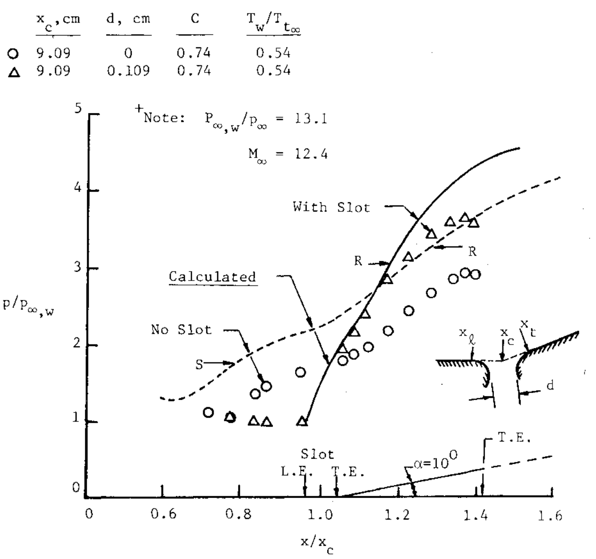

Fig. 3 Comparison of calculation results with data of Ball[4] at $M_{\infty,w}=6.7$, $Re_{c,w}=0.36\times10^6$.

A comparison with data obtained at the same freestream conditions but with bleed through a sharp-edge slot shows that the calculation correctly predicts the appreciable reduction in upstream extent produced by hinge-line bleed. However, this reduction is not as great as shown by the data. This difference is, to some extent, the result of the ramp being too short.

Figure 3 shows a comparison with the data of Ball[4] obtained with a pitched model that provided a tangent wedge Mach number of 6.7. The no-bleed data are drastically different from the calculated pressure distribution to an extent that also indicates that the ramp was too short. This indication, however, is misleading since subsequent tests[5] with longer ramps gave similar results. The most logical explanation for these results is lateral bleed caused by the pitched flat plate. This explanation is completely consistent with angle-of-attack data by Rhudy[6] that were obtained on a model with aspect ratio (2.2) nearly identical to Ball's. With this model Rhudy found that data equivalent to unpitched data could not be obtained by pitching.

Bleed data obtained with a contoured slot with a throat opening of $0.012x_c$ are also shown in Fig. 3 for comparison with the calculated results. The agreement is generally quite good with respect to both the reduction in upstream extent and the increase in pressure gradient on the ramp.

Conclusions

A series of calculations were made to determine the effect of Mach number, Reynolds number, and slot size on the pressure distribution for ramp-induced interactions with bleed. These calculations were all made for a sharp-edged slot ($d=0.014x_c$) similar to Rhudy's with downstream edge fixed at $0.986x_c$ and a ramp angle fixed at 10 deg. The conclusions based on this series are summarized as follows:

1) The upstream extent of the interaction (or size of the reverse-flow bubble) can decrease with an increase in Reynolds number. That is, sufficient bleed reverses the characteristic Reynolds number effect.

2) The upstream extent increases with Mach number increase ($4.5\leq M_\infty\leq 8.0$), and this too represents a trend reversal caused by sufficient bleed.

3) The ramp pressure gradient increases appreciably with increases in Reynolds number for a fixed bleed rate.

4) The upstream extent decreases with an increase in slot width until a critical size is reached. At this critical condition, the upstream extent decrease abruptly and the onset of interaction closely approaches the location of separation.

5) Despite the appreciable reduction in upstream extent possible through the application of hinge-line bleed, the reversed flow part of the velocity profile at the hinge line is larger with suction.

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The Nature of Differences in Some Forms of Transition in the Boundary Layer

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Introduction

According to modern theory, transition from a laminar to a turbulent boundary layer may appear as the result of amplification of small disturbances in the wavy structure. The development of waves of low intensity (Tollmien-Schlichting waves) is well described by linear hydrodynamic stability theory.[1] With the increase in wave energy, the process is more complicated and may be connected with the nonlinear effects of wave evolution. The physical mechanisms include spontaneous amplification of spatial fluctuations, subharmonic generation, and nonequivalence of process character but, in general, are not well maintained. It has been shown[2] that the disturbance spectrum in the region of nonlinear development is made up of a set of harmonics of the main frequency with similar intensities and that spatially distributed eddy structures are formed in the flow. Under other conditions,[3] subharmonic frequencies are generated together with the successive formation of harmonics; spatial nonhomogeneity is lower and does not contain pronounced regularity. A similar fact was observed experimentally[4] by injecting disturbances in the form of localized wave packets.

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It appeared that, with their periodical generation, the regular picture was preserved up to amplitudes which greatly exceeded the spectral maximum observed for the case of the injection of a single packet.

The formation of a definite regime obviously occurs in the early stages of the nonlinear development and, at low initial intensities, may be explained on the basis of a weakly nonlinear theory of stability.

The aim of the present Note is to show a strong connection of the initial distribution of the disturbance field with the character of the transition regime, where the main mechanism is three-dimensional wave resonance.

