STRONG SHOCK - VORTEX INTERACTION – A NUMERICAL STUDY

W. Schröder, O. Thomer, E. Krause
Aerodynamisches Institut, RWTH Aachen, Aachen, Germany

Summary: The intersection of a longitudinal vortex by a normal shock is studied with a numerical solution of the Euler and Navier-Stokes equations for time-dependent, three-dimensional, laminar flow. The study is concerned with the destruction of the vortex core, usually referred to as vortex breakdown or bursting, by letting the shock intersect the vortex normal to its axis. Results are presented for a Mach number $Ma_{\infty} = 1.6$. The calculations were performed on a Cartesian mesh with approximately 2 millions grid points. The computations show noticeable differences between the two solutions, and viscous forces become important in the burst part of the vortex. Visualization studies clearly reveal the time-dependent, three-dimensional nature of the flow after breakdown.

INTRODUCTION

Vortex breakdown is observed in technical applications, for example, in decelerated pipe flows as studied by Sarpkaya and Novak in [1] and by Brücker in [2] in incompressible flow. Schlechtriem and Lötzerich conjectured in [3], that vortex breakdown might also occur in compressible flow in turbine engines. When compressors are operated near their stability limit, breakdown of the tip leakage vortex, caused by an intersecting shock in the supersonic flow, might be responsible for rotating instabilities and subsequent stall. Breakdown caused by the interaction of a vortex with a strong shock is also encountered on delta wings in supersonic flight near the trailing edge. Depending on the flow conditions the vortex can burst and cause rolling motions of the aircraft as a direct result of the local loss of lift. Breakdown also occurs on delta wings with leading-edge extension, and severe vertical tail buffeting may result, when the burst part of the vortices hits the vertical tails. There are marked differences between breakdown in supersonic and subsonic flow, and for this reason the investigation is restricted to the problem of strong shock-vortex interaction. Earlier numerical studies of compressible vortical flows interacting with shocks were reported by Kandil et al. in [4]. Erlebacher et al. in [5], Mahesh in [6]. Nedungadi and Lewis in [7], and Kandil et al. in [8]. In this paper results obtained with a numerical solution for the Euler and Navier-Stokes equations will be presented for time-dependent, three-dimensional, supersonic flows.

NUMERICAL SOLUTION OF THE EULER AND NAVIER-STOKES EQUATIONS

The governing equations are introduced in dimensionless form, written in a Cartesian frame of reference The system is closed with the thermal equation of state and with relations defining the viscosity, the thermal conductivity, and the specific heats at constant pressure and constant volume. The integration is carried out in a rectangular domain. The boundary conditions in the inflow cross-section are prescribed by a Burgers vortex. The kinematic flow condition is employed on thE side boundaries. The gradient of the vector of the conservative variables normal to the boundaries is assumed to vanish on the top and on both sides of the computational domain. The pressure on the boundaries is obtained from the momentum equations. The boundary condition for the outflow cross-section is given by the assumption that there is no back-flow into the computational domain. The approximation for non-reflecting boundary conditions is used for inviscid flows and for viscous flows the approximation described by Poinsot and Lele [9]. For the initial conditions the Burgers vortex is used for the entire domain of integration. At the beginning of the integration the Rankine-Hugoniot conditions are imposed at a certain location on the bottom of the computational DOMAIN. In a second approximation, a normal shock is imposed across the entire flow field. Then a Burgers vortex is prescribed upstream of the shock, and uniform flow downstream. Comparison of the numerical results for long computational times did not reveal any noticeable differences. The time integration of the governing equations was carried out with a 5-step Runge-Kutta scheme. The details of it may be found in [10]. The spatial integration employed a node-centered scheme. An adapted cell-vertex scheme was used for the discretization of the diffusive fluxes. The computational domain is a rectangular box containing a Cartesian grid with 99 x 99 x 199 points which are clustered in the vicinity of the shock and near the *z*-axis to ensure a sufficient resolution of the vortex core. Further details of the solution see [10].

EXAMPLATORY RESULTS OF RECENT COMPUTATIONS

Interaction patterns were computed for a free-stream Mach number $Ma_{\infty} = 1.6$. An examplatory result of the calculations of normal shock-vortex interaction is shown in Fig. 1. Although the shock-vortex interaction is dominated by pressure forces, the flow structure inside of the bubble is markedly influenced by viscous forces.

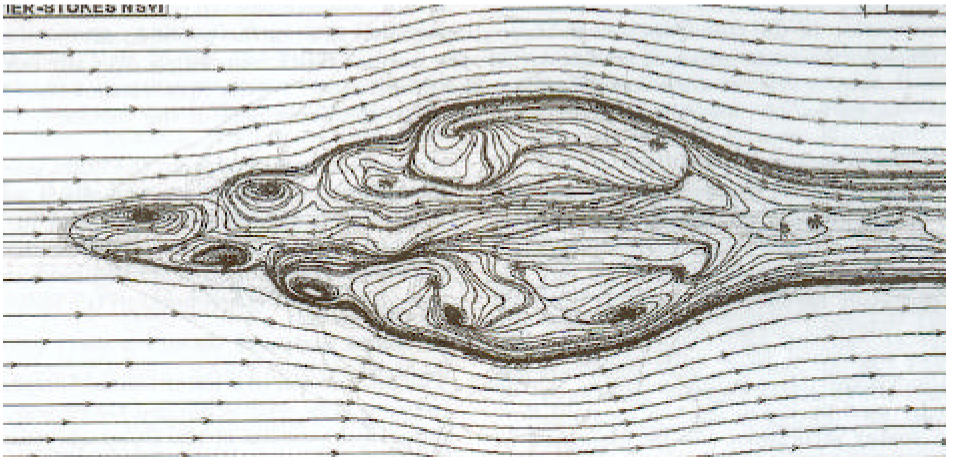

Fig. 1: Streamlines for normal shock-vortex interaction for $Ma_{\infty} = 1.6$ and $Re_{\infty} = 1.5.\ 10^3$; obtained with solution of Navier-Stokes equations.

CONCLUSIONS

The interaction of a longitudinal Burgers vortex in supersonic flow with a normal shock was studied with a numerical solution of the Euler and the Navier-Stokes equations. In the simulations only a strong shock was considered, which resulted in a bursting of the vortex. Examplatory results of computations were presented for a free-stream Mach number $Ma_{\infty} = 1.6$. The computations of both solutions showed that a cone-like bubble was formed by the interaction with the shock, which enforced a marked redistribution of vorticity in the recirculation region. It is pointed out, that the Navier-Stokes solution showed more small vortical structures in the burst part of the vortex than did the Euler solution. The visualization studies revealed, that vortex rings were shed periodically from the recirculation region, which in addition to two periodically generated and shed ring vortices, also contained supersonic nozzle flow, entering the recirculation region from the back Also small shocks were detected by the comp utation inside of the burst part of the vortex.

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