have been made to obtain some control over breakdown in flows of practical interest. In this study the response of breakdown in one geometry to disturbances of varying magnitudes is investigated computationally. The parameter space studied corresponds to the region in which hysteresis occurs; here the possibility of suppression or instigation of breakdown within this region is explored, through the introduction of an upstream disturbance to the flow. Results indicate that a jump to and from conjugate breakdown/non-breakdown states can be provoked through judicious application of a transient impulse.

Introduction

The disruptive effect of vortex breakdown over delta wings at high angle of attack, and its potential use for the destruction of the powerful vortices which trail behind heavy aircraft, have stimulated searches for the control of breakdown. Most studies have been conducted over delta wings and generally entailed a form of axial blowing ([2], [12], [11]), flap deflection ([6], [5]), or changes to wing planform ([15], [16], [10], [8], [14], [9]).

One of the characteristics of vortex breakdown is the existence of regions of parameter space in which flow hysteresis is observed. Studies of vortex breakdown over delta wings, in swirling pipe flows, and in cylinders have shown that multiple states can exist for a single set of parameter values.

In this paper, a method is considered by which changes between the two states may be realised. We aim to investigate whether transitions between states can be induced by introducing perturbations at the inlet. Our perturbations will involve changing the swirl to axial velocity ratio at the inlet; this is achieved by directly manipulating the value of Ω, where Ω is defined in the equations below describing the inlet boundary condition:

$$u(r) = 1 + \Delta v e^{-r^2} \quad (1)$$
$$v(r) = 0 \quad (2)$$
$$w(r) = \frac{\Omega}{r}\left[1 - e^{-r^2}\right] \quad (3)$$

where u, v, and w are the axial, radial, and azimuthal velocity components respectively. In the cases we consider Δv is zero, so the velocity in the axial direction is constant across the inlet.

In this manner only the swirl ratio is changed, and the axial velocity remains constant. The questions to be addressed in this investigation of these transitions are:

1. Can a perturbation to a flow which is initially without breakdown induce a persistent breakdown?
2. Can a perturbation to a flow which begins with breakdown present result in the disappearance of the breakdown bubble?

The obvious answer to both of these questions is yes, if the perturbation is sufficiently large and sustained. For example, if the flow is pushed out of the hysteresis range into the region where only the other state is possible, and held there by the inlet boundary condition, the other flow condition must come about. However, it is unknown just how large (in amplitude and duration) the perturbation must be to achieve this.

We aim to map out the transitions as a function of Ω_P and dt. Ω_P is defined as the proportional change in Ω applied to the inlet: $\Omega_P = \frac{\Omega}{1.45}$, where the initial swirl $\Omega = 1.45$. The change will be applied step-wise. dt is then the duration for which the perturbation is maintained.

A previous publication (Adams *et al.* [1]) detailed the vorticity dynamics in the pipe as a large pulse was applied. In that study it was found that a breakdown bubble could be produced in a flow initially without breakdown by the introduction of a pulse twice the initial swirl, but this bubble subsequently disappeared. In this paper we more comprehensively map out the effect of applying pulses of varying magnitude and duration to the pipe, for initial conditions with and without breakdown.

Problem Formulation

This study will focus on the region in the Ω_P/Re parameter space where hysteresis occurs in the open pipe. The pipe geometry used is defined in Darmofal and Murman [4] (1994), and is pictured in figure 1. It consists of a pipe with a constriction just downstream of the inlet, a straight test section, and a converging outlet.

For this study we use Fluent version 4.5.2. Careful attention has been paid to obtaining grid independent solutions. In addition, the numerical results obtained from this code show close correspondence with those of Darmofal and Murman [4] (1994) and Beran and Culick [3] (1992), for this pipe geometry. Modelling of Faler and Leibovich's [7] experimental study also revealed consistent results, although the bubble in our study was consistently larger than that observed by Faler and Leibovich [7]. This is attributed to the high sensitivity of the bubble to small differences in the upstream velocity profile.

