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Abstract

Transition from laminar to turbulent flow in a boundary layer is of fundamental and practical importance, and as a result has been widely studied. Receptivity is the first stage of the transition process. The term receptivity was first used by Morkovin (1969) to describe the mechanism by which energy from the free stream enters and excites instability waves inside the boundary layer. Due to important role of receptivity theory in transition process of boundary layers, quite a few research works have been carried out in past few decades. This research review report tries to highlight the major research activities in this field of study that includes: the theory, different types of receptivity, its effect in three-dimensional boundary layers and receptivity at high speeds.

Introduction

No flow in nature and engineering applications is disturbance-free. The disturbances present in the flow field may enter the boundary layer via its boundaries, which may be the wing surface and the edge separating the layer from the free stream (Figure 1.1a). Examples are roughness or vibrations of a wing surface and sound waves or eddies in the free stream, as sketched in Figure 1.1(b). These disturbances may transfer energy to the boundary layer and establish boundary-layer instabilities which may amplify and attain amplitudes far above those of the external disturbances. The coupling between the ambient disturbances and the boundary-layer instabilities is denoted "receptivity" which is finally ending to the transition of boundary layer (see Figure 2, Schrader, 2010). It is obvious that the receptivity strongly depends on the perturbation environment around the boundary layer. Thus, receptivity is not a characteristic of the boundary layer alone, but of the entire flow field including the free stream and the boundaries, e.g. the surface of a wing .

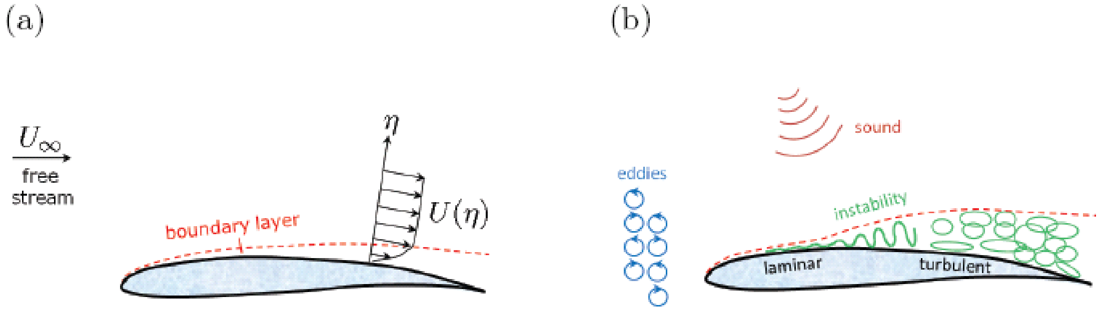


Figure 1: (a) The boundary layer on a fixed airfoil in a moving fluid. The fluid sticks to the surface of the airfoil, and the flow velocity increases from zero to the free-stream velocity across the thin boundary layer. (b) The receptivity of the boundary layer to external perturbations, e.g. free-stream eddies or sound waves, may induce instabilities inside the boundary layer.

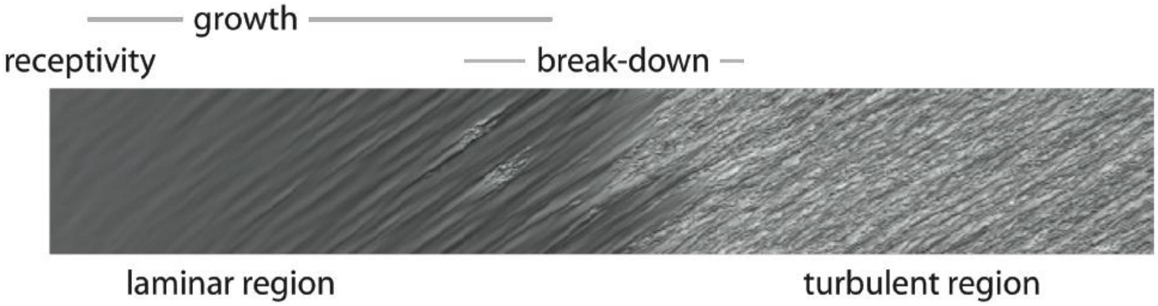


Figure 2: Different stages of Transition process

In other words, receptivity is the process which describes how environmental disturbances (such as gusts, acoustic waves or wall roughness) are filtered by a boundary layer and turned into downstream-growing waves. It is closely related to the identification of initial conditions for the disturbances and requires knowledge of the characteristics of the specific external forcing field. Without such a knowledge, it makes sense to focus on worst case scenarios and search for those initial states which maximize the disturbance amplitude at a given downstream position, and hence to identify upper bounds on growth rates, which will be useful in predicting the transition to turbulence (Bottaro, A., 2010).

The process of transition for boundary layers in external flows can be qualitatively described using Figure 3 (Saric et al., 2002) and the following scenario based on one of the different "roadmaps" to turbulence developed over the years (Morkovin et al. 1994).

Disturbances in the freestream, such as sound or vorticity, enter the boundary layer as steady and/or unsteady fluctuations of the basic state. This part of the process is called receptivity (Morkovin 1969a), and it establishes the initial conditions of disturbance amplitude, frequency, and phase for the breakdown of laminar flow. In Figure 3, the initial amplitude increases schematically from left to right. Initially these disturbances may be too small to measure, and they are observed only after the onset of an instability. A number of different instabilities can occur independently or together and the appearance of any particular type of instability depends on Reynolds number, wall curvature, sweep, roughness, and initial conditions. If Figure 3 is entered with weak disturbances and path *A* is followed, the initial growth of these disturbances is described by linear stability theory of primary modes (i.e., linearized unsteady Navier-Stokes). This growth is weak, occurs over a long streamwise length scale, and can be modulated by pressure gradients, surface mass transfer, temperature gradients, etc. As the amplitude grows, three-dimensional and nonlinear interactions occur in the form of secondary instabilities. Disturbance growth is very rapid in this stage (now over a convective length scale), and breakdown to turbulence occurs.

Because the linear stability behavior can be calculated, transition prediction schemes often assume that transition follows path A and consider only the linear regime. This is justified on the assumption that external flows typically have weak freestream disturbances and the streamwise extent of the linear growth region is large compared to that of the nonlinear region. However, because the initial conditions (receptivity) are not generally known, only correlations between two systems with similar environmental conditions are possible. Recent critical reviews of these methods are found in Arnal (1994) and Reed et al. (1996).

At times, the freestream disturbances are so strong that the growth of linear disturbances is bypassed (Morkovin 1969a, 1993) and turbulent spots or subcritical instabilities occur and the flow quickly becomes turbulent. This corresponds to path E in Figure 3, and although the phenomenon is not well understood, it has been documented in cases of roughness and high freestream turbulence (Reshotko 1984, 1994, 2001). In this case, transition prediction schemes based on linear theory fail completely.

It is generally accepted that bypass refers to a transition process whose initial growth is not described by the primary modes of the Orr-Sommerfeld equation (OSE). Historically, one had either path A or E from which to choose as the road to turbulence. Recently however, considerable work in the area of transient growth has expanded our understanding of different paths by which transition to turbulence can occur.

Transient growth occurs when two, non-orthogonal, stable modes interact, undergo algebraic growth, and then decay exponentially. Streamwise vorticity and wall-normal vorticity appear to be important. This mechanism was first elucidated by Landahl (1980) and then by Hultgren & Gustavsson (1981). The idea was used by Henningson et al. (1993) and others. Recent reviews appear in Andersson et al. (1999), Reshotko (2001), and Schmid & Henningson (2001). Studies have shown that large amplitudes can be achieved through transient growth when the boundary layer is provided with appropriate initial conditions.

Thus, the spectrum of initial conditions depends on receptivity. Returning to Figure 3, one can now say that, depending on amplitude, transient growth can lead to spanwise modulations of two-dimensional waves (path B), direct distortion of the basic state that leads to secondary or subcritical instabilities (path C), or direct bypass (path D).

In spite of progress, an overall theory remains rather incomplete with regard to predicting transition. Amplitude and spectral characteristics of the disturbances inside the laminar viscous layer strongly influence which type of transition occurs (Saric et al., 2002). Thus, it is necessary to understand how freestream disturbances are entrained into the boundary layer and create the initial amplitudes of unstable waves, i.e., to answer the question of receptivity.

