UNSTEADY PHENOMENA IN SEPARATED AND REATTACHING FLOWS: FROM STATISTICAL CHARACTERISTICS TO INSTANTANEOUS SPACE-TIME FIELDS

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ABSTRACT: The dynamics of the backflow region in a separated turbulent flow was visualized using results of a direct numerical simulation. A new parameter for description of the non-stationary cycle in a separated flow is proposed – the total wall area occupied by the reverse flow. A local multipoint identification criterion for registering basic stages of the non-stationary cycle is presented. In practice such a criterion can be realized using a rake of near-wall hot-wire probes uniformly distributed in the *z*- direction and located in the forward-flow region not far downstream from flow reattachment.

INTRODUCTION: Probably, the first work about low-frequency non-stationary processes in a separated flow was published in 1980 [1]. Since that time local one- and multipoint measurements of velocity [2,3], longitudinal skin friction component [4-6] and pressure fluctuations [7-9] have been provided. The following statistical methods of experimental data processing have been used: spectral [6-11] and correlation [6-9] analysis, conditional sampling technique [6,12], and, later, wavelet analysis [10]. But local measurements (even multipoint) and the corresponding statistical methods of data analysis provide very limited possibility to describe the whole space-time picture of a separating/reattaching flow.

From a historical point of view hot-wire probes have been the first instruments of the investigation. This tool allows only local insight into the phenomenon of turbulence. Modern methods of simultaneous measurements (LDA [6], PIV [3,10,13]) and especially numerical simulation (LES [14,15], DNS [16,17]) provide more detailed information about a flow. One may say – too much information. The problem is that there is no equivalent *language* for description of instantaneous space-time fields of flow parameters. Such a language must be quantitative, universal as the well-known language of statistical characteristics, and convenient [18].

It is the main shortcoming of the statistical approach that peculiarities of various events in a turbulent flow are neglected (as in the model of the ideal gas), but it is not the case for the turbulence. The individuality of turbulent structures and their interactions are important. Unfortunately, a full quantitative description of all individual events in a turbulent flow, even if it is technically possible, means that a researcher will be buried under the mountain of information.

Understanding of the low-frequency non-stationary processes in separated flows is essential, for instance, for the development of separation control methods. The basic facts about flow reattachment phenomena are:

1. The instantaneous reattachment point moves up- and downstream (over a range of approximately two step heights in the case of the backward-facing step [1]).

2. The pulsation of the reattachment point is closely connected with the so-called "flapping" of the shear layer normal to the wall [1,6]. The "flapping" frequency is low when compared with the frequency of large eddy formation in conventional mixing layers. This low-frequency motion has been observed in different separated flows with various geometries [19,20], and is thought to be inherent to such flows.

3. The recirculation region is not "continuous", i.e. there can be blobs of forward flow (main flow direction) reaching down to the wall inside it [17].

4. The reattachment is an essentially 3D phenomenon [21].

5. As far as is known, the underlying cause of the low-frequency pulsation in separated flows is not clear enough yet, though several more or less likely hypotheses have been proposed. Among them the possibility of a hydro-acoustic feedback loop has been considered [22].

6. On the other hand, the mechanism of the low-frequency process in the separation zone has been successfully described *qualitatively* [13,16,17,23]. For example: "... two of the eddies begin to merge in the shear layer. At the instant shown, the entrainment of fluid *from* the bubble prevails over the *reinjection* of fluid in the reattachment region. On the upstream side of the structure, fluid is being entrained from the backflow region into the shear layer. On the downstream side, positive velocity fluid from above the shear layer is being forced down into the recirculation region. This leads to a pinching of the separation bubble and shedding of fluid from the recirculation zone. Following this, the separation region becomes more contracted in size. The two eddies which have merged ... are shed from the shear layer and move downstream. The recirculation zone then gradually increases in size as the pressure within it increases. This expansion of the separation region leads to downstream movement of the instantaneous shear layer impingement point and causes the shear layer itself to move away from the recirculation zone" [15].