In order to arrive at the initial condition for this study we begin with a steady solution at $\Omega = 1.43$, without breakdown, and increase the swirl in small steps, keeping the axial velocity constant, until breakdown is observed at $\Omega = 1.461$. This process defines the limit on the upper branch for the no breakdown state; see figure 2. Next the swirl is reduced, so that the flow travels along the lower branch in figure 2, until the breakdown bubble disappears at Ω=1.43. This defines the limit point on the lower branch. This second limit point is more difficult to define - the bubble seems to be more persistent once it has evolved, and the flow takes a long time to return to the original pre-breakdown state.

The two initial conditions thus obtained are displayed in Figure 1.

Figure 1(a) has $\Omega = 1.45$, and no breakdown bubble. Fig-

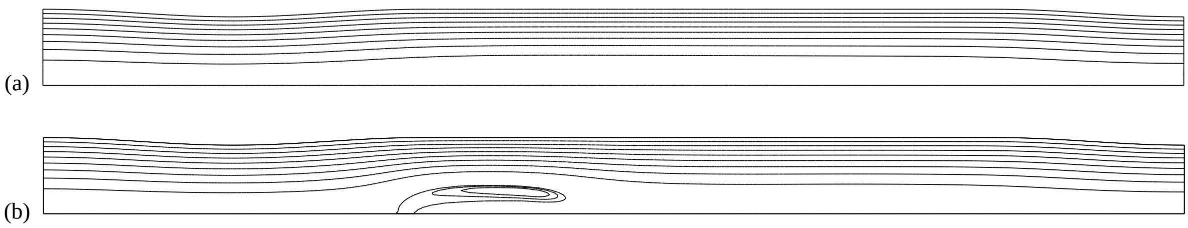

Figure 1: Streamline plots of the 2 initial conditions where $\Omega = 1.45$; (a) without breakdown and (b) with breakdown.

ure 1(b) also has $\Omega = 1.45$, but in this case a bubble is present. $\Omega = 1.45$ at $Re = 1000$ is near the centre of the hysteresis region.

The range over which hysteresis occurs compares favourably with Beran and Culick's [3] (1992) range of $1.465 < \Omega < 1.505$ for the same Reynolds number. The relative range shift may be due to the slightly different geometries considered - both of the pipes are identical apart from a converging outlet in our study. The two ranges are of comparable size. The inlet velocity profile is the q-vortex, as described in the u, v, w equations above. This profile is identical to that used in Beran and Culick [3] (1992), but Ω replaces V, the 'vortex strength', used in their study.

We aim to trip the flow into the conjugate state by sending an increase or decrease in swirl, imposed at the inlet, down the pipe. The pulse time dt is the time the pulse is maintained, normalised by the pipe length and axial velocity.:

$$\mathrm{dt} = \frac{u\Delta t}{L} \quad (4)$$

where u is the axial velocity, L is the pipe length, and Δt is the time in seconds. In some cases dt=∞ is specified for the breakdown to no breakdown transition. In these cases a steady solution is generated for the reduced (perturbation) swirl; this is equivalent to setting dt to infinity.

The pulse amplitude is represented by the pulse swirl divided by the initial condition swirl, which is 1.45 in all cases:

$$\Omega_P = \frac{\Omega}{1.45} \quad (5)$$

Hence an increase in swirl is represented by $\Omega_P > 1$, and a decrease in swirl by $\Omega_P < 1$. We conduct tests for various pulse times and amplitudes.

Transition from No Breakdown to Breakdown

The initial condition can be seen in figure 1(a). The aim is to determine a combination of the pulse amplitude Ω and pulse duration dt that will result in the evolution of a breakdown bubble from an initial state without breakdown. If the pulse is kept on indefinitely breakdown is expected to evolve and remain, as all pulse magnitudes increase the swirl Ω to the point where only the breakdown solution exists. It is unknown whether the breakdown will remain once the swirl is reduced again, however. The situation being tested here is represented schematically in figure 2:

Although the schematic shows a descent to the lower branch, the introduction of the pulse pushes the flow into a region not necessarily represented by the two curves. The final state will be somewhere on one of two curves specified however.

