Measurement of Nonlinear Receptivity to Surface Irregularities

Summary of Research

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Abstract

Acoustic receptivity is the process by which acoustic disturbances are internalized into the shear layer to generate instability waves. Experiments have shown that, when tuned to the eigenvalue modes, the amplitude of the resulting T-S waves scales with the acoustic field intensity. When a surface irregularity is present, the characteristic wall wavenumber forces a spatial mode onto the near-wall mean velocity field, thus providing modal length scales comparable to those of T-S waves. In this experiment an attempt was made to increase the acoustic receptivity by exciting a difference mode via a quadratic interaction between two larger-wavenumber, forced modes. The difference mode is tuned to the dominant T-S eigenmode wavenumber. As expected, an increased receptivity corresponding to the difference mode was measured downstream of branch I, suggesting the presence of the nonlinearity.

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Introduction

Acoustic receptivity is the process by which long-wave, free-stream acoustic disturbances generate instability modes in the laminar boundary layer. If the forced modes scale temporally and spatially with the boundary layer instability modes the former will be amplified in the region downstream of the lower branch of the instability curve (branch I). The temporal scales are provided by the external acoustic field. However, the acoustic length scales are orders of magnitude larger than the instability length scales. In a flat plate boundary layer, the leading-edge curvature and the presence of a localized surface irregularity can facilitate receptivity at smaller scales. Goldstein (1985) proposed a wave "scatter" mechanism by which the long waves transfer their energy to the shorter T-S waves via nonlinearities involving the many scales associated with the curvature or with the irregularity. Crouch (1992) approached the problem by studying a non-localized irregularity with a single wavenumber. He found that the acoustic mode interacted with the wall-forced mode to produce a forced traveling wave with the frequency of the acoustic wave and the wavenumber of the surface irregularity. Saric et al. (1990) and Wiegel & Wlezien (1993) among others experimentally confirmed these predictions.

In this experiment a two-dimensional, non-localized, spatially-coherent surface irregularity, containing two distinct fundamental wavenumbers, is introduced in the region around branch I to detect increased receptivity at the difference wavenumber mode. The wall modes, characterized by fundamental wavenumber values α_{w1} and α_{w2}, are assumed to interact quadratically to produce a forced difference mode with wavenumber α_{w12} ($=\alpha_{w2}-\alpha_{w1}$) near in value to α_{TS}, the T-S eigenmode wavenumber. The acoustic field produces a forced mode with frequency ω_A, near in value to ω_{TS}, the frequency of the eigenmode. Following Crouch's line of thought, in the presence of both the external acoustic forcing and the above-mentioned quadratic difference interaction, the resulting forced mode is a traveling wave of frequency ω_A and wavenumber α_{w12}. Its amplitude at branch I is the initial condition for the T-S wave amplification process that occurs further downstream. If the nonlinearity is strong, the difference mode would be excited, and the amplitude would be larger, at branch I and downstream. If it is weak or nonexistent, the surface irregularities would generate only forced modes at α_{w1} and α_{w2}. Since both are quite different from α_{TS}, there would be no measurable receptivity amplitude increase in the T-S scale.

Experimental Set-up

Measurements were performed using hot-wire anemometry in a low-turbulence, closed-loop wind tunnel facility, the 2' x 3' Low Speed Wind Tunnel, in the Fluid Mechanics and Control Branch at the NASA Langley Research Center. The tunnel has an adjustable floor and ceiling height which was used to maintain a near-zero streamwise pressure gradient. The nominal temperature and free-stream velocity are 22 °C and 10 m/s, respectively.

A highly polished flat-plate model was used for this experiment. The model has a 24:1 elliptic leading edge to minimize the leading-edge receptivity. The x-coordinate is measured streamwise from the leading edge, and the y-coordinate is measured cross-tream from the plate surface. The section is 91.4 cm spanwise and 61.0 cm cross-stream. The model extends 262 cm streamwise and it spans the tunnel section. Measurements were made as far downstream as x=201 cm. The model has a removable insert of the plate, where the surface irregularities were attached. Figure 1 shows the surface irregularity patterns in plan view. The pattern in figure 1a was created and mounted on the removable plate insert. The desired pattern of 0.847-cm-wide (streamwise) stripes was etched using copper-plated circuit boards. The pattern

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of 1.27-cm-wide (streamwise) stripes in figure 1b was applied by attaching 0.423-cm- and 0.847-cm-wide polyester tape strips over the copper pattern, thus creating the combined (sum) pattern on figure 1c by superposition. This pattern, which has a 5.08-cm spatial period, is repeated eleven times along 55 cm streamwise on the removable plate. It extends 81 cm spanwise. In figure 1c the white stripes denote a zero height (plate surface without copper, without tape), the diagonal shading denotes a nonzero height for one or the other pattern. The close-knit pattern denotes a nonzero height for both. Stripe height is 30 μm for copper and 33 μm for the tape.

