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The objective of the work is to use dynamical system theory to determine the mechanisms that are responsible for the breakdown of laminar flows and to investigate the possibility of modifying the transition process to affect the subsequent well-developed turbulence structure. Experiments performed in low-disturbance wind-tunnels established two scenarios for the laminar-boundary-layer breakdown: the fundamental- and subharmonic-modes of breakdown. The experimental observations of the subharmonic breakdown are very similar to our observations of the breakdown of regular motions in metallic and composite structural systems into chaotic motions. Therefore, we used dynamical system theory to conduct an analysis for the subharmonic breakdown in boundary layers similar to the one we successfully used to explain the breakdown in the response of the structural systems. The results can be used to modify the breakdown process and hence the resulting turbulent motion.

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FINAL REPORT
ONR Contract Number: N00014-91-J-1309
LAMINAR BOUNDARY-LAYER BREAKDOWN
Scientific Officer: S. G. Lekoudis
Principal Investigator: Ali H. Nayfeh
Department of Engineering Science and Mechanics
Virginia Polytechnic Institute and State University

Abstract

The objective of the work is to use dynamical system theory to determine the mechanisms that are responsible for the breakdown of laminar flows and to investigate the possibility of modifying the transition process to affect the subsequent well-developed turbulence structure. Experiments performed in low-disturbance wind-tunnels established two scenarios for the laminar-boundary-layer breakdown: the fundamental- and subharmonic-modes of breakdown. The experimental observations of the subharmonic breakdown are very similar to our observations of the breakdown of regular motions in metallic and composite structural systems into chaotic motions. Therefore, we used dynamical system theory to conduct an analysis for the subharmonic breakdown in boundary layers similar to the one we successfully used to explain the breakdown in the response of the structural systems. The results can be used to modify the breakdown process and hence the resulting turbulent motion.

The following is a brief summary of the accomplishments under this contract.

Publications

1. A. H. Nayfeh and J. A. Masad. "Recent Advances in Secondary Instabilities in Boundary Layers," *Computing Systems in Engineering*, Vol. 1, No. 2-4, 1990, pp. 401-414.

A review of the state of the art of secondary instabilities in two-dimensional incompressible and compressible boundary layers is presented. Recent experiments established two distinct routes of transition from laminar to turbulent flow. In both routes, two-dimensional Tollmien-Schlichting waves amplify in accordance with linear theory until their amplitudes exceed a threshold, beyond which three-dimensionality sets in. The three-dimensionality may be the result of a subharmonic (the peaks and valleys are staggered) or a fundamental instability (the peaks and valleys are split). The paper will review available numerical simulations as well as theoretical models that have been developed for the prediction of these secondary instabilities.

2. A. A. Al-Maaitah, A. H. Nayfeh, and S. A. Ragab. "Effect of Suction on the Stability of Subsonic Flows Over Smooth Backward-Facing Steps," *AIAA Journal*, Vol. 28, No. 11, 1990, pp. 1916-1924.

The effect of suction on the stability of compressible flows over backward-facing steps is investigated. Mach numbers up to 0.8 are considered. As expected, suction considerably reduces the separation region. The results show that continuous suction stabilizes the flow outside the separation bubble, as expected, but it destabilizes the flow inside it. Nevertheless, the overall N factor decreases as the suction level increases. This is due to the considerable reduction of the separation bubble. For the same suction flow rate, properly distributed suction strips stabilize the flow more than continuous suction. Furthermore, the size of

the separation bubble, and hence its effect on the instability can be considerably reduced by placing strips with high suction velocities in the separation region.

3. J. A. Masad and A. H. Nayfeh, "Effect of Heat Transfer on the Subharmonic Instability of Compressible Boundary Layers," *Physics of Fluids A*, Vol. 3, 1991, pp. 2148-2163.

The effect of heat transfer on the subharmonic instability of a two-dimensional compressible boundary layer over a flat plate is analyzed using the Floquet model. The resulting problem is solved numerically by using both finite differences and the computer code SUPORT. Results are presented for different Mach numbers. For supersonic flows results for the first and second modes are presented. The results for an adiabatic flat plate are in good agreement with the results of the numerical simulations of Thumm et al. When the wall temperature is decreased and the primary wave is a second-mode wave, it is found that the subharmonic instability is shifted to higher frequencies and downstream locations. When the primary wave is a first-mode wave, the effect of cooling might be stabilizing or destabilizing depending on the frequency. When the primary wave is a first mode, cooling stabilizes the subharmonic wave at low spanwise wavenumbers and destabilizes it at higher spanwise wavenumbers. When the primary wave is either a first- or a second-mode wave, the most amplified subharmonic mode shifts towards a higher spanwise wavenumber as the cooling level increases.

4. J. A. Masad and A. H. Nayfeh, "Effect of Suction on the Subharmonic Instability of Compressible Boundary Layers," *Physics of Fluids A*, Vol. 3, 1991, pp. 2179-2190.