As said already, receptivity has many different paths through which to introduce a disturbance into the boundary layer. They include the interaction of freestream turbulence and acoustic disturbances (sound) with model vibrations, leading-edge curvature, discontinuities in surface curvature, or surface inhomogeneities. Moreover, the picture for 2-D flows is expected to be different than that of 3-D flows. Any one or a combination of these effects may lead to unstable waves in the boundary layer. The incoming freestream disturbance (sound or turbulence) at wave-number α_{fs} interacts with a body in such a way (roughness, curvature, etc) so as to broaden its spectrum to include the response TS wave-number α_{TS}. If the initial amplitudes of the disturbances are small, they will tend to excite the linear normal modes of the boundary layer. The normal modes in the case of a typical experiment dealing with a Blasius boundary layer are of the T-S type (Mack, 1984). If the initial amplitudes are large, the boundary layer may respond directly to nonlinear 3-D effects that can lead prematurely to transition (Saric, et al., 1999).

Mathematically, the receptivity problem differs from stability (Reshotko, 1976, 1984a, 1994). Stability analysis describes the normal modes of disturbances within the boundary layer. These normal modes are determined from the solution of the linearized Navier-Stokes equations with appropriate boundary conditions (i.e. the O-S equation). The history of the development of this area is given by Mack (1984). Receptivity differs in the fact that either the equations or the boundary conditions are no longer homogeneous since the boundary layer is being forced by an external disturbance. Therefore, the problem no longer has the form of an eigenvalue problem but rather an initial-value problem (Saric, et al., 1999). The governing system of equations for the receptivity problem is therefore typically the full Navier-Stokes system with appropriate boundary and initial conditions. Thus, the objective of any transition program should address initial conditions for T-S wave generation.

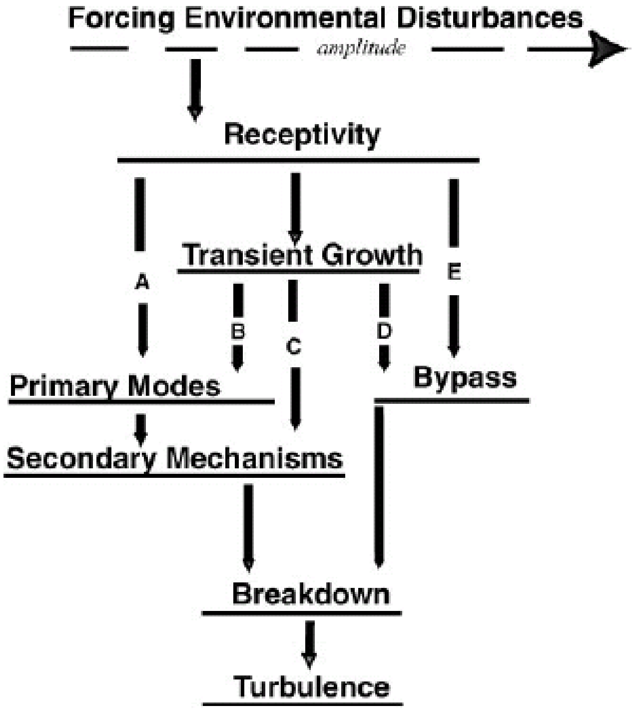


Figure 3: The paths from receptivity to transition

The early theoretical works of Goldstein (1983, 1985), Goldstein et al., (1983), Zavol'skii et al. (1984), and Ruban (1985) solidified the mechanisms by which long-wavelength freestream disturbances at a particular frequency are converted to a wavelength commensurate with the boundary-layer instability wave. They utilized high Reynolds number asymptotic methods to analyze the receptivity problem. They showed that receptivity occurs in regions where the boundary-layer flow changes abruptly in the streamwise direction, i.e. significant nonparallel effects.

Two general classes of receptivity regions were recognized by Goldstein, I) the leading edge regions where the boundary layer is thin and growing rapidly and II) regions further downstream where the boundary layer is forced to make a rapid adjustment. A common feature between both receptivity regions, classes I and II, is the importance of nonparallel effects and is manifested via the disturbance motion being governed by the unsteady boundary-layer equations. Class II can be further subdivided into "localized and non-localized receptivity". According to King (2000), localized receptivity results from an interaction between the freestream disturbances and steady localized disturbance generated by a surface inhomogeneity (e.g. humps, gaps, suction/blowing slots, etc.). On the other hand, nonlocalized receptivity stems from an interaction in boundary-layer flow with unsteady freestream disturbances and the steady disturbance created over surfaces with extended regions of short-scale variations (e.g. waviness, distributed roughness, uneven suction, etc.).

Reviews of different receptivity mechanisms are given by Goldstein & Hultgren (1989), Kerschen (1989), Heinrich et al. (1988), Choudhari & Streett (1994), Crouch (1994), Nishioka & Morkovin (1986), Kozlov & Ryzhov (1990), Wlezien (1994), Saric et al. (2000), and Kachanov (2000).

This report highlights some of theoretical and experimental works carried out in past few years on receptivity theory.

Receptivity Theory

According to Saric et al. (2002), receptivity concerns the generation of instability waves, rather than their evolution. Because boundary layers are convectively unstable, an unsteady disturbance is required to generate the instability waves. This may be a naturally occurring disturbance or an artificial forcing mechanism such as a vibrating ribbon or localized suction/blowing.

For localized, unsteady forcing mechanisms such as a vibrating ribbon or wall suction/blowing, the wave-number spectrum of the forcing function is broad. Thus, in "forced receptivity," the input disturbance generally contains energy at the appropriate frequency-wavelength combination to directly excite an instability wave. Hence, streamwise gradients of the mean flow do not play an essential role in forced receptivity, and this phenomenon can be analyzed within the parallel flow OSE (Orr-Sommerfeld equation) framework. For more information on forced receptivity, see Kerschen (1989) and Kachanov (2000).

Naturally occurring freestream forcing mechanisms consist of acoustic disturbances that propagate at the speed of sound relative to the fluid and vertical disturbances that convect at the freestream speed. In contrast, instability waves have phase speeds that are a fraction of the freestream speed. Hence, the energy for naturally occurring freestream disturbances is concentrated at wave-numbers that are significantly different than the instability wave-number. Therefore, natural receptivity mechanisms require a wavelength conversion process.

Based on studies by Goldstein (1983, 1985) and Ruban (1985), who employed asymptotic analysis to investigate receptivity at the first neutral point of Tollmien–Schlichting (TS) instability in Blasius flow, they pointed out that resonance regarding frequency and wave vector between the external disturbances and the unstable eigenmode of the base flow is necessary to trigger boundary-layer instability. The excitation of TS waves, for instance, requires unsteady external perturbations, e.g. acoustic or vortical free-stream disturbances. However, free-stream perturbations feature in general larger chordwise wavelengths than the discrete eigenmodes of the mean flow. Hence, scale reduction is necessary to trigger TS instability by free-stream disturbances. Goldstein (1985) shows that scale conversion requires a short-scale downstream variation of the base flow. This requirement is fulfilled in two regions: just downstream of the leading edge where the boundary layer grows rapidly, and in the vicinity of a localized surface non-uniformity. Thus, two different receptivity mechanisms to unsteady free-stream perturbations are imaginable: (i) a direct process in the leading-edge region, associated with the unsteady free-stream disturbance, and (ii) a mechanism associated with the interaction between unsteady free-stream perturbations and the steady disturbance induced by localized surface non-uniformity. For acoustic free-stream perturbations only the second receptivity mechanism proved to be efficient (Schrader et al., 2009).

The theory of leading-edge receptivity, in which the work of Goldstein (1983, 1985) has played a seminal role, has lead to all of the progress that was later achieved by DNS and experiments.

Direct numerical simulations (DNS) are playing an increasingly important role in the investigation of transition; the literature is growing, especially recently. This trend will continue as considerable progress is made in the development of new, extremely powerful computers and numerical algorithms. In such simulations, the full Navier-Stokes equations are solved directly by employing numerical methods, such as finite-difference, finite-element, or spectral methods. Kleiser and Zang (1991) and Reed (1993) serve as complementary companions to review temporal and spatial simulation techniques, respectively.