In our opinion, extraction of useful information from a statistical approach for the description of the non-stationary processes are practically exhausted. Statistical analysis could be useful for developing/improving corresponding turbulence models but it is not able to significantly assist our understanding of the phenomenon. In the case of turbulence, the "structure" must conform to a taxonomy that is as quantitative as possible; see, for example, [24].

The gap between the qualitative description of non-stationary processes using instantaneous space-time fields and the quantitative statistical characteristics of parameters of a turbulent flow can be filled with identification criteria similar to those used in the conditional sampling technique. It is worthy to note, that in this case the criteria are not intended for constructing of conditionally-sampled fields of turbulence parameters (this also leads to 'smearing' of flow details). The main goal is to formulate the criteria as the elements of the quantitative flow description language based on instantaneous fields of turbulence parameters. As a matter of fact, such an approach has been used in investigations of coherent structures (e.g. the so called VITA technique and so on, see for example, [25]).

In this paper, the multipoint criterion is sought in order to describe quantitatively the main stages of the low-frequency non-stationary cycle in a turbulent separated flow. The skin friction seems to be an appropriate parameter for this criterion because experiments have shown that the dynamics of instantaneous skin friction fields is correlated with the extremely complex process of the separated shear layer reattaching [11,12].

NUMERICAL MODELLING: The DNS database, presented in [26], for a separated turbulent boundary layer on a flat plate is used. The well-validated finite-difference code [27] based on a staggered grid has been used for the simulation.

The reference length is the displacement thickness δ_0^* at the reference location (x=0). This location is not the physical inflow of the domain, which is located at x/δ_0^* = -65, since the recycling/rescaling boundary conditions [28] have been used to specify the velocity at the inlet. The flow needs some distance to develop. The recycling plane is located in the zero-pressure-gradient region and upstream of the region of interest. x=0 is the location where the Reynolds number Re^* based on the local displacement thickness δ_0^* and free-stream velocity U_0 reaches 550. Periodic conditions have been used in the spanwise direction z. On the top boundary the vertical velocity component V_∞ has been imposed to match the condition used by [29]. The mean streamwise component has been obtained from the continuity equation:

$$V_\infty(x,t) = U_\infty \frac{d\delta^*}{dx} + (\delta^* - h)\frac{dU_\infty}{dx},$$

where h is the height of the computational domain. The fluctuating streamwise u and spanwise w components of the velocity have been computed using the condition that the vorticity is zero at the free-stream. The convective boundary condition [30] has been applied at the outlet, and the no-slip conditions have been used at the wall.

The DNS has been performed using 1024×192×192 grid points. The grid is uniform in the x- and z-directions, but non-uniform in the y- direction. The streamwise and wall-normal components of the free-stream velocity are shown in fig.1.

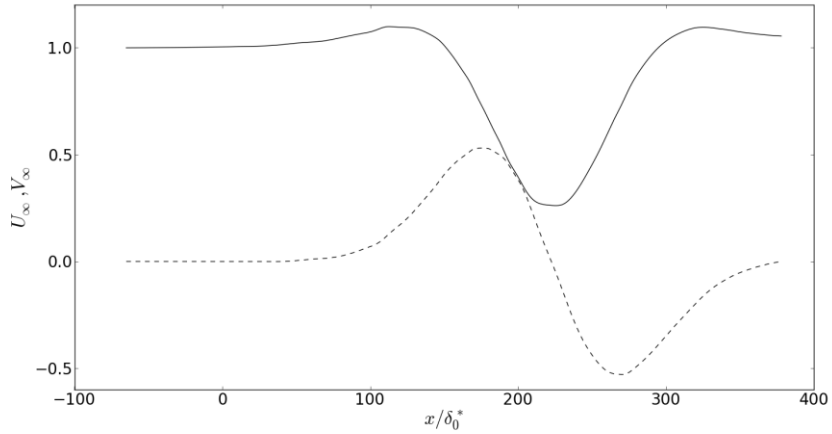

Fig. 1. Free-stream parameters: —— U_∞, - - - V_∞

RESULTS AND DISCUSSION: The probability of reverse flow γ is often used for description of the recirculation zone in separated flows (fig.2). As is clearly seen in the figure, the region of reverse flow is extremely unstable. There is no core where γ=1.0 as in a flow behind a backward-facing step, for instance. Also, two important points are indicated in fig.2: the mean reattachment point X_r ($\gamma(X_r)=0.5$) and the so called point of late reattachment X_r^{late} ($\gamma(X_r^{late})=0.1$).