The effect of self-similar suction distributions on the subharmonic instability of a two-dimensional (2-D) compressible boundary layer over an insulated flat plate is analyzed using the Floquet model. The resulting problem is solved numerically by using finite differences. Results are presented for different Mach numbers. For supersonic flows results for

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first- and second-mode primary waves are presented. It is found that when the primary wave is a first mode, suction stabilizes the subharmonic wave at low and moderate Mach numbers. However, at high Mach numbers suction loses its effectiveness. When the primary wave is a second mode, suction is also found to stabilize the subharmonic mode. When the primary wave is a first mode merging with a second mode, the subharmonic wave is strongly destabilized by suction.

5. A. A. Al-Maaitah, A. H. Nayfeh, and J. A. Masad, "Effect of Suction on the Stability of Supersonic Boundary Layers I. Second-Mode Waves," Journal of Fluids Engineering, Vol. 113, 1991, pp. 591-597.

The effect of suction on the second (Mack) mode of instability in supersonic and hypersonic two-dimensional boundary layers is investigated. The results show that suction has a stabilizing effect on these waves; it reduces the peak amplification and shifts it towards a higher frequency. In the presence of suction, the most amplified Mack mode remains two-dimensional. The effectiveness of suction in stabilizing Mack waves decreases as the Mach number increases. Variations of the growth rates of the most amplified Mack mode and the corresponding frequencies and wavenumbers with mass flux are found to be almost linear. The frequencies and wavenumbers corresponding to the most amplified Mack mode increase by increasing the suction level.

6. J. A. Masad, A. H. Nayfeh, and A. A. Al-Maaitah, "Effect of Suction on the Stability of Supersonic Boundary Layers II. First-Mode Waves," Journal of Fluids Engineering, Vol. 113, 1991, pp. 598-601.

The effect of suction on the first mode of instability of compressible two-dimensional boundary layers is investigated. Suction is found to be more effective in stabilizing the viscous instability, and hence it is more effective at low Mach numbers. Suction decreases the amplification rates at all frequencies and narrows down the band of unstable frequencies. Moreover, for a given frequency, suction decreases the amplification rates

at all streamwise locations. Variations of the growth rates of the most amplified first-mode waves with mass flux are found to be almost linear.

7. A. H. Nayfeh, "On Triple-Deck Structure," *Computers & Fluids*, Vol. 20, 1991, pp. 269-292.

The asymptotic foundation of two-dimensional steady triple-deck theory is reviewed. The total flow is assumed to be the sum of a basic-flow component $Q(x,y)$ governed by the boundary-layer equations and a disturbance component $q(x,y)$, resulting from a sudden streamwise change (localized disturbance), such as that caused by a hump or dip, a suction or blowing discontinuity, a heating or cooling discontinuity, a trailing edge, etc. Substituting the total flow $Q + q$ into the steady two-dimensional Navier-Stokes equations and subtracting the basic-flow quantities yields nonlinear equations describing the disturbance quantities q . The disturbance quantities are assumed to vary with the streamwise scale $X = (x - 1)R^\alpha$, where $x = x^*/x_r^*$, x_r^* is the center of the localized disturbance, $R = U_\infty x_r^*/\nu$, U_∞ is the freestream velocity, and ν is the kinematic viscosity of the fluid. Introducing the stretching transformation $Y = yR^\beta$, $\beta > 0$, and scaling $\hat{\psi}$ as $\hat{\psi} = \psi R^\chi$, where $\hat{\psi}$ is the streamfunction of the disturbance, we find that there are three distinguished limits when $0 < \alpha < \frac{1}{2}$ and hence three sets of least degenerate problems, resulting in a triple-deck structure. These limits correspond to $\beta = \alpha$, $\beta = \frac{1}{2}$, and $\beta = \frac{1}{2} + \frac{1}{3}\alpha$. Matching the pressure in these decks demands that $\alpha = \frac{3}{8}$ and leads to the triple-deck structure. The upper- and middle-deck problems are linear, whereas the lower-deck problem is linear when $\chi > \frac{3}{4}$ and nonlinear when $\chi \leq \frac{3}{4}$. When $\alpha = \frac{1}{2}$, there are two distinguished limits corresponding to $\beta = \frac{1}{2}$ and $\frac{2}{3}$. The upper-deck problem is linear, whereas the lower-deck problem is linear when $\chi > \frac{5}{6}$ and nonlinear when $\chi \leq \frac{5}{6}$. The theory is self-consistent and does not depend on the problem being investigated. Application of these theories to the linear three-dimensional compressible stability of two-dimensional compressible boundary layers is described and limitations of the triple-deck theory are discussed.

8. A. Al-Maaitah, A. H. Nayfeh, and J. A. Masad, "Effect of Heat Transfer on the Stability of Compressible Boundary Layers," *Computers & Fluids*, Vol. 21, 1992, pp. 43-61.