The coupling between the long-wavelength acoustic disturbance and a T-S wave, having wavelengths two orders of magnitude smaller, occurs when the boundary layer is required to adjust locally (Goldstein, 1983; Goldstein et al., 1983; Goldstein, 1985; Goldstein and Hultgren, 1989; Heinrich et al., 1988; Kerschen, 1990; Crouch, 1991 and 1992a) or globally (Crouch, 1992b). This can occur at four positions on a flat-plate model: the leading edge, the discontinuity in the surface curvature occurring at the flat-plate and leading-edge junction, the presence of very strong, localized, pressure gradients, and any surface inhomogeneities.

Experimentally, the most popular receptivity model has been the flat plate with an elliptic leading edge (Saric et al., 1999). Thus it is reasonable that computational models consider the same geometry. However, the curvature at the juncture between the ellipse and the flat plate is discontinuous and provides a source of receptivity (Goldstein 1985; Goldstein and Hultgren 1987). Lin et al (1992) introduced a new leading-edge geometry based on a super-ellipse. The shape of this modified super-ellipse (MSE) is given by:

$$\left[(a-x)/a\right]^{m(x)}+\left[y/b\right]^{n}=1, \quad 0<x<a$$

$$m(x)=2+\left[x/a\right]^{2} \text{ and } n=2$$

where a=b(AR), b is the half-thickness of the plate, and AR is the aspect ratio of the "elliptic" nose. For a usual super-ellipse, both m and n are constants. These super-ellipses will have the advantage of continuous curvature (zero) at the juncture with the flat plate as long as m>b at x/b=AR. The MSE (modified super-ellipse), with m(x) given above, has the advantage of having a nose radius and geometry (hence a pressure distribution) close to that of an ordinary ellipse with m=2 and n=2.

Leading Edge Receptivity

The transfer of energy from the free-stream disturbance to the instability wave generally comes about through nonparallel mean flow effects, which may arise either in the leading-edge region (Figure 4), or in a localized region farther downstream in the boundary layer (Goldstein & Hultgren 1989; Kerschen 1990).

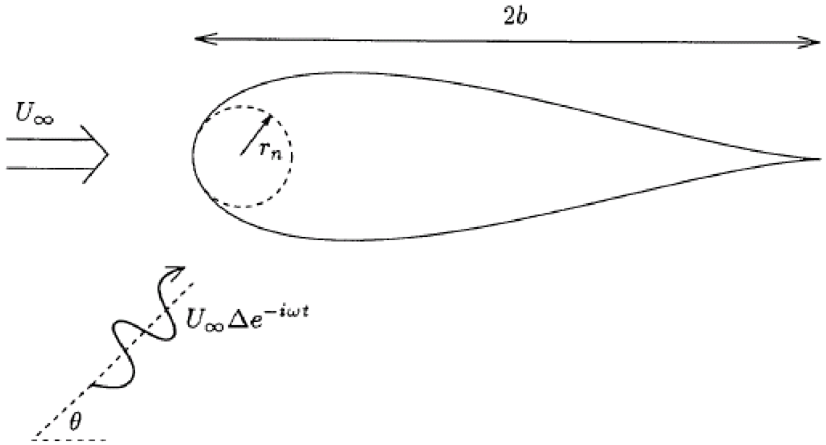


Figure 4: A thin, symmetric airfoil of chord 2b is at zero angle-of-attack in a uniform flow of speed U∞, with a plane wave incident at an angle θ with respect to the airfoil chord.

The leading-edge receptivity theory has been extended by Hammerton and Kerschen (1998) to address the influences of leading-edge thickness and mean aerodynamic loading. Receptivity coefficients have been calculated for the case of acoustic free-stream disturbances in a low Mach number flow. A number of general conclusions were drawn. The introduction of leading-edge thickness causes a decrease in receptivity levels relative to the case of a flat plate. It is also clear that modest levels of aerodynamic loading decrease the receptivity on the upper surface, but increase the receptivity on the lower surface. The effects are more pronounced at higher values of the Strouhal number, where the region of receptivity is concentrated nearer the stagnation point (Figure 5). A rise in receptivity level on the upper surface occurs for larger values of aerodynamic loading. The decrease in receptivity level on the upper surface in the presence of modest aerodynamic loading is of significance for applications such as laminar flow design. The subsequent rise in receptivity for values of μ (effective angle of attack parameter) nearer the critical value for separation also has important practical implications.

Haddad et al. (1998) used a similar numerical approach to study the receptivity of the boundary layer flow over a slender body with a leading edge of finite radius of curvature to small streamwise velocity fluctuations of a given frequency. The body of interest was a parabola in order to exclude jumps in curvature, which are known sites of receptivity and which occur on elliptic leading edges matched to finite-thickness flat plates. They found that the leading-edge receptivity coefficient depended on the nose radius of curvature, with the largest receptivity occurring for the infinitely sharp leading edge (Figure 6). This agreed with the numerical results of Murdock (1980, 1981) and the asymptotic analysis of Hammerton & Kerschen (1992).

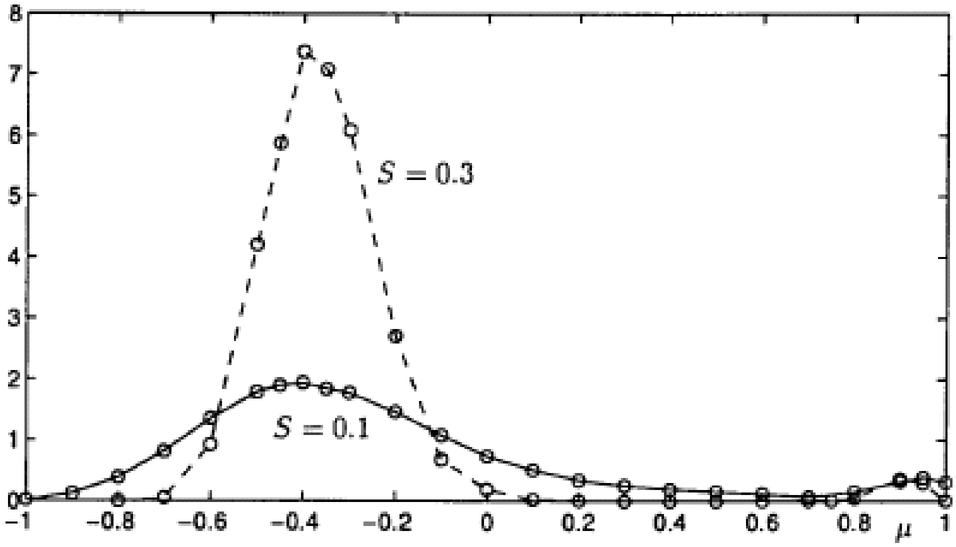


Figure 5: Variation of the magnitude of the receptivity coefficient as a function of the aerodynamic loading parameter μ, for two Strouhal numbers, S = 0.1 and 0.3. Receptivity due to the free-stream disturbance component symmetric about the nose, ICsl.

For a given nose radius, the leading-edge receptivity was also found to increase with increased pressure loading produced by a mean angle of attack of the body. This trend agreed with Hammerton & Kerschen (1992) for their larger angles of attack, but did not consistently show the slight decrease in receptivity that they observed for initial small angles of attack.

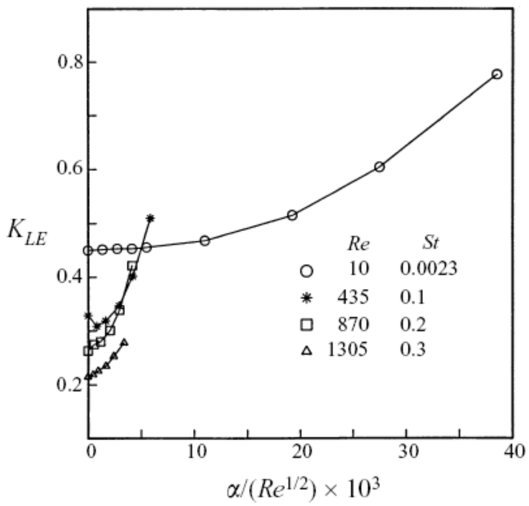


Figure 6: Effect of angle of attack on the leading-edge receptivity coefficient for different nose radii.