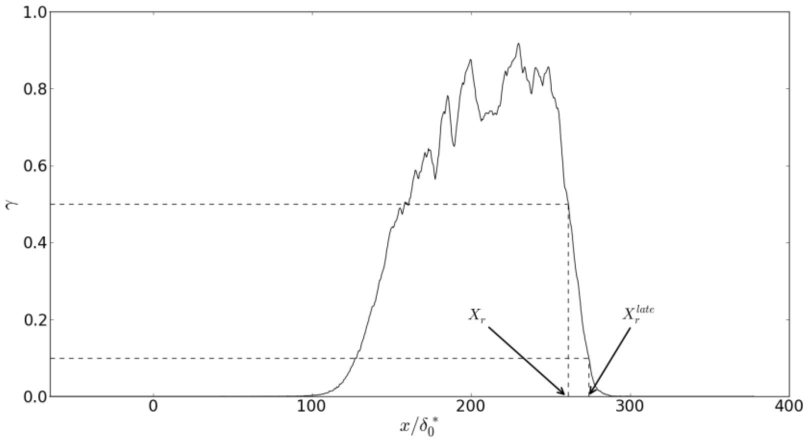

Fig. 2. Probability of reverse flow (averaged over time and *z*-direction)

The probability of reverse flow is a statistical characteristic, with all its limitations, but modern methods of numerical simulation are able to give us much more information and of higher quality. The time evolution of the backflow region is shown in fig. 3 and 4. (Only the first snapshots are presented in this paper. The full movies as well as the conference presentation can be found at http://www.russianlutheran.org/turbulence/author_english.html.) The white color denotes the reverse direction of the instantaneous streamwise velocity (or skin friction) in both cases. It is a simple yet powerful criterion for analyses of the separation/reattachment dynamics. The movies confirm the previous conclusion that the backflow region is very unstable. Moreover, at some instances the region consists of several parts separated from each other by forward flow.

It is clear that the intermittency of the separation/reattachment hinders following a low-frequency non-stationary cycle using a few local probes. Introduce a new parameter - *the total area of the backflow region*, i.e. the number of numerical grid points n_s where the instantaneous skin friction is negative (backflow). The time evolution of this parameter together with the well-known pulsation of the instantaneous reattachment point averaged over *z*-direction is shown in fig.5.

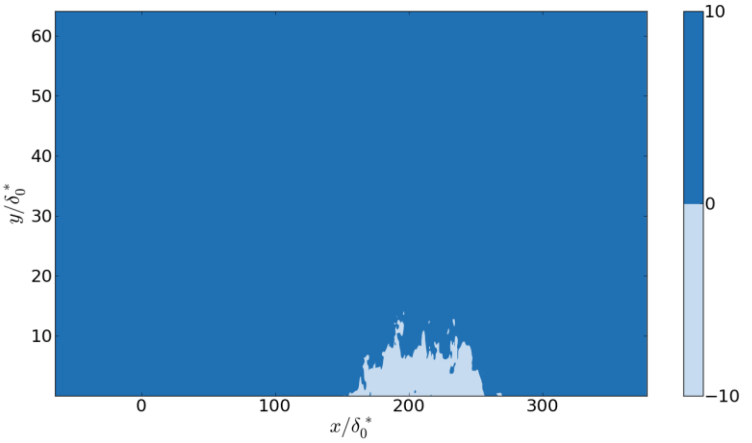

Fig. 3. Time evolution of backflow region ($z \approx 25\delta_0^*$)