The wind tunnel flow conditions were chosen to produce T-S waves with a dominant eigenmode near a frequency of 65 Hz. Using a loudspeaker system, a monotonic external acoustic field was used to generate a long-wave forced mode at 65 Hz, thus exciting a fast-growing mode. Per the theoretical dispersion relation the eigenmode has a wavelength of approximately 5.08 cm, much shorter than the acoustic wavelenth. The surface irregularity patterns provide the proper length scale in the following way: The copper pattern has a fundamental wavelength of 1.693 cm (twice the width of the stripes). Similarly, the tape pattern has a fundamental wavelenth of 2.54 cm. A quadratic difference interaction between these two modes would yield a forced mode of wavelength of 5.08 cm. Thus by adjusting the free-stream velocity and sizing the irregularity patterns, the dominant T-S mode wavenumber and the difference-interaction target wavenumber are matched. The removable plate is placed with its center at x=53 cm, very near the branch I location for the 65-Hz mode.

Experimental Procedure and Results

Efforts were made to obtain an acoustic downstream traveling wave in the free stream by using upstream and downstream speakers. The measured acoustically-forced amplitude near branch I was 0.019 percent of the free-stream velocity. However, the measured amplitude and phase characteristics show that the attempt to cancel the standing wave was not entirely successful. The experiment was continued in spite of this problem, knowing well that it limits the generality of the results. Figure 2 shows the velocity profiles at several downstream locations for the smooth plate without forcing. As usual, u/U_0 is the normalized mean velocity, y is the distance normal to the plate, and Re_x is the Reynolds number based on x_{corr} (=x-4.2cm). The profiles are compared with the theoretical Blasius profile, shown in solid line.

The relative effect of the nonlinearity was determined by comparing the amplitude and phase variation of the T-S wave between x=190.5 cm and x =200.7 cm near the point of maximum narrow-band rms fluctuation for each condition. This is a short streamwise traverse at the downstream limit of the traverse mechanism, in the region where the T-S wave amplitude is expected to be significant. The measurements presented here include the total disturbance levels which primarily include the Stokes wave, T-S waves due to leading-edge receptivity, and T-S waves due to surface irregularity receptivity. No attempt was made to extract the T-S component due to surface irregularity, which is expected to be the dominant component for measurements taken well downstream of branch I. Figures 3 and 4 show polar plots over two T-S wavelengths (over a 10.1 cm streamwise traverse) for the smooth surface (no surface irregularity) and one-wavenumber pattern (copper only), and for the two-wavenumber pattern (combined copper and tape), respectively. The amplitude is the rms velocity of the total boundary layer disturbance at 65 Hz. The phase, measured relative to the forcing input, corresponds to the spatial phase variation of the disturbance.

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Discussion

In all conditions the amplitudes show some modulation over distances comensurate with the T-S wavelength. Coherence measurements were made with no acoustic forcing, using pressure tansducers. They revealed the presence of spatially coherent disturbances near 65 Hz. It is not clear what causes this amplitude modulation. It may be due to the presence of naturally-ocurring (tunnel-background) coherent disturbances near the 65 Hz forcing. All three plots show full-circle forms indicative of the 5.08-cm wavelenth. But as expected, the amplitude in the (two-wavenumber) combined pattern condition is much larger than the amplitudes in the smooth and in the (one-wavenumber) copper-pattern-only conditions. This larger receptivity amplitude suggests that the nonlinearity has excited the T-S amplitudes and is thus present in the combined pattern condition.

Concluding Remarks

Evidence has been shown that there might be a nonlinear waveform interaction which facilitates acoustic receptivity in the form of modes with length scales not present in a distributed surface irregularity. Therefore, simply determining the wavenumber spectrum of the surface irregularities may not be sufficient to predict which T-S modes will be targeted for amplification.