Wanderley and Corke (2001) investigated the leading-edge receptivity to acoustic waves of two-dimensional bodies, using a spatial solution of the Navier-Stokes equations in vorticity/stream function form in general curvilinear coordinates. Their results document the importance of the leading edge, junction between the ellipse and flat plate, and pressure gradient to the receptivity coefficient at Branch I of neutral-growth curve. Comparison to the past experiments and other numerical simulations showed the influence of the elliptic leading-edge/flat-plate joint as an additional site of receptivity which, along with the leading edge, provides a wavelength selection mechanism which favours certain frequencies through linear superposition (Figure 7).

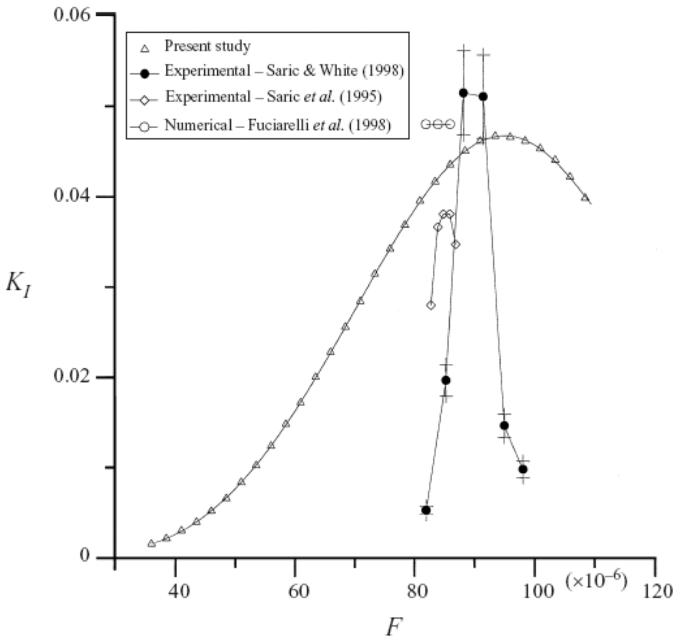


Figure 7: Receptivity coefficient at Branch I as a function of frequency over a flat plate with a 20:1 MSE (modified super ellipse) leading edge, and comparison to the experimental results of Saric et al. (1995), Saric & White (1998), and Fuciarelli et al. (1998);R_b=2400 (b= plate half-thickness).

Saric et al. (2002) pointed out that, whereas the results for the flat-plate geometry provide important insights on leading-edge receptivity, the bodies of interest for practical applications generally have parabolic or elliptical leading edges and an asymmetric mean flow owing to the presence of aerodynamic loading. To analyze the influences of body nose radius and aerodynamic loading on leading-edge receptivity, Hammerton & Kerschen (1992, 1996, 1997, 2000) extended the asymptotic theory to the case of a parabolic leading edge. The nose radius r_n, enters the theory through a Strouhal number,

$$S = r_n 2\pi f / U_\infty$$

In the absence of aerodynamic loading and a parallel acoustic wave, lCsl (receptivity parameter) first rises slightly (as S is increased) and then falls monotonically, to 15% of the flat-plate value at S=0.3. This behavior appears to be related to the favorable pressure gradient near the nose of the parabola. For obliquely incident acoustic waves, the finite nose radius weakens the influence of leading-edge scattering, although this effect still generally dominates over the receptivity from the parallel component of the acoustic wave.

Localized Receptivity

Transition to turbulence in boundary layers is known to result from a sequence of linear and nonlinear instabilities. These instabilities permit the evolution of small amplitude velocity perturbations into large-amplitude disturbances leading to breakdown. An essential part of this process is the transformation of free-stream disturbances into the small-amplitude velocity perturbations which “feed” the instabilities. In general, perturbations in the free-stream environment are characterized by long wavelengths while boundary-layer disturbances are characterized by short wavelengths. Thus any mechanism to describe the induction of free-stream disturbances into the boundary layer must account for the length-scale reduction.

Early analytical studies of receptivity were based on non-homogeneous Orr-Sommerfeld problems (Mack, 1975; Rogler and Reshotko, 1975; Tam, 1981). Disturbances in the free stream, either acoustic or vertical, provided the forcing necessary to introduce perturbations into the boundary layer. These perturbations, however, were not linked to the instability eigenmodes. An additional feature missing in these early studies is a mechanism for length-scale reduction. More recently, Goldstein (1983, 1985) linked the process of scale reduction to short-scale streamwise variations in the mean flow. For a flat plate boundary layer, variations of this form occur in two principal regions. The first region is near the leading edge where the boundary layer is thin and changing rapidly. The second region is in the neighborhood of some form of localized irregularity, which occurs downstream. Receptivity in this second region is known as “localized receptivity”.

A localized surface irregularity produces a steady velocity perturbation in the boundary layer. This disturbance field interacts with the acoustic disturbance to generate traveling waves that can, in turn, feed the natural instabilities. This interaction can be captured using asymptotic analysis if specific assumptions are made about the scaling and the position of the surface irregularity.

In the work of Crouch (1992a), the boundary-layer receptivity resulting from acoustic forcing over a flat plate with a localized surface irregularity is analyzed using perturbation methods. The length-scale reduction, essential to acoustic receptivity, is captured within the framework of the classical stability theory. At first order, two disturbances are calculated: an unsteady disturbance resulting from the acoustic forcing and a steady disturbance resulting from the surface irregularity. These disturbance fields interact at second order to produce a traveling-wave field bearing the frequency of the acoustic wave and wave numbers associated with Fourier components of the surface irregularity. Components of the traveling-wave field scale linearly with both the acoustic forcing and the height of the surface irregularity. Receptivity occurs when the frequency and wave number of a traveling-wave component perfectly match the local eigenmode. Results are in general agreement with asymptotic analyses for irregularities in the neighborhood of branch I. Downstream of branch I, the current results show significant deviations from the asymptotic theory.

In the research work of Kerschen (1993), localized receptivity analyses have been developed for the case of vortical free-stream disturbances interacting with a wall hump. The Mach number of the flow is assumed to be small, and high-Reynolds-number singular perturbation techniques are utilized. In all cases the hump height is assumed small, say $\delta << 1$. The case of small roughness heights is applicable to many practical situations, and has the advantage that analytical solutions to the triple-deck equations can then be found. A theory that is also linear in the amplitude A of the vertical free-stream disturbance was developed and this theory showed that localized receptivity to vortical disturbances is significantly weaker than the localized receptivity to acoustic disturbances. However, the results of the theory also suggested that, even at small amplitudes, nonlinear effects could be important for localized receptivity to vortical disturbances. Therefore, the localized receptivity theory was extended to account for nonlinear effects that arise at larger free-stream disturbance amplitudes.

As mentioned by Saric, (2002), localized receptivity is caused by the interaction of disturbances with short-scale variations in surface geometry. These localized mechanisms can be important even when the variations are small. For example, the localized receptivity of the curvature discontinuity at the ellipse/flat-plate junction could double the overall receptivity (Lin et al., 1992).

Localized receptivity analyses, in which the triple-deck equations are replaced by the exact equations for a small perturbation to a parallel shear flow, have been developed by Choudhari & Streett (1992) and Crouch (1992a). This "finite-Reynolds number approach" contains exactly the same physical mechanism as the Goldstein (1985) theory. The receptivity arises owing to nonparallel mean-flow effects, which are expressed in terms of a perturbation series with respect to the amplitude of the wall inhomogeneity, identical in form to the localized receptivity analyses of Goldstein, Kerschen, and Choudhari. Crouch (1992b) and Choudhari (1993) have also used the finite-Reynolds-number approach to analyze "distributed receptivity" for wall waviness of wave-number $\alpha_w \approx \alpha_{TS}$.

Localized Disturbances

Transition from laminar to turbulent flow in wall bounded shear flows follows a sequence which can be divided into excitation of perturbations, amplification of induced disturbances and finally breakdown to turbulence. A majority of earlier receptivity studies has focussed on the generation of Tollmien-Schlichting (TS) waves due to acoustical disturbances (see Nishioka and Morkovin, 1986 for a review). In order to efficiently induce TS-waves with sound, the acoustical perturbations have to interact with local changes in the mean flow, for instance in the leading edge region or close to surface roughnesses. Another source of disturbance is free stream turbulence (FST). It has been observed that FST can induce at least two types of boundary layer disturbances: randomly occurring TS-wave packets, and large amplitude low-frequency fluctuations in the streamwise velocity component. Unless the FST-level Tu is low, the latter type of disturbances will be dominant inside the boundary layer with rms-amplitudes in the streamwise velocity component of the order of 10% before transition occurs (Tu is defined as u_{rms0}/U_0 measured at the leading edge, where u_{rms0} is the streamwise component of the free stream turbulence and $U_0$is the free stream velocity). However, both types of disturbances may co-exist in the boundary layer, even at rather high levels of FST, and interaction between them may be of importance for transition.