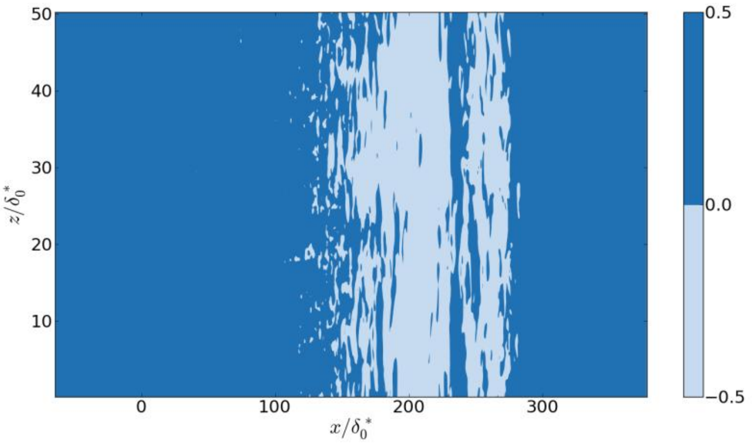

Fig. 4. Time evolution of skin friction in recirculation region

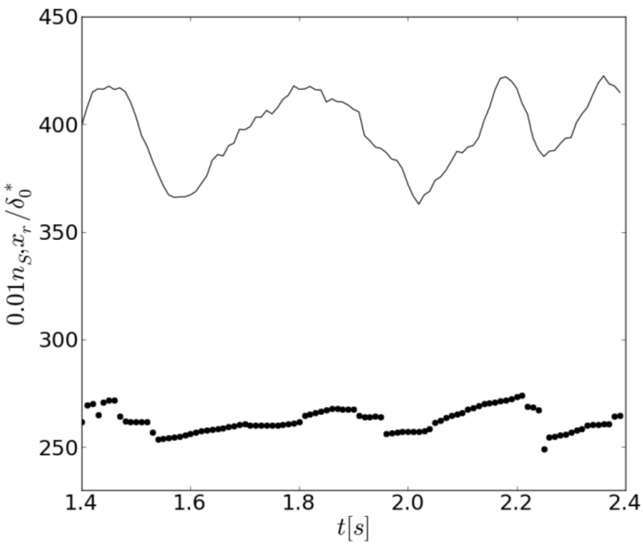

Fig. 5. Time evolution of the total area of the backflow region n_s (——) and the pulsation of the instantaneous reattachment point averaged over *z*- direction x_r/δ_0^* (•••••)

Evidently, both graphs correspond to the same process of the low-frequency pulsation of the recirculation zone. The reattachment point pulsation has been used as a characteristic of this unsteady process, for example in [16,29]. So, the unstable and irregular recirculation bubble has the integral characteristic, which changes in a regular way. Using of the total area of the backflow region is preferable compared to the conventional pulsation of the instantaneous reattachment point for description of the non-stationary cycle in a separated flow.

The next step is to search for a local multipoint criterion for the description of the low-frequency non-stationary cycle. The total area of the backflow region is not local: in order to use it the dynamics of the whole instantaneous skin friction field will need to be either measured or simulated.

The criterion of the late reattachment as a part of the conditional sampling and averaging technique has been used for the skin friction in the reattachment region of a separated flow (for example, [6,12]). This criterion has fixed the statistical correlation between the instantaneous reattachment position and other overall characteristics of the separated region, but the physical meaning of the late reattachment in terms of the low-frequency non-stationary cycle is still unclear (figs.2,6).

