DEGREE OF REPEATABILITY OF THE DETERMINISTIC WALL TURBULENCE

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Abstract The present work deals with analysis of turbulent-flow structures formed in experiments in a 2D post-transitional boundary layer with moderately unfavorable pressure gradient. By means of the deterministic-turbulence method, the instantaneous structure of turbulent boundary layer was reproduced many times due to precise reproduction of the initial disturbance field, which initiated the turbulence origin process. Downstream evolution of typical vortical structures and degree of repeatability of the instantaneous flow fields within an ensemble of realizations has been documented and analyzed.

INTRODUCTION

The recently introduced term ‘the deterministic turbulence’ refers to the post-transitional boundary-layer flow, which looks like a turbulent one (according to a common viewpoint, thought that viewpoint is not well defined) but displays a noticeable degree of determinism, i.e. multiple reproducibility of the instantaneous flow field. Such kind of turbulence may occur in boundary layers where transition is caused solely by instabilities of convective type. The experimental realization of the deterministic turbulence has been demonstrated not long ago [1].

There was a common viewpoint on the boundary layer laminar-turbulent transition in the middle and second half of XX century that a phenomenon called the beginning of the flow ‘randomization’ must occur at a certain late stage of the transition process. It was usually assumed by this term that some random, broadband, and uncontrolled disturbances have to be amplified rapidly and lead to the appearance of stochastic turbulent motions making finally the boundary layer fully turbulent. However, the detailed experimental and numerical studies performed during past decade at more and more controlled disturbance conditions (i.e. at better signal-to-noise ratios) do not result in discovering any clear mechanisms of the final flow randomization. Moreover, the majority of the previously suggested mechanisms of the randomization have been rejected by subsequent, more detailed, investigations. That is why the question appeared: “Is it possible that the instantaneous structure of transitional flow would remain deterministic, reproducible and repeatable in the main (at repetition of the same initial conditions) even at super-late, final stages of transition and even in the post-transitional fully turbulent boundary layer?” The affirmative answer to this question was given experimentally in [1]. These experiments were conducted in a flat plate boundary layer in presence of an adverse pressure gradient at free-stream speed of about 9 m/s. The flow was self-similar with constant Hartree parameter equal to −0.115. The laminar-turbulent transition in this boundary layer occurred due to natural development of Tollmien-Schlichting waves. The uncontrolled background velocity disturbances were kept as low as it was possible, their rms level was less than 0.04% of the incident flow velocity (in the frequency range above 1 Hz). The controlled (reproducible) initial disturbances were introduced by means of a special generator. They were a mixture of a quasi-2D TS-wave (corresponding to the most amplified one) and a broadband 3D disturbance consisted of a wide range of various TS-modes of the frequency-spanwise-wavenumber spectrum. Downstream evolution of those controlled disturbances was natural. It started from the linear-instability amplification region, went through nonlinear stages, and ended with the fully turbulent state of the flow. The post transitional boundary layer was shown to be deterministic, basically. It was possible to reproduce many times the instantaneous velocity field in the turbulent flow. The reproducibility, in turn, provided the possibility of performing detailed quantitative hot-wire measurements in the flow under investigation.

The deterministic turbulence can be regarded as a powerful tool for both applied and fundamental researches. Its first practical application has been demonstrated in [2]. In the boundary layer, which was similar to that described above, the instantaneous flow field $U(x, y, z, t)$ was documented in detail in the range of Re = 800 to 1200. Then a Large-Eddy-Break-Up (LEBU) device was installed at a position with Re = 1050, where the boundary layer was practically fully turbulent, and the instantaneous flow field was documented again. Side-by-side comparison of two instantaneous flow fields allowed us to shed some new light on the physical mechanism of the LEBU device affect on the turbulent boundary layer.

The described above method gives us the unique possibility of experimental comparison of various instantaneous realizations of turbulent flows performed in the present investigation. Such kind of comparison was carried out recently in numerical experiments [3] and showed some very intriguing results. It was found that the divergence of turbulent flow fields caused by small difference in initial disturbance conditions can be described by some universal constants. In particular, it was found that the unrepeatable (unreproducible) component of instantaneous velocity fluctuations increased unavoidably in a turbulent channel flow either with time or with the streamwise coordinate in an exponential way. The increment turned out to be a universal constant, which is independent practically of the problem parameters.