If a small amplitude disturbance is introduced at supercritical Reynolds numbers it usually results in a TS-wave packet. This was first studied by Gaster and Grant (1975), who observed a downstream development with phase speeds in agreement with TS-waves and a spanwise spreading of the wave packet. Further downstream, low-frequency oblique waves could be observed in the spectra, suggesting that sub-harmonic resonances were at play. Similar observations were made in experiments by Cohen et al. (1991), who followed the evolution of the initially linear wave packet through the non-linear stage until it evolved into a turbulent spot. They also showed that for measurements in the region with sub-harmonic growth, the spanwise wave pattern was rather different whether the probe was positioned outside or inside the boundary layer. The distortion of the wave fronts observed inside the boundary layer was ascribed to an increased contribution from normal vorticity, which can be forced by growing three-dimensional subharmonic waves. A much stronger initial amplitude was used by Amini and Lespinard (1982), who obtained a structure which they denoted as an 'incipient spot'. The propagation velocities of the front and rear part were $0.95U_0$ and $0.5U_0$ respectively, and it showed a rather slow spanwise spreading with a lateral growth angle of about 4 degree.

Grek et al., (1985, 199lb) showed that three different types of disturbances could be obtained from a point source positioned inside a flat plate boundary layer. Beside the wave packet and the turbulent spot, they found a third type of disturbance. The spanwise spreading of this structure was very small throughout its evolution (in contrast to TS-wave packets), and the propagation speed for the front part of the disturbance was around 80% of the free stream velocity. Furthermore, the maximum disturbance amplitude was found approximately in the middle of the boundary layer, but with a downstream decay of the amplitude. Due to the limited connection with the wall and the large propagation speed, this type of boundary layer disturbance was at the time named a 'Puff'. This term was borrowed from Wygnanski et al., (1975), who used it to denote a localized disturbance in pipe flow.

A similar 'puff-like' structure was also observed by Breuer and Haritonidis (1990). This transient part propagated with the local mean velocity, it was stretched in the streamwise direction but showed only a very limited spanwise spreading. However, the disturbance amplitude of the transient decayed quickly, and the disturbance became dominated by a growing TS-wave packet.

An attempt to generate localized disturbances from the free stream was carried out by Grek et al., (1991a), who introduced a short duration jet through a pipe located upstream of the leading edge. This resulted in boundary layer disturbances with characteristics similar to the previously described 'puff'.

The receptivity of a laminar boundary layer to free stream disturbances has been experimentally investigated (Westin et al., 1998) through the introduction of deterministic localized disturbances upstream of a flat plate mounted in a wind tunnel. Hot-wire measurements indicate that the spanwise gradient of the normal velocity component (and hence the streamwise vorticity) plays an essential role in the transfer of disturbance energy into the boundary layer. Inside the laminar boundary layer the disturbances were found to give rise to the formation of longitudinal structures of alternating high and low streamwise velocity (Figure 8). Similar streaky structures exist in laminar boundary layers exposed to free stream turbulence, in which the disturbance amplitude increases in linear proportion to the displacement thickness.

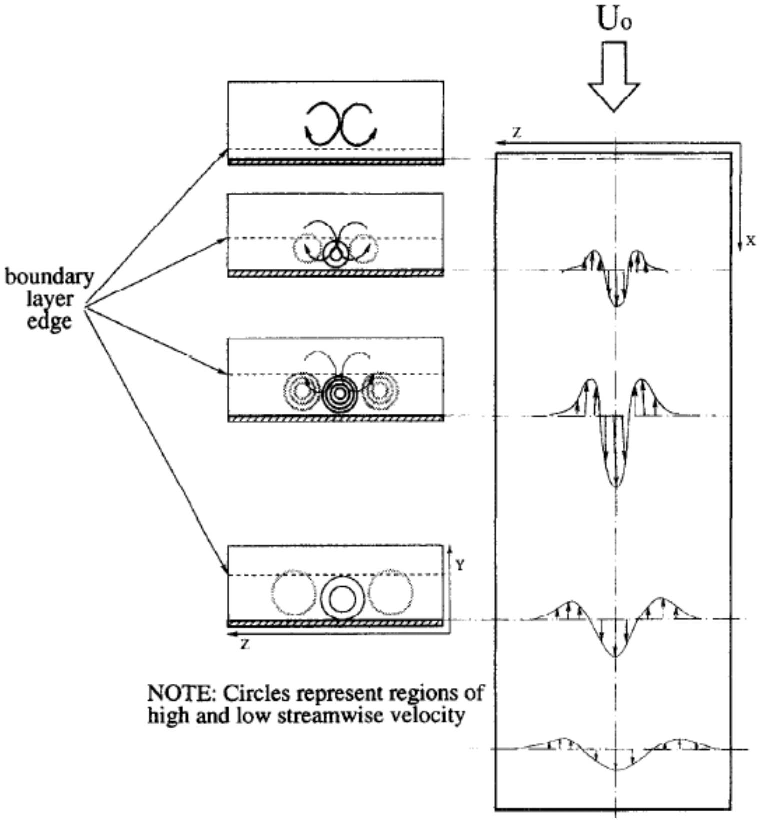


Figure 8: Illustration of the receptivity process.

It is proved that, at moderate levels of free stream turbulence (FST) the transition process can be promoted by the introduction of Tollmien-Schlichting (TS) waves due to the receptivity of the boundary layer. In the research work of Bakchinov et al. (1998), the interaction between localized boundary layer disturbances and controlled TS-waves is studied experimentally. The localized disturbances are generated either from a controlled free stream perturbation, or by means of suction or injection through a slot in the flat plate surface. Both methods result in boundary layer disturbances dominated by elongated streamwise streaks of high and low velocity in the streamwise component. A strong interaction is observed preferably for high frequency TS-waves, which are damped when generated separately, and the interaction starts as a local amplification of a wide band of low-frequency oblique waves. The later stages of the transition process can be identified as a non-linear interaction between the oblique structures, leading to regeneration of new and stronger streamwise streaks. A qualitative impression of the effect of the interaction can be obtained from Fiigure 9, which shows peak-to-peak amplitudes (u_{pp}) of the ensemble averaged disturbances. u_{pp} was determined by making a spanwise traverse approximately at the y-location where the largest perturbation amplitude was observed, whereafter a few (y, t)-planes were measured in the most interesting regions. It can be observed that, the amplitude of the localized disturbance is decaying downstream, although the initial amplitude is high. Also the TS-wave is continuously damped, despite the large initial amplitude. However, when the two disturbances are generated simultaneously, the total disturbance amplitude is decaying initially, but between x=160 mm and x=300 mm a rapid amplification is observed which shows the strong effect of interaction.

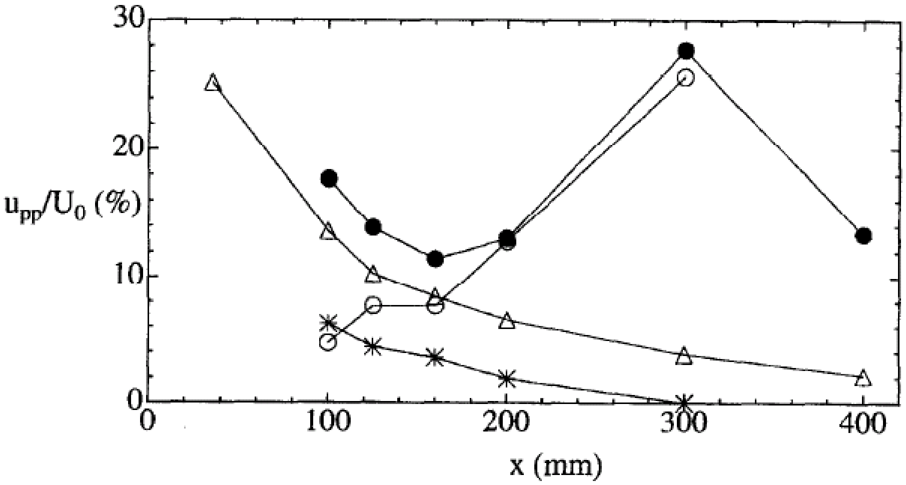


Figure 9: Downstream development of the maximum peak-to-peak amplitude of the streamwise disturbance velocity (u_{pp}): localized disturbance (Δ), TS-wave (*) , total disturbance (•), total disturbance with initial disturbances subtracted (o).