Figure 3 displays breakdown incidence as a function of Ω_P and

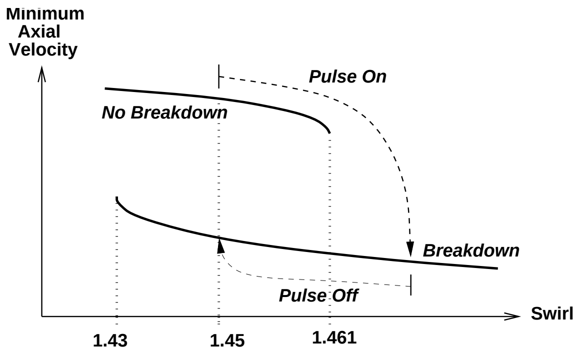

Figure 2: Schematic of the procedure for no breakdown to breakdown transition tests.

dt. Triangles indicate the presence of a breakdown bubble in the final state, after the swirl perturbation has passed through. Crosses represent a final flow without breakdown.

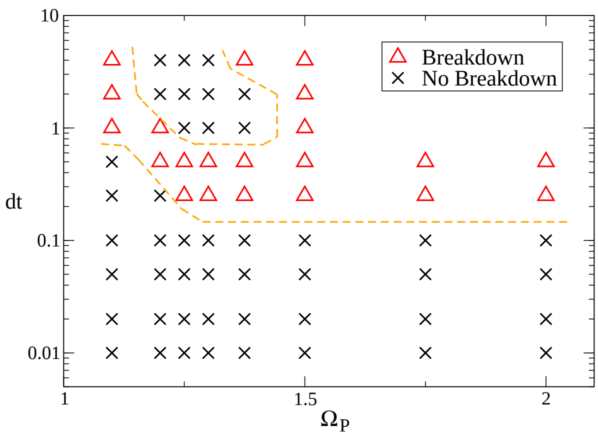

Figure 3: Plot of dt vs Ω_P for the no breakdown to breakdown transition

Figure 3 shows that for pulse durations dt$\leq$0.1 all final solutions are free of breakdown. A bubble may have evolved as the pulse passed through the pipe, but after the swirl reverted back to the initial condition level the bubble disappeared.

As pulse magnitude reduces below $\Omega_P = 1.25$ final solutions without breakdown become possible for dt>0.1. This is an expected result as the lower pulse amplitude results in less rapid generation of negative azimuthal vorticity, and hence more time would be required, for lower Ω_P, for sufficient negative azimuthal vorticity to be generated to bring about breakdown.

Increasing dt to dt=0.25 results in the onset of breakdown in the final solution for all $\Omega_P \geq 1.25$. A bubble frequently developed while the pulse was on, but for all dt< 0.25 the bubble disappeared again. It was not until dt$\geq$0.25 that a bubble could be maintained. As dt is increased further, for $1.20 \leq \Omega_P \leq 1.375$ the final solution reverts back to no breakdown. For values of Ω_P outside this region the progression from no breakdown to breakdown is monotonic. It was expected that once an Ω_P/dt combination was found which resulted in breakdown, an increase in Ω_P or dt would also result in breakdown. However, for $1.20 \leq \Omega_P \leq 1.375$ increasing dt beyond the level where breakdown occurred eventually resulted in the disappearance of the bubble. It is apparent that the response of the pipe flow to a pulse is not as simple as was first anticipated. It turns out that for $\Omega_P > 1.05$ the flow is periodic, so it may be that the phase in the cycle at which the swirl is reduced also has an effect on whether the bubble persists or not. That is, the state of the flow when the reduced swirl reaches the breakdown region partly determines whether or not breakdown will persist.

Results for dt>0.10 in the Ω_P=1.75 and 2.00 cases were not pursued, as at these high values of Ω the bubble progressed past the converging section and up to the inlet for dt>0.10, rendering the solution unphysical.

We see from these results that a transient impulse can be used to promote breakdown. The length of the pulse required is relatively short. For the next part of the study it will be shown that the reverse transition is also possible, but dt must be much larger to ensure the breakdown bubble is suppressed.

Transition from Breakdown to No Breakdown

For the next stage of this work the opposite transition was investigated - from the breakdown state to no breakdown, as represented in figure 4.