References

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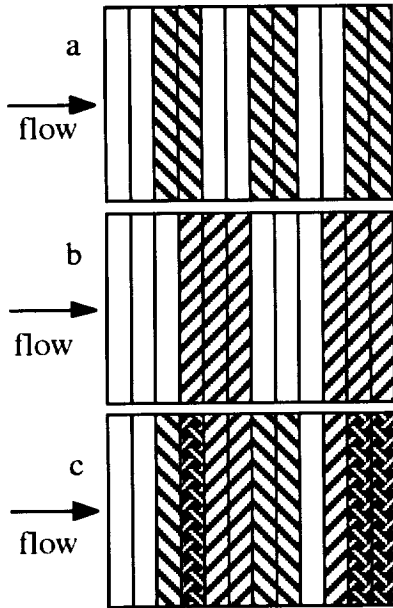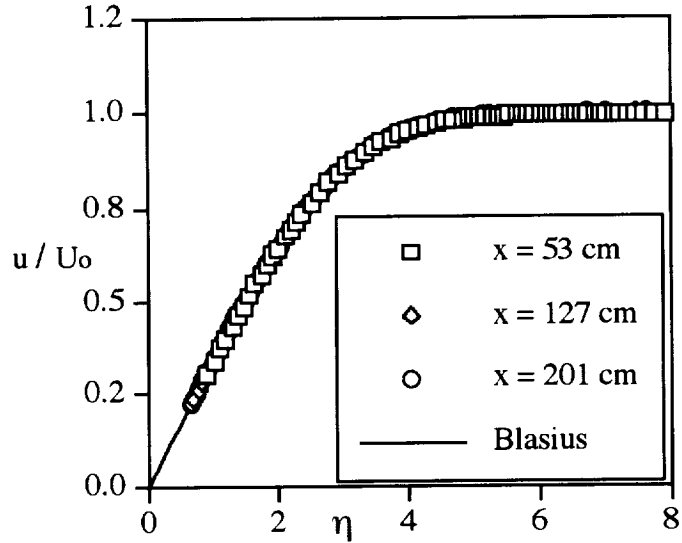
Figures

Figure 1. Surface
irregularity patterns

Figure 2. Boundary profiles,
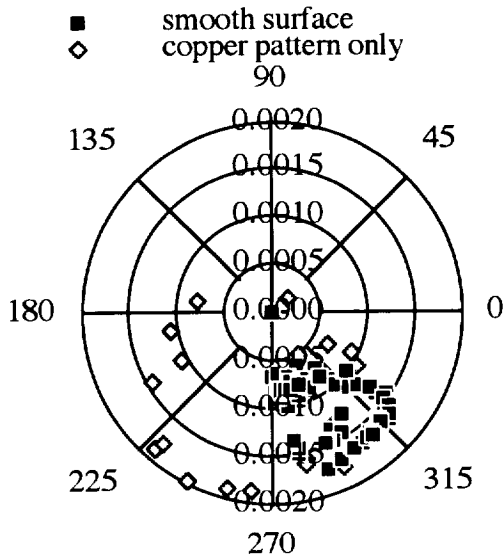$\eta = (y/x_{corr})\, Re_x$.
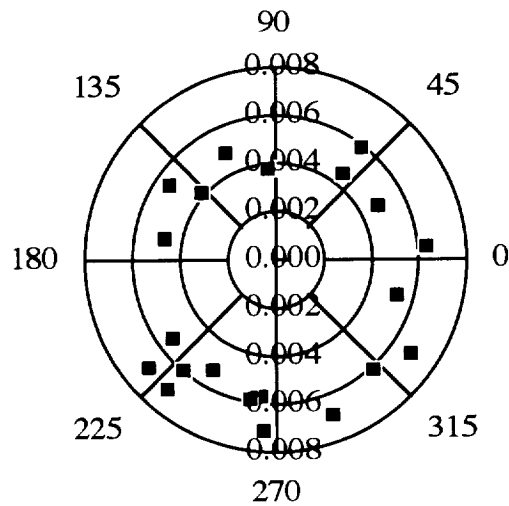

Figure 3. Amplitude (m/s)-phase locus
of the 65 Hz mode.

Figure 4. Amplitude (m/s)-phase locus
of the 65 Hz mode, combined pattern.