In fact a similar experiments has been performed by the author (Jahanmiri, 2000) and co-workers (Dey et al., 1991). To simulate the effect of free stream turbulence on turbulent spot formation, experiments were conducted on the interaction of localized three-dimensional disturbances with the harmonic waves (TS waves) in a laminar boundary layer on a flat plate. Experiments conducted in three-dimensional diverging flow (but zero pressure gradient) (Figure 10). The results showed, while individually the disturbances decay downstream, their interaction leads to amplification of three-dimensional disturbance leading to formation of the turbulent spot (Figure 11). Also flow divergence exhibited the least effect in the interaction process as it had similar effect on spot srtructure (Jahanmiri et al., 1996).

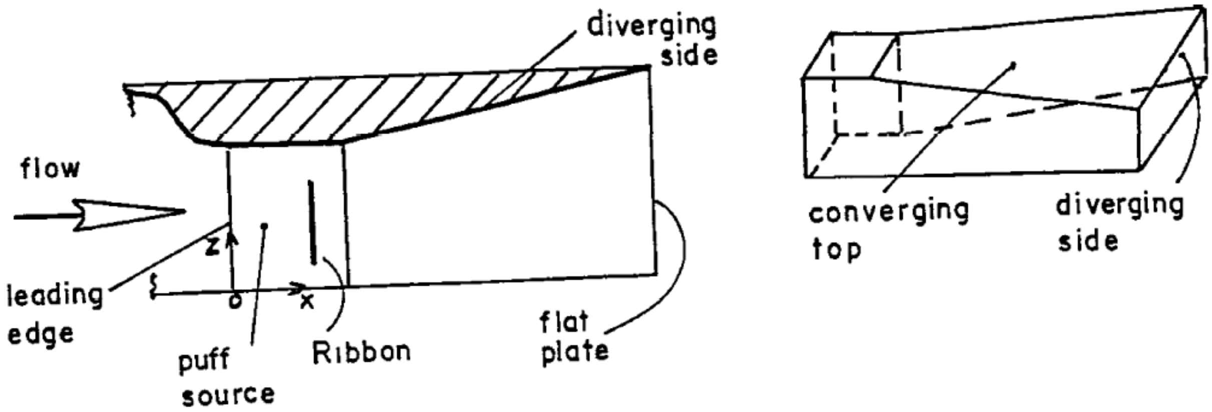


Figure 10: The experimental set-up and 3-D duct.

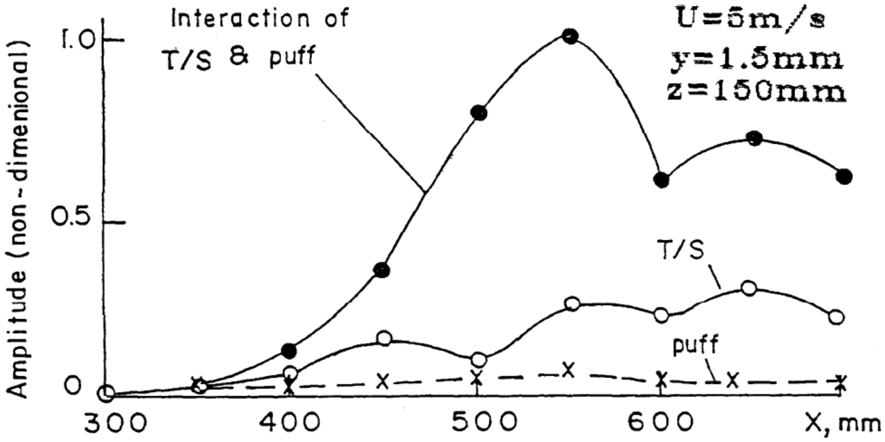


Figure 11: Streamwise variation of intensity of u-fluctuation.

Three-Dimensional Boundary Layer

As commented by Schrader et al. (2009), three-dimensional boundary layers can be found on swept wings or blades and are therefore of importance in aeronautics and turbomachinery. In particular, the flow over a swept flat plate subject to a chordwise pressure gradient has often been considered in the literature. This is a prototype for swept wings, being referred to as a Falkner–Skan–Cooke boundary layer. Most studies focus on cross-flow instability waves, since they dominate the perturbation scenario inside the boundary layer, given a large sweep angle. In contrast to TS instability, cross-flow instability is of the inviscid type and can be stationary as well as travelling.

Results on receptivity and stability in three-dimensional boundary-layer flow have been reviewed by Saric et al. (2003). In the 1990s, the finite reynolds-number theory (FRNT), originally developed by Zavol'skii, Reutov & Ryboushkina (1983) for two-dimensional boundary layers, has been addressed by e.g. Crouch (1993), Choudhari (1994) and Ng & Crouch (1999). Ng & Crouch (1999) and Collis & Lele (1999) consider receptivity to localized roughness of flow over a swept parabolic cylinder. While the former authors use this configuration as base flow for a FRNT study, Collis & Lele (1999) perform both non-parallel FRNT calculations and direct numerical simulations based on linearized perturbation equations.

Receptivity in three-dimensional boundary-layer flow to localized surface roughness and free-stream vorticity is studied by Schrader et al. (2009). A boundary layer of Falkner–Skan–Cooke type with favourable pressure gradient is considered to model the flow slightly downstream of a swept-wing leading edge. Three scenarios are investigated: the presence of low-amplitude chordwise localized, spanwise periodic roughness elements on the plate, the impingement of a weak vortical free-stream mode on the boundary layer and the combination of both disturbance sources. Three receptivity mechanisms are identified: steady receptivity to roughness, unsteady receptivity to free-stream vorticity and unsteady receptivity to vortical modes scattered at the roughnes. They found that stationary cross-flow modes dominate for free-stream turbulence below a level of about 0.5 %, whereas higher turbulence levels will promote the unsteady receptivity mechanism. Under the assumption of small amplitudes of the roughness and the free-stream disturbance, the unsteady receptivity process due to scattering of free-stream vorticity at the roughness has been found to give small initial disturbance amplitudes in comparison to the direct mechanism for free-stream modes. However, in many environments free-stream vorticity and roughness may excite interacting unstable stationary and travelling cross-flow waves. This nonlinear process may rapidly lead to large disturbance amplitudes and promote transition to turbulence.

Like the direct receptivity mechanisms for steady and unsteady crossflow modes, the receptivity process due to a combination of free-stream vorticity and roughness becomes most efficient in the region between the leading edge of the plate and the first neutral point of the excited travelling crossflow wave (Figure 12).

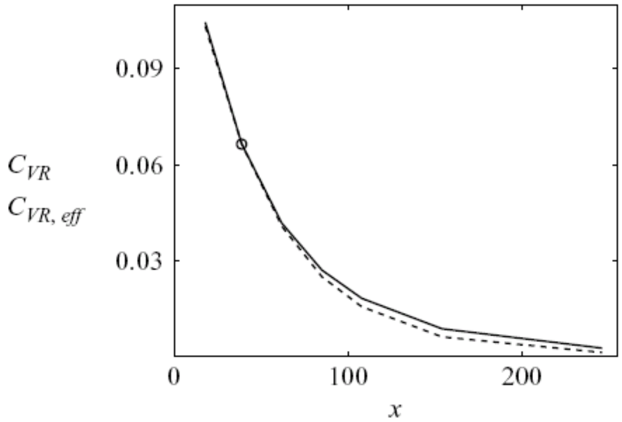


Figure 12: Coefficient for receptivity to free-stream vorticity combined with surface roughness versus chordwise location (—) and effective receptivity coefficient (---).

Earlier, Kachanov (2000) made a review of results of some recent (mainly experimental) studies devoted to a quantitative investigation of the problem of receptivity of the 2D and 3D boundary layers with respect to various 3D (in general) external perturbations.