Analysis

In accordance with Ref. 5, nonlinearity of spatially temporal evolution of wave disturbances of restricted intensity in the boundary layer shows initially as three-dimensional wave resonance. Their effectiveness is provided on the condition that $\omega_j - \omega_i - \omega_\ell \leq O(\epsilon)$ and $k_j - k_i - k_\ell \leq O(\epsilon)$, where ω_j is the frequency, $k_j = k(\omega_j + i\gamma_j)$ the wave vector, γ_j the increment of wave j, and $\epsilon \ll 1$ is an averaging parameter. Among the possible synchronized triads, those with the spectrum $k_1 = (2\alpha, 0)$, $k_2 = (\alpha, \beta)$, $k_3 = (\alpha, -\beta)$, $\omega_1 = 2\omega$, and $\omega_2 = \omega_3 = \omega$ are of the greatest interest. For the first time,[6] the existence of a particularly strong connection between them has been noted. Spatial evolution of such triads is expressed by a set of equations, with complex amplitudes,

$$\left(b_1(x)\frac{\partial}{\partial x} + c_1(x)\frac{\partial}{\partial z} - \gamma_1(x)\right)A_1 = \epsilon A_2 A_3 S_1(x) + O(\epsilon^2)$$

$$\left(b(x)\frac{\partial}{\partial x} + c(x)\frac{\partial}{\partial z} - \gamma(x)\right)A_{2,3} = \epsilon A_1 A_{3,2}^* S(x) + O(\epsilon^2)$$

$$A_j(x_0, \epsilon z) = \int_{-\infty}^{\infty} a_j(\lambda)\exp(i\lambda z)\,\mathrm{d}\lambda \tag{1}$$

and has been examined in Refs. 7 and 8.

Let us examine a case where $|A_1| > |A_{2,3}|$ in the initial evolution. For the waves of maximum intensity this situation is usually found in boundary-layer experiments. Together with the ratio $|S_1/S| \ll 1$, it leads to parameter resonance $A_{2,3}$ in field A_1. Then with the assumption of local parallelism of the flow, the solution of Eqs. (1) is expressed by cylindrical functions and, at definite $x > x_0$ in the area $\gamma_1 > 0$, a sudden amplification of three-dimensional waves takes place.

Specifications connected with nonparallelism of the flow and consideration of nonlinear self-interaction for A_1 [members $\epsilon^2 |A_1|^2 A_1$ in Eqs. (1)] do not change the general regularity. The behavior of this mechanism is likely to explain the rapid disturbance of the subharmonics and that intensities of three- and two-dimensional waves become equal.

Some results of numerical analysis for initial conditions $|A_1| = a_1$, $|A_{2,3}| = a$, $\lambda = 0$ are given in Fig. 1. The dimensionless quantities were introduced using the displacement thickness and the freestream velocity. The Orr-Sommerfeld eigenfunctions $\varphi_j(y)$ were normalized by taking $\max|\varphi_j| = 1$. Lines represented by I correspond to two-dimensional waves and the pointers (↔) connect combined fluctuations. It can be seen that nonlinear process which follows the parameter development phase leads to intensity explosion of all interacting waves. The growth rate of three-dimensional disturbances remains dominant. $\arg a_j \neq 0$, $\lambda \neq 0$ may slow down only the initial growth. The characteristic of the triads are preserved for other values of ω. The calculations were performed for values $\omega = (0.8 - 1.25) \times 10^{-4}$. $\arg a = [0 - (3/2)\pi]$, $\lambda = (0/0.02)$. The relative intensity of nonlinearly interacting waves is decisive for the realization of the explosive process.

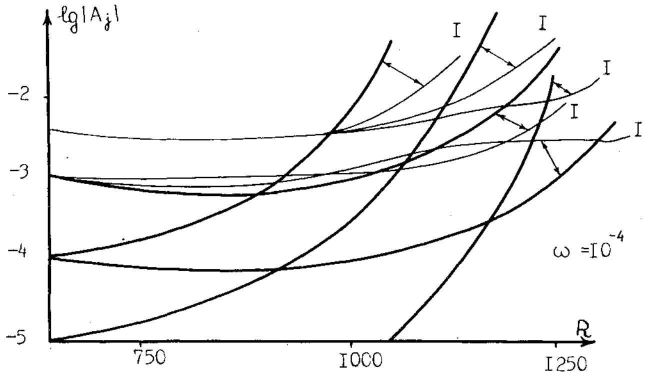

Fig. 1 Results of numerical analysis.

It is necessary to point out that the transmission of energy to two-dimensinal waves, when $|\alpha_{2,3}| \gg |\alpha_1|$, leads only to small growth rates $|A_1| \sim \exp\int_{x_0}^{x} 2\gamma/b\,\mathrm{d}x$. Then the resonant effectiveness may be compared with the influence of other interaction mechanisms.

Discussion

The above analysis becomes incorrect with the increase of $|A_j|$, $|(1/A_j)(\partial/\partial x)A_j|$. But the nature of a set of phenomena in the boundary layer is connected with the resonant mechanism and may be explained on the basis of the results.

