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► **To cite this version:**

Alexander Ni. Structural transitions and stability in swirling compressible flows. EUROMECH Colloquium 525 - Instabilities and transition in three-dimensional flows with rotation, Jun 2011, Ecully, France. hal-00600355

**HAL Id: hal-00600355**

**<https://hal.science/hal-00600355>**

Submitted on 14 Jun 2011

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EUROMECH Colloquium 525, 21-23 June 2011, Ecully, France  
Instabilities AND TRANSITIONS IN THREE-DIMENSIONAL FLOWS WITH  
ROTATION

## **Structural Transitions and Stability Issues in Swirling Compressible Flows**

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A theory similar to that of Laval Nozzle is developed for swirling compressible flows in annular axisymmetric ducts. On the basis of this theory structural transitions in these flows and their stability are examined. The goal of the study is to provide a simple unified view of the topic, which gives insight into the key physical features, and the overall parametric dependence of the transitions behavior.

Vortex breakdown and shock waves are well-known flow structural transitions in many flows of technological interest. Being a useful flow element in gas turbine combustors as a flame holder, a vortex breakdown may stimulate a flow separation and corresponding undesirable losses in diffusers. Control of a vortex breakdown and shock wave is a serious technical challenge. Theory of shock waves is well advanced. In classical gas dynamics shock wave represents a surface where flow parameters change by jump, being connected by Hugoniot-Rankine conditions. In some cases this approximation does not work, and internal shock wave structure must be considered. The general theory of a vortex breakdown describing quantitatively all its aspects still does not exist despite the importance of the problem, and the efforts expended on it over a period of more than fifty years. This is due to extreme complexity of the flow.

Internal compressible swirling flows are of a growing interest for needs of modern technologies: supersonic compressors, supersonic separators in oil-processing industry etc. One of the main challenges of these technologies is a reduction of pressure losses. It makes an understanding of flow transitions from subsonic to supersonic regimes and vice versa to be the key issue for proper aerodynamic channel shape design. Currently a main theoretical instrument for complex flow prediction is computational fluid dynamics. However, analytical methods like the Laval Nozzle theory still preserve their importance for flow evaluations. Their advantage is in ability to capture main physical factors governing complex flows. In the paper a theory similar to that of Laval Nozzle is developed for swirling compressible flows. The presented analysis predicts existence of both structural transitions corresponding to vortex breakdown at low Mach numbers, and those analogous to shocks in supersonic velocities range. As distinct from non-swirled flows the “evolutionarity” (stability) of transitions is controlled by inertia waves. This fact was postulated for vortex breakdown in incompressible flows by Benjamin in [1] and is generalized in the article to the case of compressible flows. It is established that for each type of transition a wave mode responsible for its “evolutionarity” exists. Benjamin’s concept of flow transitions is linked closely with duct geometry. Benjamin treated a flow transition as a jump between flow states having same flow radial boundaries and flow integrals. These states can be connected virtually in a continuous way by introduction a duct of an appropriate shape. It is shown that the virtual duct must contain a critical cross-section (its geometrical interpretation is given in the text) where the speed of a corresponding to the transition wave mode turns to zero. The number of possible critical duct cross-sections coincides with the number of possible transitions and

depends on inlet flow parameters distribution. In all previous publications only first eigenmodes were considered to propagate in swirling flow. We show that higher orders eigenmodes are also possible. The proposed in the article approach allows easily investigate flows with arbitrary inlet density, entropy, velocity distributions. It is particularly important for analysis of flows in combustors where variations of these parameters are large. The approach provides guidelines for design of transitions-free channels.

Stability analysis of swirling flows relative 3D helical perturbations shows strong influence of losses to flow stability.

## References

- [1] Benjamin, T.B. 1962. Theory of the vortex breakdown phenomenon. *J. Fluid Mech.* 14, 593-629.