Summarizing the results are as follows:

1. The 2D incompressible boundary layers are more receptive to 3D perturbations rather than to 2D ones for all the kinds of receptivity mechanisms studied at present. Together with greater growth rates of the 3D TS-waves, observed in the vicinity of the lower branch of the neutral stability curve in previous experimental and theoretical studies (which take into account the flow non-parallelism), this fact suggests that the 3D instability waves can dominate in the subsonic boundary layers (in contrast to a common belief) even in cases when the 2D surface non-uniformities have the same order of magnitude as that of the 3D non-uniformities.
2. The adverse pressure gradient leads to a very significant decrease of the surface receptivity coefficients, especially for the 3D modes. This compensates partially the flow destabilization observed within the framework of the linear stability theory.
3. The swept-wing boundary layers are significantly more receptive to the unsteady surface non-uniformities (i.e. to vibrations) rather to steady non-uniformities (i.e. to the roughness or waviness).
4. The vibration-acoustic receptivity mechanism is studied at present only in the case of the quasi-stationary scattering of the acoustic wave (both in the 2D and 3D boundary layers). At the same time, the non-stationary vibration-acoustic receptivity mechanism can be significant, especially in 2D boundary layers because, in particular, it can provide a redistribution of the external disturbance energy in the frequency spectrum.
5. The receptivity theories and the DNS results are able to predict correctly the quantitative values of the receptivity coefficients obtained in experiment (see Figure 13). This figure clearly shows that the theory is able to predict correctly the initial spectrum of the CF-waves excited by the surface vibrations in the swept-wing boundary layer, especially in a range of the spanwise wave-number corresponded to the most unstable cross-flow modes. These theoretical approaches can be used in the modern advanced methods of transition prediction based on accurate physical notions about the processes of turbulence origin in the boundary layers.

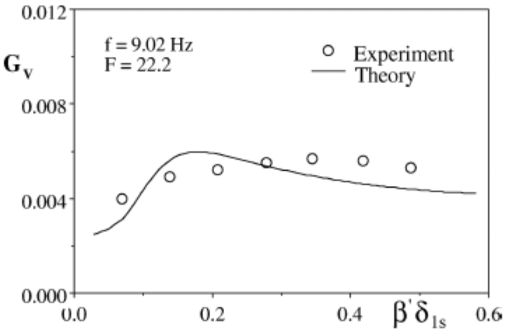


Figure 13: Experimental and theoretical amplitudes of vibration receptivity functions for a swept-wing boundary layer (Crouch et al. [81,82]).

Recently, an experimental study of the receptivity of disturbances and their subsequent development into a three-dimensional boundary layer has been carried out (Kurian et al. 2011). The three-dimensional boundary layer was set up using a flat plate with a swept leading edge and a pressure gradient using a displacement body at the ceiling of the test section. It was found that the boundary layer receptivity to FST (free-stream turbulence) was linear for the range of turbulence levels and length scales studied. For increasing turbulence intensity travelling modes start to dominate and eventually inhibit the growth of the stationary mode present at lower turbulence intensities which confirms the results of Deyhle and Bippes (1996). Also it is observed, the amplitudes of the disturbances increase with increasing roughness height, as expected. The energy of the disturbances scale well with $Re_k^{2.3}$, meaning that the receptivity at these roughness heights is nonlinear (Figure 14).

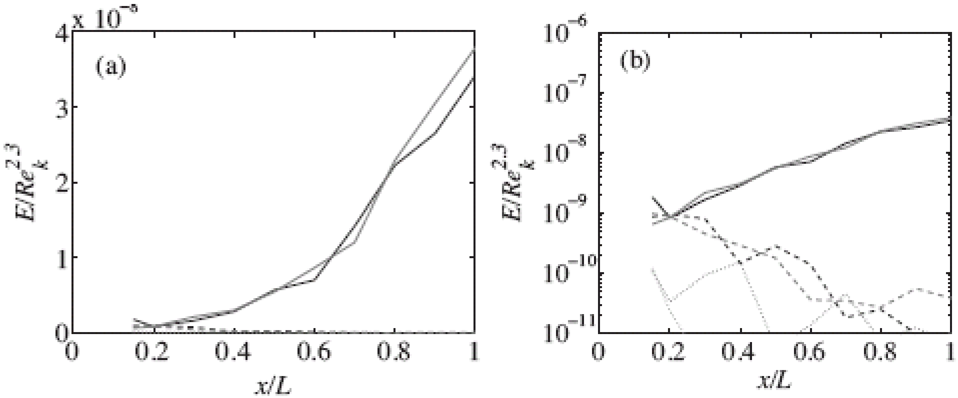


Figure 14: The disturbance development of the stationary modes, for two roughness heights, normalized with the $Re_k^{2.3}$ for $Re_k=26$ (gray) and $Re_k=92$ (black). —:mode 1, – – –: mode 2, ⋯⋯:mode 3 . (a) With linear axes. (b) In a semi-log plot to show the exponential behavior.

Receptivity at High Speeds

The stability experiments of Kendall (1975) showed that the evolution of disturbances in the supersonic boundary layer on a flat plate at Mach numbers 3, 4.5 and 5.6 is essentially different from the case of subsonic flows. Kendall reported that "fluctuations of all frequencies were observed to grow monotonically larger in the region of a boundary layer extending from the flat plate leading edge to the predicted location of instability; i.e. in a region where no growth was expected". Similar observations were reported by Stetson et al. (1991) for a planar boundary layer at Mach 8 and by Graziosi & Brown (2002) for the boundary layer on a flat plate at Mach 3. Mack (1975) developed a forcing theory, which was successfully applied to the Mach 4.5 data of Kendall (1975). However, Mack noted that "the major difficulty in the use of the forcing theory is that forced disturbances are distinct from free disturbances, and the process by which the former becomes the latter is unknown". These findings motivated further theoretical studies of the disturbance field in the leading-edge region. Fedorov & Khokhlov (1991, 1993, 2001) showed that the disturbance spectrum reveals new features in boundary layers at supersonic and, especially, hypersonic speeds when the second mode becomes the dominant instability.

Maslov et al. (2001) performed wind-tunnel experiments on receptivity of the boundary layer to two-dimensional and three-dimensional acoustic disturbances interacting with a sharp leading edge of a flat plate at the free-stream Mach number $M_\infty=5.92$. These data provide an opportunity to verify the theoretical model of Fedorov & Khokhlov (1991, 1993). The direct numerical simulation (DNS) of Ma & Zhong (2001) gives another opportunity to compare theoretical predictions with the numerical experiment on receptivity to two-dimensional acoustic waves at $M_\infty=4.5$.

Fedorov (2003), revised the theory of Fedorov & Khokhlov (1991, 1993), and incorporated the results into the multiple-modes method accounting for an inter-modal exchange and verify the theoretical predictions by comparison with the experimental data and DNS. In his study, the receptivity of a high-speed boundary layer on a flat plate to acoustic disturbances has been modelled using a combination of asymptotic and numerical methods. It was shown that acoustic waves are synchronized with the first and second boundary-layer modes in the vicinity of the leading edge. This property of the disturbance spectrum leads to a new asymptotic structure of the disturbance field and causes significant changes in the coupling coefficient compared with the subsonic boundary layer.

Later, the receptivity and the stability of hypersonic boundary layers due to the interaction of two-dimensional slow and fast acoustic waves with a blunt 5-degree cone and a blunt wedge are numerically investigated by Kara et al., (2007) at a free stream Mach number of 6.0 and at a Reynolds number of $7.8\text{x}10^6$/ft. Both steady and unsteady solutions are obtained.

The unsteady simulations showed that the instability waves are generated very close to the leading edge region. The simulations for the cone showed that the first mode starts to grow starting from the leading edge due to the nonparallel effects before they grow strongly due to the unstable second mode. In the wedge case, the first mode disturbances decay first before they start to grow due to the second mode. The receptivity coefficient of the instability waves generated by the slow acoustic wave is about 4 times the amplitude of the free stream acoustic wave. It is also found that the amplitude of the instability waves generated by the slow acoustic waves is about 67 times larger than that for the case of fast acoustic waves. Therefore, forcing by slow acoustic wave is much more relevant in the transition process involved in hypersonic boundary layers.

Figure 15 (Kara et al., 2007) shows the contours of the density fluctuations inside the boundary layer at different streamwise locations to illustrate the structure and the evolution of the instability waves inside the boundary layer. The contours show that the disturbances are concentrated near the edge of the boundary layer and in downstream the disturbances exhibit the classical 'rope' like structures associated with the second mode.