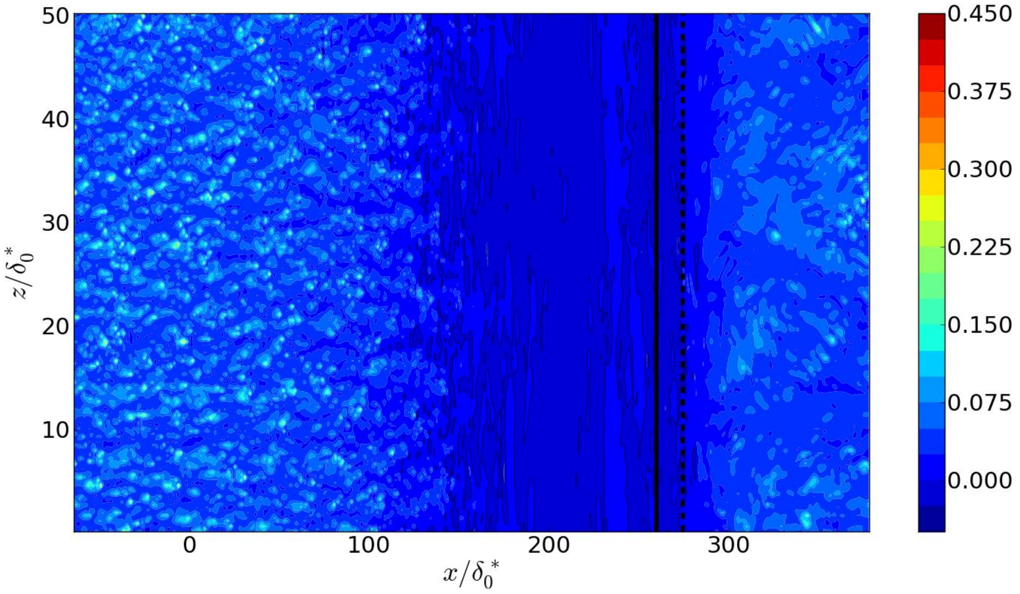

Fig. 6. An instantaneous skin friction field corresponding to the late reattachment event: —— mean reattachment line, - - - late reattachment line

Unfortunately, the present analyses showed that using of the late reattachment criterion (or its modifications) for studying of the non-stationary cycle is not practical due to the highly intermittent nature of the reattachment region. The other possibility may be drawn from previous studies: the velocity profile and skin friction in the beginning of the reattached shear layer are statistically correlated with the change of the separation region registered using the late reattachment criterion [12,11]. It can be supposed that a rake of common hot-wire probes located on the wall (1-wire, not sensitive to a flow direction) and uniformly distributed in the reattached shear layer (γ=0.0) along the *z*- axis not far downstream of the reattachment region would be able to fix main stages of the non-stationary cycle.

Consider the cross-section at x/δ_0^*=369.2 chosen without prejudice. The instantaneous skin friction averaged over *z*- direction $C\tau_w^{192}/\tau_{w0}$ (192 points, *C*=*const*, no smoothing, τ_{w0} is the mean skin friction at *x*=0) is shown in fig.7. Obviously, even without smoothing the graph “follows” the general trends of the non-stationary cycle. Clearly, use of 192 hot wires experimentally is impractical. The same skin friction characteristics averaged over 7 points $C\tau_w^{7}/\tau_{w0}$ (192 points, *C*=*const*, smoothed) is presented in fig.7. As can be observed, the use of 7 rather than 192 sampling points enables the maximums and minimums of the low-frequency non-stationary cycle to be highlighted.

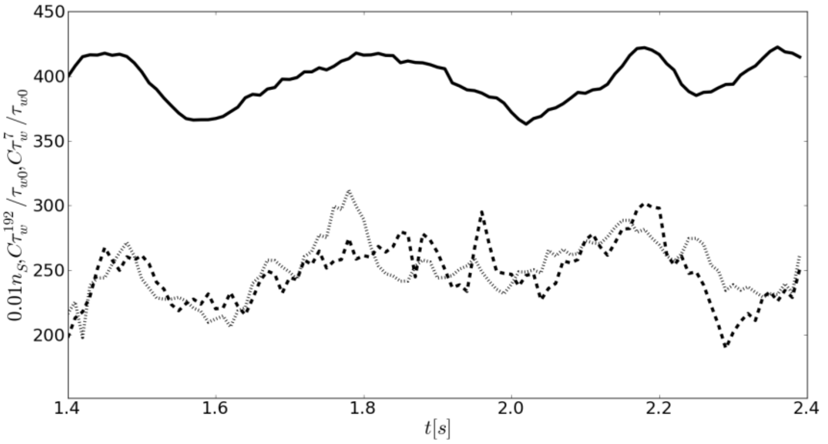

Fig. 7. Time evolution of the following parameters: —— total area of the backflow region n_S;
- - - instantaneous skin friction averaged over z- direction $C\tau_w^{192}/\tau_{w0}$ (192 points, C=*const*, x/δ_0^*=369.2);
········ instantaneous skin friction averaged over z- direction $C\tau_w^{7}/\tau_{w0}$ (7 points, C=*const*, x/δ_0^*=369.2);

CONCLUSIONS:

1. The dynamics of the backflow region in a separated turbulent flow was visualized using results of a direct numerical simulation.

