ANALYSIS OF DIFFERENT VORTEX BREAKDOWN STATES

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Summary Vortex breakdown has in previous investigations of columnar vortices been explained either as an abrupt change between two stable states of vorticity distributions or as an instability. In the present work we combine the two approaches to explain various states of vortex breakdown. From stability analysis it is shown that secondary multiple vortex structures (multiplets) arise from the instability of an initially axisymmetric vortex state. However, the analysis also shows that the instability boundary divides two regimes with stable solutions, one containing columnar vortices and the other various states of stable helical vortices.

Introduction

Vortex breakdown is a phenomenon inherent to many practical problems in aerodynamics, geophysics, and engineering, such as tip vortices over wings and behind propellers, atmospheric tornadoes and cyclones, flame-holder vortex in combustion devices etc. The breakdown of these vortices is associated with an abrupt deceleration of the axial velocity on the vortex axis which sometimes develops to a recirculation zone. Although now about ten forms of vortex breakdown have been identified [1-3], the gist of the phenomenon is not yet fully explained. In our communication we will try again to look at the phenomenon as a transition between two stable states of vorticity distributions.

Transition between different axisymmetric states of a single vortex (conventional vortex breakdown)

One of the first theories of vortex breakdown are due to Benjamin [4], who explains the phenomenon as a transition between conjugate flow states, like a hydraulic jump in an open channel flow. In [5] this idea has been utilized to describe an abrupt change - transition between two vortex states with different helical symmetry of the vorticity lines which gives a change in axial velocity from a jet-like profile before breakdown to a wake-like profile after breakdown (fig. 1,*a*). Using a control volume (CV) analysis [6] conserving five characteristic quantities of swirling pipe flows (flow rate, velocity circulation, axial flux of angular momentum, axial flux of momentum and axial flux of energy) shows the existence of four equivalent flow states described by different velocity profiles (fig. 2). Two (1 and 3) of these solutions are in very good agreement with experimental velocity profiles measured before and after breakdown [7].

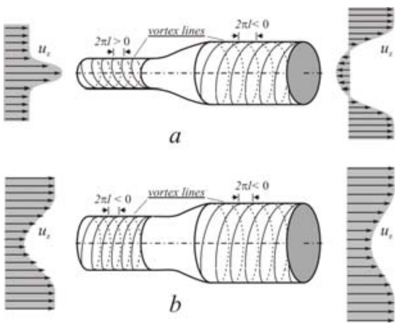

Fig 1. Sketch of two transitions:
(*a*) vortex breakdown with reversal flow;
(*b*) slight type of vortex breakdown.

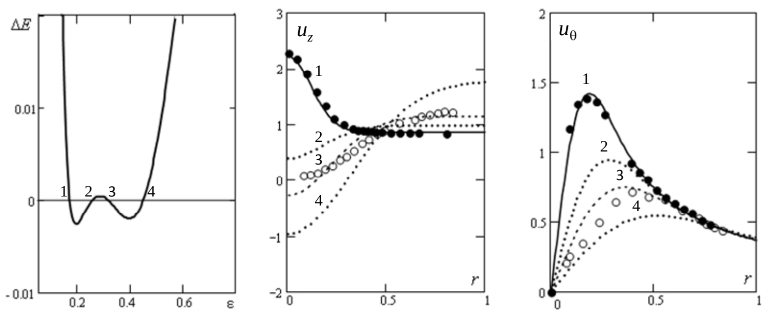

Fig 2. *Left*: the roots of the energy balance gives 4 solutions for 4 vortex states; *Middle and right*: profiles of axial u_z and azimuthal u_θ velocities of the different states: lines – solutions [5, 6]; points and circles - experimental data from [7].

This CV-analysis describes not only the usual form of vortex breakdown with a change from jet-like to wake-like profile (fig. 1,a), but it also predicts any transition between 1-4 states. One of them is a transition between different states with wake-like profiles (2-3) as is shown in Fig. 1(b). Recently this type of slight transition (figs 3-4) was shown to appear in the wake behind a vortex generators [8].

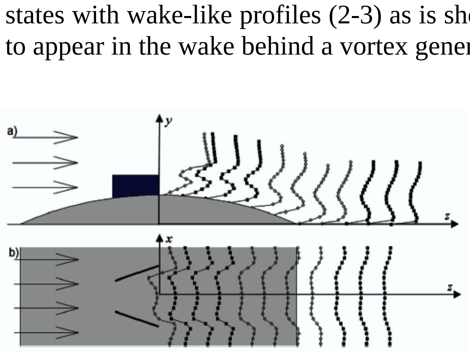

Fig 3. Fragments of flow behind cascade of vortex generators with slight vortex breakdown.