Their results also show that, The receptivity coefficient in the wedge case is about 0.8 which is about 5 times smaller than that in the cone case. This is due to the initial growth of the first mode in the cone case compared to the decay in the wedge case and also due to the strong stabilization effect of the bluntness in the wedge case.

Semionov and Kosinov (2008) carried out an experimental research study on receptivity of supersonic boundary layer on a blunted plate. The controlled disturbances field, introduced into free stream with the help of the local source of disturbances. Disturbances in the flat plate boundary layer, excited by the external controlled acoustic oscillations in the vicinity of the blunted leading edge, were measured. It was found, that the excitation of disturbances in the boundary layer by the external disturbances at the case of blunted leading edge occurs considerably more heavily than at the case of sharp leading edge.

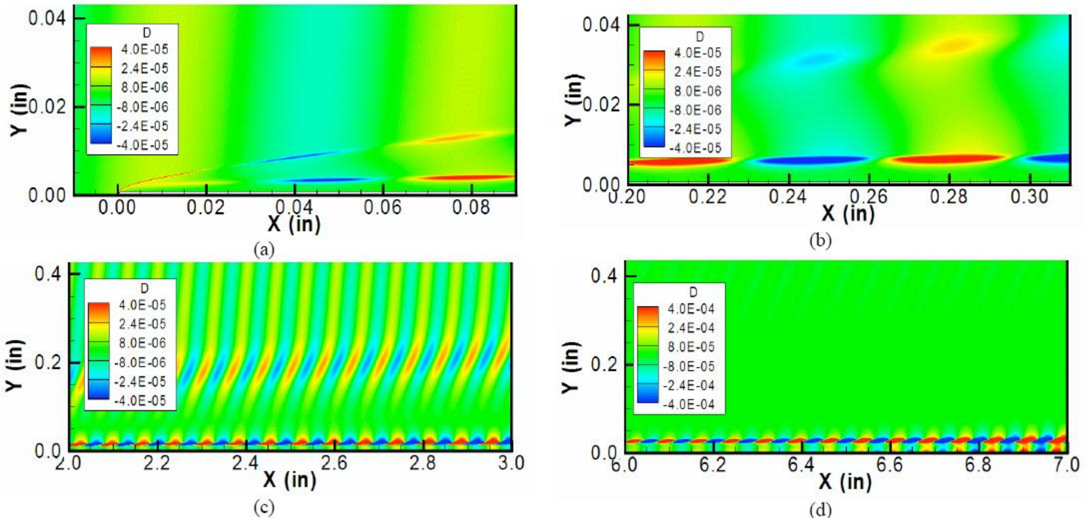


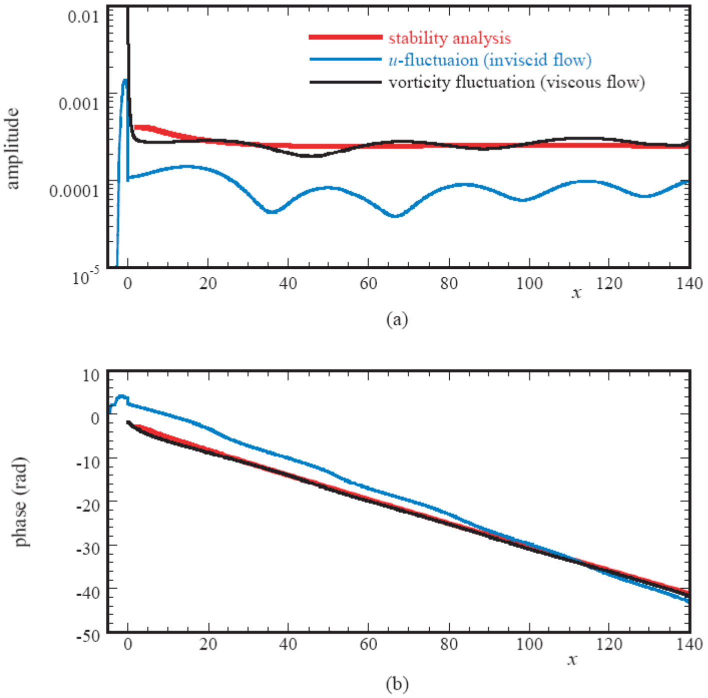
Figure 15: Contours of unsteady density fluctuations inside the boundary layer at different streamwise locations.

Also, two-dimensional direct numerical simulation (DNS) of receptivity to acoustic disturbances radiating onto a flat plate with a sharp leading edge with a porous coating in the Mach 6 free stream is carried out by Egorov and co-workers (2008). The shock wave, which is formed near the leading edge owing to viscous–inviscid interaction, produces a profound effect on the acoustic near field and excitation of boundary-layer modes. DNS of the porous coating effect on stability and receptivity of the hypersonic boundary layer is done and it is found that, a porous coating of regular porosity (equally spaced cylindrical blind micro-holes) effectively diminishes the second-mode growth rate in accordance with the predictions of linear stability theory, while weakly affecting acoustic waves.

They concluded that, receptivity depends on both the level of acoustic near field and the difference between phase speeds of unstable boundary-layer waves and incident acoustic disturbances (synchronization condition). As this difference increases, the coupling between disturbances decreases in accordance with the theoretical model of Fedorov & Khokhlov (1991, 1993, 2001). An interplay between the synchronization detuning and the waveguide excitation leads to a non-monotonic dependency of the receptivity level on the angle of incidence θ. Receptivity to slow acoustic waves is higher than to fast waves. Note that slow acoustic waves are naturally radiated by vortices propagating in the turbulent boundary layer on walls of supersonic wind tunnels (Laufer, 1964). In summary, two-dimensional direct numerical simulation confirms the UAC (ultrasonically absorptive coating) stabilization concept for hypersonic flow over a flat plate.

Sakaue and Nishioka (2004) have presented the simulation results for supersonic boundary layer receptivity to oscillating Mach waves incident onto leading edge of the plate at freestream Mach number 2.2. The results show that the oscillating Stokes layer is induced by the incident Mach wave near the leading edge, and it develops into T-S wave. The amplitude ratio of the excited T-S wave to the Stokes layer in the vicinity of the leading edge is almost of unity.

To examine the excited fluctuations, the streamwise variations of amplitude and phase of the u-fluctuation on the wall for the case of the inviscid flow and the vorticity fluctuation on the wall for the case of the viscous flow are illustrated in Figure 16. In these figures, red lines indicate the T-S wave behavior predicted from the linear stability analysis. The result for the inviscid flow shows that the fluctuation consists of two waves with the phase velocity $1-1/M_\infty$ and $1+1/M_\infty$. As seen from the figure, though the streamwise variation of amplitude of the vorticity fluctuation on the wall slightly undulates due to the existence of the external disturbance, both amplitude and phase variations on the wall agree well with the result from the linear stability analysis and clearly show that the excited fluctuation in the boundary layer is governed by T-S wave.



(a)

(b)

Figure 16: Streamwise variations of (a) amplitude and (b) phase of u-fluctuation on the wall for the inviscid flow and the vorticity fluctuation on the wall for the viscous flow. Red lines represent the result from linear stability analysis.

Conclusions

The past decade has seen considerable progress in the understanding of receptivity mechanisms. The agreement between theory and experiment on two-dimensional roughness is remarkable. Experimental issues on leading-edge receptivity have been settled, and DNS has been established as a viable framework for more detailed studies on different geometries. Challenges still exist in the areas of freestream turbulence and bypasses (Saric et al., 2002).

The acoustic receptivity of the 3D boundary layers on swept wings has not yet been studied in such detail. However, the experimental results show that the acoustic perturbations do excite the traveling cross-flow instability waves in presence of a surface roughness or vibration. For the roughness acoustic receptivity, the receptivity coefficients independent of the roughness shape are obtained experimentally (Kachanov, 2000).

The supersonic receptivity has not been clarified yet and still a wide scope of research is open. This is mainly because, for the case of the oscillating Mach wave incident onto boundary layer, the forced waves appear and persist long to make the excited flow complex, and it is rather hard to singled out the T-S waves from the total fluctuations contaminated by the forced waves.

It is expected, progress to occur when theoretical, computational, and experimental methods are combined to address these important problems.

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