The effect of heat transfer on the spatial stability of compressible boundary layers is investigated by using a formulation that accounts for variable-fluid properties of both the mean-flow and stability problems as well as a constant Prandtl number formulation. It is found that heat transfer is more effective in stabilizing or destabilizing flows at low Mach numbers than at high Mach numbers. Cooling always stabilizes first-mode waves and destabilizes second-mode waves. Cooling increases the peak amplifications of second-mode waves and shifts them towards higher frequencies. The least stable second-mode wave remains two-dimensional in the presence of heat transfer. The theoretical results are in good agreement with the experimental data of Lysenko and Maslov for the first mode and in reasonable agreement with their experimental data for the second mode. The theoretical results are also compared with the experimental data of Lebiga et al. and Kosinov et al.

9. J. A. Masad and A. H. Nayfeh, "Effect of a Bulge on the Subharmonic Instability of Subsonic Boundary Layers," *AIAA Journal*, 1992, in press.

The effect of a two-dimensional (2-D) hump on the three-dimensional (3-D) subharmonic instability of subsonic flow over a flat plate was investigated. The mean flow was calculated by using interacting boundary layers (IBL), thereby accounting for viscid/inviscid interactions and capturing separation bubbles. The results show that increasing the hump height produces an increase in the amplification factors of both the primary and subharmonic waves. When the hump causes separation, the growth rates of both the primary and subharmonic waves are considerably larger than those in the case of no separation. The effect of compressibility on reducing the amplification factors of the primary and subharmonic waves decreases as the hump height increases.

10. J. A. Masad and A. H. Nayfeh, "Effects of Suction and Wall Shaping on the Fundamental Parametric Resonance in Boundary Layers," *Physics of Fluids A*, Vol. 4, 1992, pp. 963-974.

The effects of self-similar as well as uniform-suction distributions on the primary and fundamental parametric spatial and temporal instabilities of incompressible flows over a flat plate are studied. The Floquet model is used to analyze the fundamental instability. This model is also used to analyze the effect of wall shaping on such instabilities. The mean-flow problems as well as the stability problems are solved using finite differences. The effects of suction and wall shaping are evaluated and discussed in relation to previous works. The relation between spatial and temporal fundamental instabilities is also considered.

11. Y. H. Zurigat, A. H. Nayfeh, and J. A. Masad, "Effect of Pressure Gradient on the Stability of Compressible Boundary Layers," *AIAA Journal*, 1992, in press.

An investigation into the influence of pressure gradient (wall shaping) on the stability of compressible boundary layers is presented. The steady compressible nonsimilar boundary-layer equations are solved with a potential flow velocity distribution corresponding to a power-law edge Mach number distribution. The stability of the mean flow is investigated using the small-disturbance compressible linear stability theory. The results indicate that two-dimensional (2-D) second-mode (Mack) waves can be stabilized with pressure gradient. However, the effectiveness of the pressure gradient on the natural laminar flow control of 2-D second-mode waves decreases at hypersonic speeds. The maximum growth rate varies almost linearly with the pressure gradient level. The effect of pressure gradients on stabilizing three-dimensional (3-D) first-mode waves is much larger than its effect on stabilizing 2-D first-mode waves.

12. J. A. Masad and A. H. Nayfeh, "Laminar Flow Control of Subsonic Boundary Layers by Suction and Heat-Transfer Strips," *Physics of Fluids A*, Vol. 4, 1992, pp. 1259-1272.

The effect of wall cooling and heating on first and second modes of instability is considered. Results are obtained for Mach numbers up to 7.5. Cooling is found to stabilize first-mode waves for all frequencies, wave angles, and Reynolds numbers. On the other hand, cooling destabilizes and heating stabilizes the most amplified second-mode waves. The Mach number at which second-mode waves start to appear decreases as the wall temperature decreases. Although the frequency and Reynolds number corresponding to the most amplified first-mode waves are not affected much by heat transfer, cooling (heating) increases (decreases) them for second-mode waves. On the other hand, the wave angles corresponding to the most amplified first- and second-mode waves are not affected by heat transfer.

Presentations

1. A. H. Nayfeh and J. A. Masad, "Recent Advances in Secondary Instabilities in Boundary Layers," Symposium on Computational Technology for Flight Vehicles, Washington, DC, November 5-7, 1990.
2. J. A. Masad and A. H. Nayfeh, "Subharmonic Instability of Boundary Layers," Boundary Layer Transition and Control Conference, Cambridge, England, April 9-12, 1991.
3. J. A. Masad and A. H. Nayfeh, "The Influence of Imperfections on the Stability of Subsonic Boundary Layers," Symposium in Honor of Eli Reshotko, Newport News, VA, July 28, 1991.

Students

J. A. Masad

A. Al-Maaitah