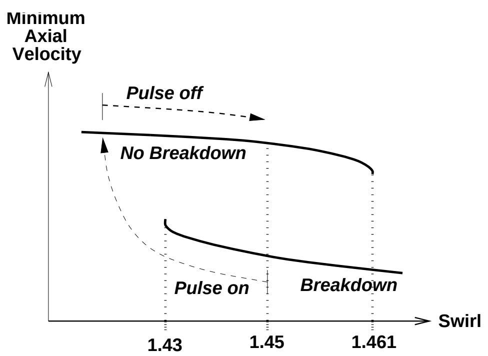

Figure 4: Schematic of the procedure for breakdown to no breakdown transition tests.

This part of the study is of relevance to the control of breakdown. If a bubble has evolved, can it be destroyed by applying a perturbation from upstream? This study is performed at a very low *Re* compared with flows of practical interest; however, hysteresis has been documented in the more practical flows. Lowson [13] observed hysteresis in relation to vortex breakdown over delta wings up to $Re = 30000$, and it is noted (Lowson [13]) that since *Re* does not have a large effect on flow on slender wigns, hysteresis is also expected for higher *Re* flows of practical interest.

For this series of tests we begin with the initial condition containing breakdown, as shown in figure 4. Again Ω_P and dt will be varied and each solution examined once the transients have passed through the pipe.

The results are summarised in figure 5.

In this plot we have included dt=∞ results. In these cases the pulse was maintained until the flow became steady, then the swirl reverted to $\Omega = 1.45$. Hence these cases define the limit

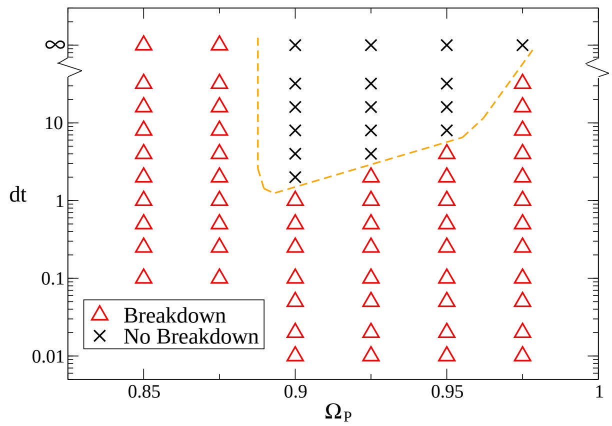

Figure 5: Plot of log dt vs Ω for the breakdown to no breakdown transition

for pulse duration. At $dt = \infty$ the region in Ω_P for which a no breakdown solution is obtained is $0.9 \leq \Omega_P \leq 0.975$. Below $\Omega_P = 0.90$ it is not possible to remove the bubble by this method. This was also observed during the setup of the two initial conditions; a large sudden increase in swirl invariably resulted in the appearance of a breakdown bubble in the steady state. Hence the key to suppressing breakdown in this scenario is the imposition of a small perturbation for a longer time.

For a permanent transition to the state without breakdown a minimum of dt=2.00 is required, whereas for the previous no breakdown to breakdown transition, dt=0.25 was sufficient to cause breakdown to appear in the final solution. The bubble appears to be a more robust form than the flow without breakdown. A sudden imposition of sufficiently large swirl will invariably lead to breakdown, rather than its conjugate form.

The range over which breakdown can be eliminated decreases with decreasing dt, until for pulses with duration of dt=1.00 or less it is not possible to eliminate breakdown once it has evolved. Hence there is an optimal value at $\Omega_P = 0.90$, below which breakdown suppression is not observed, and above which the pulse application time *dt* increases.

Conclusions

Based on these results we come to a number of conclusions, which we re-state below:

- The no breakdown to breakdown transition is easier to trip than breakdown to no breakdown; it is much easier to bring about breakdown within the parameter space considered than it is to suppress it.
- With smaller perturbation magnitude, initial breakdown onset takes longer.
- Removal of the bubble requires pulses of longer duration than those required to generate the bubble. The pulse magnitudes which bring about transitions are similar for both cases.

Further work

This study considers only the response to a top hat profile swirl increase and decrease. The initial conditions with and without breakdown were achieved by a gradual increase/decrease of swirl to the required state. Hence we have explored two scenarios, one of instantaneous swirl change, and the other a very gradual ramping of swirl. The gradual ramping guarantees the required change, while the sudden swirl change can result in either a reversion to the original state or transition to a new state. Between these cases there is potential to explore the region of varying ramping times. This will be considered in a further study.

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