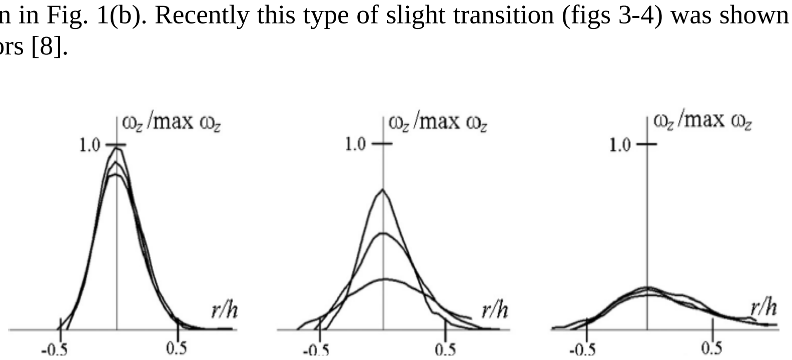

Fig 4. Changes of the vorticity during the slight vortex breakdown [8].
Left and right: initial and final stable vortex states; *middle*: zone of transition.

Instability in swirling cavity flow and transition to multi vortex states (multi vortex breakdown)

There have been many attempts to explain vortex breakdown, but most theories only deal with a part of the phenomenon [1]. In the present work we seek to explain vortex breakdown as a change between different states of vorticity distributions, understanding that instability of the initial vortex state is an intrinsic part of the phenomenon. In earlier investigations of swirling flows in a rotating cavity, we made parametrical studies of vortex breakdown [9] and, by using stability analysis, detected new vortex breakdown states [3]. The plot shown in Fig. 5, where solid lines are based on stability theory, shows a good agreement between computed boundaries and experimental observations. These states are described by three different non-axisymmetric forms of the central vortex structures (e.g. fig. 6) which are transformed from an initial axisymmetrical state. The appearance of the new stable forms, subject to a constant rotating movement, was confirmed by 3-D simulations [10]. In the plots we employ two different ways of subtracting the axisymmetric part of the solution. In one of these, visualizations of the vorticity takes the form of multi-poles (rotating waves), whereas the other displays the perturbed vorticity as multiplets (fig. 7). However, the visualizations shown in Fig. 8 clearly show that the vortex structures consist of multiplets. Of course both interpretations of the perturbed vorticity contributes to the understanding of the vortex breakdown phenomenon.

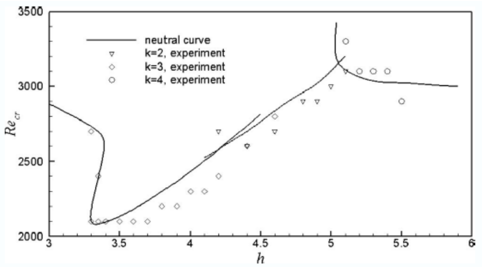

Fig 5. Neutral curves and points - boundary between axisymmetric and non-axisymmetric flow states in cavity flow.

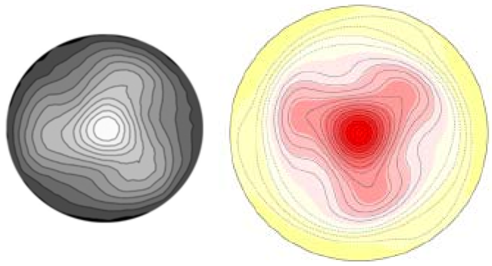

Fig 6. Example of state after vortex breakdown: Left – experiment [3], Right – 3-D simulation [10]

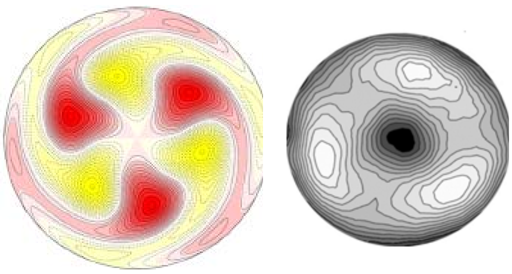

Fig 7. Example of two types of disturbed vorticity: Left – multipole or rotating wave [10]; Right – multiplet [3]

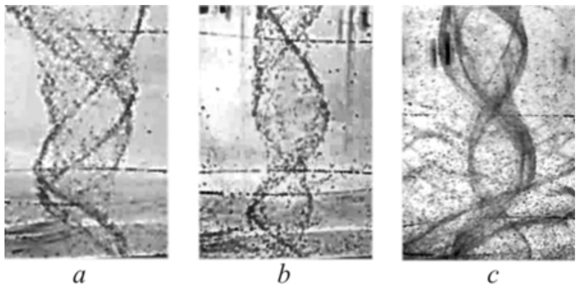

Fig 8.. Bubble visualization of multiple vortex breakdown in cavity flow: (*a*) triplet, (*b*) doublet, (*c*) quadruplet.

CONCLUSIONS

In our communication we have combined the approaches of conjugate state theory and stability analysis to explain vortex breakdown as a transition between two stable vortex states. Analysing vortex breakdown of columnar vortices as well as multiple vortex breakdown shows that that a combined approach may explain ‘classical’ configurations of single vortex breakdown as well as multiple vortex breakdown. Generally, the two approaches have been utilized independently and the present investigation is the first successful attempt to combine both types of analysis.

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