2. A new parameter for description of the non-stationary cycle in a separated flow is proposed – the total wall area occupied by the reverse flow. The time evolution of the parameter illustrates the non-stationary cycle in a very clear way, much better than the conventional pulsation of the instantaneous reattachment point.

3. A local multipoint identification criterion for registering basic stages of the non-stationary cycle is presented. It is based on the fact that the time evolution of the skin friction (averaged over z- direction) follows the non-stationary cycle. In practice such a criterion can be realized using a rake of near-wall hot-wire probes (for example, 7 probes) uniformly distributed in the z- direction and located in the forward-flow region (γ=0) not far downstream from flow reattachment.

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References

1. Eaton J.K., Johnston J.P. *Turbulent Flow Reattachment: An Experimental Study of the Flow and Structure behind a Backward-Facing Step.* Rept. MD-39. 1980, Dept. of Mechanical Engineering, Stanford Univ.
2. Adams E.W., Johnston J.P. *Flow Structure in the Near-Wall Zone of a Turbulent Separated Flow*. AIAA J. 1988, vol.26, pp.932-939.
3. Piirto M., Saarenrinne P., Eloranta H., Karvinen R. *Measuring Turbulence Energy with PIV in a Backward-Facing Step Flow*. Exp. Fluids. 2003, vol.35, pp.219-236.
4. Westphal R.V., Eaton J.K., Johnston J.P. *A New Probe for Measurement of Velocity and Wall Shear Stress in Unsteady, Reversing Flow*. ASME J. Fluids Eng. 1981, vol.103, pp.478-482.
5. Adams E.W., Johnston J.P. *Effects of the separating shear layer on the reattachment flow structure Part 2: Reattachment length and wall shear stress*. Exp. Fluids. 1988, vol.6, pp.493-499.
6. Driver D.M., Seegmiller H.L., Marvin J.G. *Time-Dependent Behavior of a Reattaching Shear Layer*. AIAA J. 1987, vol.25, pp.914-919.

7. Farabee T.M., Casarella M.J. *Measurements of Fluctuating Wall Pressure for Separated/Reattached Boundary Layer Flows*. J. Vibration, Acoustics, Stress and Reliability in Design. 1986, vol.108, pp.301-307.
8. Lee I., Sung H.J. *Characteristics of Wall Pressure Fluctuations in Separated and Reattaching Flows over a Backward-Facing Step. Part I. Time-Mean Statistics and Cross-Spectral Analyses*. Exp. Fluids. 2001, vol.30, pp.262-272.
9. Hudy L.M., Naguib A.M., Humphreys Jr. W.M. *Wall-Pressure-Array Measurements beneath a Separating/Reattaching Flow Region*. Phys. Fluids. 2003, vol.15, no.3, pp.706-717.
10. Spazzini P.G., Iuso G., Onorato M., Zurlo N., Di Cicca G.M. *Unsteady Behavior of Back-Facing Step Flow*. Exp. Fluids. 2001, vol.30, pp.551-561.
11. Zanko P.S., Miheev N.I. *Transport of Skin Friction Pulsations in a Turbulent Separated Flow behind a Backward-Facing Step.* Proc. of Turbulence, Heat and Mass Transfer 4, Antalya, Turkey, 2003, pp.213-218.
12. Zanko P.S., Miheev N.I. *Reattached Shear Layer under Condition of Pulsation of Turbulent Separated Region behind Backward-Facing Step*. Izvestiya RAN. Energetika. 1998, vol.4, pp.97-102 (in Russian).
13. Shih C., Ho C.-M. *Three-Dimensional Recirculation Flow in a Backward Facing Step*. ASME J. