EXCITATION OF UNSTEADY GÖRTLER-INSTABILITY MODES BY FREE-STREAM VORTICES

A.V. Ivanov, Y.S. Kachanov [a)] & D.A. Mischenko
Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch of Russian Academy of Sciences, Novosibirsk 630090, Russia

Summary In various practical situations (such as in turbomachines), the free-stream turbulence is one of important factors responsible for excitation of Görtler vortices in boundary layers developing over concave walls. Amplification of such vortices is able to lead to the laminar-turbulent transition and change dramatically the skin friction, heat fluxes, and other important aerodynamic characteristics. These experiments are devoted to investigation of several possible mechanisms of excitation of unsteady Görtler-instability modes by free-stream vortices in presence of various non-uniformities of surface and base flow. It is found that the majority of the studied vortex-receptivity mechanisms are very weak, while the mechanism of distributed (in the streamwise direction) excitation of Görtler vortices by streamwise free-stream vortices due to their scattering on natural base-flow non-uniformities is rather strong. This mechanism is investigated quantitatively under fully controlled disturbance conditions. The corresponding distributed receptivity coefficients are defined and estimated experimentally.

INTRODUCTION

The Görtler instability may appear in boundary layers developing over concave surfaces. In cases when the Görtler instability is rather intensive, the transition from laminar to turbulent state may happen earlier than in the corresponding boundary layer over a flat surface. This is explained by the formation of intensive streamwise Görtler vortices, which grow downstream leading finally to the onset of non-linear interactions of disturbances and then to a final breakdown to turbulence. The Görtler vortices can be both stationary and non-stationary [1] depending on predominant mechanisms of their excitation describing by the boundary-layer *receptivity problem*. This problem is related to the very first stage of the *laminar-turbulent transition* and describes how various external (with respect to boundary layer) perturbations penetrate into the boundary layer providing initial seeds for the Görtler vortices. Previous experiments in this series published in [2] were devoted to investigation of the mechanism of excitation of unsteady Görtler vortices (including a particular steady case) by surface non-uniformities. As the result, values of the corresponding receptivity coefficients have been obtained for the first time for this particular receptivity problem.

At enhanced free-stream turbulence levels (such as in turbomachines), the free-stream vortices can be considered as one of the most important factors responsible for excitation of Görtler vortices. The present paper is devoted to experimental investigation of several mechanisms of generation of Görtler-instability modes in a boundary layer over a concave wall under the effect of *free-stream vortices*. Four types of the unsteady vortex-receptivity mechanism have been investigated: (*i*) scattering of 2D free-stream vortices on 3D surface non-uniformities, (*ii*) scattering of 3D free-stream vortices with streamwise orientation of vorticity vector on 2D surface non-uniformities, (*iii*) scattering of 2D free-stream vortices on uncontrolled 3D non-uniformities of the base flow, and (*iv*) scattering of 3D (in general) free-stream vortices on natural 2D non-uniformity of the base flow. The non-uniformities studied in cases (*i*) and (*ii*) were localized in the streamwise direction. Accordingly, the receptivity mechanisms under study were localized in these cases. Meanwhile, the mechanisms investigated in cases (*iii*) and (*iv*) corresponded to the distributed boundary-layer receptivity.

EXPERIMENTAL PROCEDURES

The experiments were performed in a low-turbulence wind-tunnel T-324 of the Khristianovich Institute of Theoretical and Applied Mechanics (ITAM) of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk) at the free-stream speed of 9.18 m/s. The boundary layer was developed over an experimental model representing a plate of 2.38 m long and 1 m wide with concave surface having a radius of curvature in streamwise direction of R = 8.37 m. An adjustable wall bump was installed above the concave plate in the wind-tunnel test section. The bump shape was adjusted in a way to provide the base flow having zero streamwise pressure gradient. It was shown that the base flow represented the Blasius boundary layer. The main measurements were performed by a hot-wire anemometer in a range of the streamwise coordinates, which corresponded to values of the Görtler number (based on the local boundary-layer displacement thickness) G^* = 7 to 21, approximately.

The experiments were carried out under completely controlled disturbance conditions. Both the free-stream vortices and the unsteady surface non-uniformities (vibrations) were generated by special disturbance sources.

