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Weakly-nonlinear interactions of modulated T-S waves in the boundary layer of an airfoil

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Abstract

Weakly non-linear interactions of Tollmien-Schlichting (T-S) waves are investigated experimentally for an incompressible 2D boundary layer. The number of waves introduced in the boundary layer is varied, covering regimes composed of few waves or bands of T-S waves (frequency and wavenumber). The experiments are carried out on the pressure side of an airfoil designed to achieve a long region of laminar flow. The results show that modulations of fundamental wave tend to generate disturbances in a range of low frequencies, via nonlinear wave interaction, which can act as self-generated seeds for subharmonic resonance. This sequence of weakly non-linear events were recently described\textsuperscript{1} for regimes composed of few waves. The results shown here, for wave bands, are in qualitative agreement with previous findings. The mechanism seems to be a possible route for transition in the case of Natural Laminar Flow airfoils under 'natural' environment disturbance conditions.

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1. Introduction

The role of transition to turbulence in a boundary layer under natural\textsuperscript{7} environmental disturbance conditions is still a challenging problem. Although many aspects of the phenomenon are well described by theory\textsuperscript{2,3,4}, the whole process is still not completely understood. Since Gaster & Grant\textsuperscript{5}, the use of localized disturbances in space and time (wave packet) became common as a model for the investigation of 'natural' transition. Important aspects of phenomenon were clarified by experiments involving wavepackets\textsuperscript{5,6,7}. Some of those works reported a higher non-linear activity of perturbations developing inside the wavepackets, especially for strong modulation of the disturbance amplitude in time. From the spectral viewpoint such stronger modulation corresponds to a broader frequency spectrum of the wavepacket. Different explanations were proposed previously\textsuperscript{8,9,10}. However, no any definitive, indubitable

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arguments were found. Therefore, the present investigation deals with the study of interactions involving bands of deterministic T-S waves at weakly nonlinear stages of boundary layer transition.

Simplified regimes composed by few fundamental waves with different frequencies were recently investigated\(^1\). Such scenario could be interpreted as a single fundamental wave with amplitude modulation in time, similar to wavepackets. Their results have shown that the modulation of fundamental waves did not alter the growth of subharmonics due to resonant interactions. Also, the production of subharmonics in the nonlinear stages of the wave evolution could be clearly described and substantiated. The self production of subharmonics was also observed for wave packets\(^2\). The current investigation is a continuation of\(^1\) towards the understanding of mechanisms present at the weakly nonlinear stages of ’natural’ transition in an airfoil boundary layer.

2. Results

The experiments were conducted in the Laminar Wind Tunnel of the IAG. The measurements are carried out on an airfoil at controlled disturbance conditions. T-S waves are excited in the boundary layer by a slit source, which was mounted flush with the surface. Below the slit, 116 equally spaced pneumatic tubes are located and connected to 116 loud-speakers, which are driven by power amplifiers and a 128 channel arbitrary waveform generator. This device enables the generation of well-defined disturbances within a broad band of frequencies and spanwise wavenumbers. Phase-locked hot-wire measurements with respect to the disturbance generation are performed downstream of the slit. A complete description of the set up can be found in\(^1\).

In previous experiments\(^1\), amplitude modulations of the disturbances were obtained by exciting two or three 2-D fundamental waves with different frequencies. The frequency of modulation was given by the difference in frequency of the fundamental waves. Here, the same conditions are kept and the carrier frequency is set to 634Hz with a modulation frequency (\(\Delta F\)) of 156Hz. Figure 1 shows the evolution of two excited fundamental waves, introduced at the source, and fluctuations having the modulation frequency (\(\Delta F\)). It is important to note that difference modes are not introduced directly by the source; they arise from non-linear interaction between the excited fundamental waves. Linear stability calculations (LST) are also displayed in the figure. A good agreement with the theory is seen, except for the \(\Delta F\) modes.

Measurements along the spanwise direction are carried out and the spectra of spanwise wavenumbers of the waves at \(\Delta F\) frequency are depicted in figure 2. These measurement are performed at one displacement thickness from the wall, which corresponds to the maximum in the eigenfunction profiles given by LST for 2-D and 3D waves at \(\Delta F\) frequency. The curves are shifted by a factor of 10, for sake of clarity. The spectra show that, initially, \(\Delta F\) modes consist mainly of 2-D waves (\(\beta = 0\)rad/mm). Further downstream, a band of 3-D modes is amplified. Additional insight is gained by an amplitude scaling of the curves with the initial amplitude of the excited fundamentals. Note that in all cases \(A_{f1}(\Delta s = 0) = A_{f2}(\Delta s = 0)\) and the reference case (\(A_R\)) is the one shown in figure 1. It can be seen that at \(\Delta s = 40\) and 80mm the normalized spectra are well scaled by the square of fundamental waves amplitude. This was previously reported\(^1\) and it is an indicative that pure product of fundamentals are forcing the excitation of difference modes. In that work the nature of three-dimensionality seen already in this non-resonant stage was associated with the efficiency of the non-linear interaction between fundamentals waves. Further downstream the quadratic scaling does not offer a good correlation of measured spanwise spectra and resonance is likely to occur\(^1\).

The above sequence of nonlinear events was observed and substantiated in de Paula et. al\(^1\) for a few modes, however it is not clear how it develops for cases composed of several waves, like in wave band regimes. An experiment was set to address this case. To this end, bands of waves having the same central frequency of 634Hz and several modulation frequencies are investigated. The frequency-spanwise-wavenumber spectra shown in figure 3 is obtained for a modulation frequency of 134Hz. The maximum amplitude within the time series of the driving signal is also maintained constant and equals to the case composed of few waves. The spectral distributions of figure 3 show qualitatively a similar behavior when compared to the case where only two fundamental waves were excited. It can be seen that at \(\Delta X = 20\)mm mainly the disturbances introduced by the source are visible. Further downstream, at \(\Delta X = 80\)mm, some seeds of disturbances in the range of \(\Delta F\) frequencies are already noticeable and at the last station, 3-D waves of such modes reach high amplitudes. At the last station, traces of detuned subharmonic resonance can be observed. The detuned resonance is suggested by the filling of the spectral distribution at frequencies right below the band of excited waves, i.e. below the dashed line. Apparently, this is the most probably route for the amplification of
the disturbances toward the late stages of transition. The scenario observed here, is in agreement with the findings for wavepackets and wavetrains and is also considered to occur in the case of ‘natural’ transition.

Fig. 3. Spectral distribution of streamwise velocity fluctuations for the regime with 2-D band of T-S waves. The gray scale corresponds to log(A) in % of $U_e$

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