EXPERIMENTAL RESULTS

Some of experimental results obtained in the present study (at conditions similar to those described in [1] and [2]) are illustrated in Figs. 1 and 2. Shown in Fig. 1 is an example of three wall-normal profiles of rms intensity of: (*i*) total velocity disturbance A_t (obtained from non-averaged time-traces of fluctuations of the streamwise velocity component), (*ii*) deterministic (reproducible) broadband velocity disturbance A_d (obtained from ensemble-averaged time-traces of the streamwise velocity component) and (*iii*) fully random (unreproducible) broadband disturbance A_{ur} (obtained as a difference $A_{ur} = A_t - A_d$). The stage of the flow evolution at x = 590 mm corresponds approximately to the early post-transitional turbulent flow. It is seen that the reproducible (deterministic perturbations still dominate at this stage. However, very near the wall the uncontrolled (random) perturbations become comparable with the deterministic ones at this stage. This experimental observation obtained for the boundary-layer flow is in a qualitative agreement with the numerical results obtained in [3] for the channel flow.

The streamwise evolution of the uncontrolled perturbations is shown in Fig. 2. It displays the evolution of maximum (in the wall-normal profiles) rms intensity of total streamwise-velocity disturbance A_t and fully random (unrepeatable) disturbance A_r obtained in the regions of transitional and post-transitional, turbulent boundary layer. It is seen that the total disturbance amplitude grows in an exponential way at nonlinear stages of transition (including late stages) but saturates at super-late stages of transition and remains constant (about 12%) in the post-transitional turbulent boundary layer. Meanwhile, the amplitude of the uncontrolled perturbations grows downstream exponentially in a long streamwise region until the beginning of the post-transitional turbulent boundary layer. It is very important to note that no any jump-like or explosive increase of the random disturbances is observed. The exponential behaviour is in consistence with that obtained in the numerical study [3] (performed for the flat-channel flow). The experiment shows, in addition, that the growth of the random component saturates when the random-mode amplitude A_r approaches the total-disturbance amplitude A_t (after $x \approx 600$ mm).

Main conclusions of the present experimental study are the following. The deterministic turbulence method has displayed again its powerful ability. None of previously used approaches is able to provide us with such information. It is found that the degree of unrepeatability of the deterministic boundary-layer turbulence increases downstream gradually, in an exponential way, and has the largest values in the near-wall region of the post-transitional turbulent flow.

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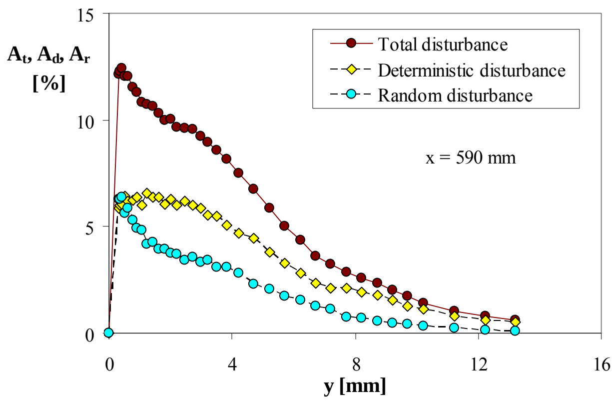

Figure 1. Example of wall-normal profiles of rms intensity of: (*i*) total velocity disturbance A_t (obtained from non-averaged realizations), (*ii*) deterministic (reproducible) broadband velocity disturbance A_d (obtained from ensemble-averaged realizations) and (*iii*) fully random (unreproducible) broadband disturbance A_{ur} (obtained as difference $A_{ur} = A_t - A_d$). x = 590 mm.

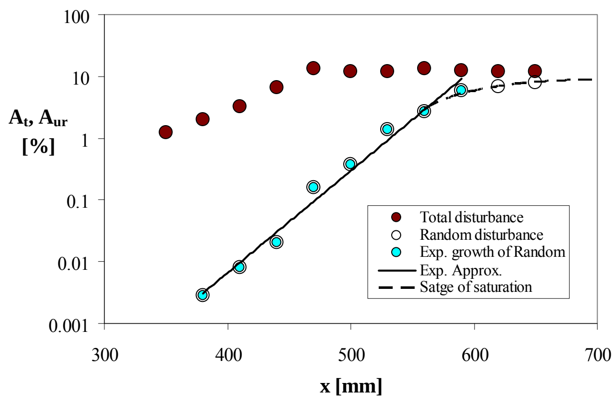

Figure 2. Streamwise evolution of maximum (in *y*-profiles) rms intensity of total streamwise-velocity disturbance A_t (obtained from non-averaged realizations) and fully random (unrepeatable) disturbance obtained as difference $A_{ur} = A_t - A_d$ of total and deterministic amplitudes.

References

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