The *two-dimensional* controlled free-stream vortices, used in cases (*i*) and (*iii*), were produced by a thin oscillating wire placed in the potential flow upstream the experimental model parallel to its leading edge. The harmonic wire oscillations (occurred in the direction perpendicular to the leading edge and the free-stream velocity vector) were forced by two small stepping motors, which were controlled electronically. The oscillations generated in the flow a low-

[a)] Corresponding author. Email: kachanov@itam.nsc.ru

amplitude vortex street of required frequency f_v having zero spanwise wavenumber β. Such orientation of the vibrating wire leaded to excitation of the free-stream vortices having the spanwise orientation of the oscillating vorticity vector. The generated antisymmetric vortex street propagated downstream along the external edge of the boundary layer.

The *three-dimensional* controlled free-stream vortices having streamwise orientation of the oscillation vorticity vector, used in cases (*ii*) and (*iv*), were produced in a similar way. However, the vibrating wire was even thinner in this case (of 50 microns in diameter) but was equipped with a localized non-uniformity, representing a thickening (an excrescence or a bulb) applied onto the wire surface. The non-uniformity was made of a bituminous lacquer and had a typical diameter of about 100 μm and a spanwise length of approximately 5 mm. Its edges were smoothed during manufacturing. Three-component hot-wire measurements have proved that the flow motions produced in the wake behind such non-uniformity had rather intensive streamwise vorticity component (at spanwise sides from the non-uniformity the vortex street, of course, remained two-dimensional).

The source producing harmonic *3D* surface non-uniformities (of frequency f_s), used in case (*i*), represented a spanwise row of circular vibrating membranes flush mounted with the model surface. The membranes were made of latex film about 80 μm thick, and were forced to vibrate under influence of pressure fluctuations produced by closed loudspeakers. The loudspeakers were placed outside the test section, while pressure pulsations were delivered under the membranes by means of flexible plastic pipes. Every two neighboring membranes were vibrating in antiphase, so the produced surface non-uniformity was essentially three-dimensional and periodic in span. In the present experiments, the 3D surface sources modeled non-uniformities with a spanwise period λ_z = 8 mm. The source simulating *2D* surface non-uniformities (oscillating with frequency f_s), used in case (*ii*), was also driven pneumatically in a similar way but had a single elongated membrane with dimensions of 160 mm in span and 9 mm along the streamwise coordinate.

EXITATION OF GÖRTLER VORTICES

Localized receptivity mechanisms

The accuracy of measurements performed in groups of regimes (*i*) and (*ii*) was very high and enabled (at the present experimental conditions) to measure very accurately even very weak unsteady boundary-layer disturbances, which could have as low amplitudes as 10^{-3}% and even lower (depending on frequency). However, no excitation of any Görtler vortices was detected in the boundary layer at combination frequencies $f = f_v \pm f_s$ in experiments (*i*) and (*ii*) devoted to investigation of scattering of freestream vortices on surface non-uniformities (does not matter, 2D vortices on 3D non-uniformities or 3D vortices on 2D non-uniformities). This result was much unexpected. Indeed, the excitation of Görtler vortices was not observed even at extremely large dimensionless amplitudes A_s/δ^* of 2D surface vibrations reaching values of 64%! The only kind of detected boundary layer perturbations represented, as was shown, the Tollmien-Schlichting instability waves. The most efficient excitation of them was detected at high frequencies of the combination modes (several dozens of Hz, usually), although at low frequencies some attenuating Tollmien-Schlichting waves were found as well.

Thus, the excitation of Görtler vortices by means of the receptivity mechanisms associated with scattering of freestream vortices on localized surface non-uniformities (cases (*i*) and (*ii*)) is found to be extremely weak. The same turned out to be true for scattering of 2D freestream vortices on uncontrolled 3D non-uniformities of the base-flow itself (case (*iii*) indicated above).

Nevertheless, the measurements have shown that the three-dimensional freestream vortices are able to interact rather efficiently with the natural 2D spatial non-uniformity of the boundary layer (case (*iv*), indicated above). This case is studied in much detail and discussed below.

Distributed receptivity mechanism

The mechanism of distributed excitation of unsteady Görtler vortices in a boundary layer on concave wall under the influence of streamwise (3D) freestream vortices turned out to be rather efficient and is able to change significantly the growth rates of the Görtler vortices (in comparison with the linear-instability growth rates). In particular, the presence of streamwise freestream vortices can convert attenuating Görtler vortices into the amplified ones. The coefficients of the distributed vortex receptivity of boundary layer with excitation of Görtler vortices have been defined (similar to experiments [3]) and estimated experimentally for the first time. It is found, that the distributed receptivity mechanism excites most efficiently those Görtler vortices, which have spanwise wavelengths corresponding the most amplified linear-instability modes. The amplitudes of receptivity coefficients are found to decay with the streamwise coordinate.

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