In fact, the two-dimensional waves involved in the linear stage not only generate harmonics with the growth of intensity but also carry out the transmission of energy to their resonant fluctuations. Because of the strong internal connection, simultaneous evolution of triads is almost independent, and the increments of plane waves are near to linear.[9] An important role in the process of formation is played by the spectrum of injected disturbances. If the intensity of spatial waves is nearly two-dimensional at the initial stage, the intensities of waves become equal for short periods of time, and explosive nonlinear growth for all synchronized fluctuations takes place. This causes the instant transmission of energy over a large spectrum and the process is characterized by a large number of waves and is strongly three-dimensional.

Another regime is possible in spectrally clearer flows when the amplitudes of the relevant fluctuations outnumber all other amplitudes. Nonlinear self-interaction becomes the dominant mechanism and, unlike the previous case, its development is connected with generation of a large number of harmonics and thus the role of low frequencies remains unimportant.[2] In the boundary layer, this regime is likely to be found outside the field of application of weakly nonlinear theory, so that the three-dimensionality of the flow is fully defined by initial conditions and may not be connected with the characteristics of Tollmien-Schlichting waves.

In the intermediate case, a subharmonic of the main frequency stands out together with the generation of harmonics. Similar development has been observed elsewhere,[3] and it is interesting to point out that, in these experiments with amplitude growth, the picture of the process appeared to be close to that described in the previous case.

Due to the proximity of group velocities of triad wave, the same idea may be used to explain the fact that the maximum of fluctuations when irregularities appear depends on the method of packet injection.[4] As the boundary layer is disturbed by a single packet, a wide spectrum of three- and two-dimensional waves exist with similar amplitudes. Consequently, conditions for resonant nonlinear growth are realized in the early stage of evolution. With periodic packet generation in the spectrum, only waves with the main and multiple periods grow. Two-dimensional wavy disturbances with the main frequency essentially exceed three-dimensional ones with $\omega_1/2$; $n\omega$ $(n = 2,3...)$ belongs to the area of strong linear disappearance. An interval of parameter strengthening appears, in which a wave of the main frequency reaches a higher level.

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Buried Wire Separation Detector Simulation in Compressible Flow

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Introduction

BOUNDARY-layer separation on aerodynamic airfoils is of prime importance in stalled flows, in shock wave interaction with boundary layers, and in other cases of severe adverse pressure gradient.[1,2] The separation bubble can be extremely thin and very difficult to define by present methods used to detect separation and reattachment (Preston tubes, orifice dams, skin friction balance, oil flows, etc.). Other shortcomings of these methods are the low resolution, slow response, and disturbance to the sensitive flow which might cause premature separation or delay the reattachment.

An instrument designed to overcome these shortcomings is the separation detector.[3,4] Its principle of operation is based on measurement of the temperature differences between two sensors located on both sides of a heat source (Fig. 1). As a result of the heat convection from the source, the temperature of the downstream sensor will be higher than that of the upstream sensor. When the gage is in a separated region, where the flow direction is reversed, the heat will be convected in the upstream direction and the sign of the temperature difference will be changed.

An analysis of the solid temperature field and its interaction with the boundary-layer flow is essential for the design of a gage with maximum sensitivity and minimum disturbance to the flow. Such an analysis can be carried out experimentally, but it will be highly expensive and complex.

A solution of the temperature field around a point heat source for incompressible flow is described by Brosh et al.[5] However, this solution covers only cases of low Mach number where incompressible flow can be assumed.

Principles of Analysis

The model suggested in the present paper is based on a solution of two-dimensional time dependent Navier-Stokes equations for compressible turbulent flow coupled with the solution of the heat conduction in the solid (see Fig. 1).

The strong conservation law form of the Navier-Stokes equations in Cartesian coordinates is

$$\bar{q}_t + \bar{E}_x + \bar{F}_y = Re^{-1}(\bar{R}_x + \bar{S}_y) \qquad (1)$$

where

$$\bar{q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad \bar{E} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(e+p) \end{bmatrix}, \quad \bar{F} = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(e+p) \end{bmatrix}$$

$$\bar{R} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ E_R \end{bmatrix}, \quad \bar{S} = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ E_S \end{bmatrix}$$

with

$$\tau_{xx} = (\lambda + 2\mu)u_x + \lambda v_y, \quad \tau_{xy} = \mu(u_y + v_x)$$

$$\tau_{yy} = (\lambda + 2\mu)v_y + \lambda u_x$$

$$E_R = u\tau_{xx} + v\tau_{xy} + \kappa P_r^{-1}(\gamma - 1)^{-1}\partial_x a^2$$

$$E_S = u\tau_{xy} + v\tau_{yy} + \kappa P_r^{-1}(\gamma - 1)^{-1}\partial_y a^2$$

and

$$p = (\gamma - 1)[e - 0.5\rho(u^2 + v^2)]$$

where p is the pressure and the sound speed a is given by

$$a^2 = \gamma(\gamma - 1)[e/\rho - 0.5(u^2 + v^2)]$$

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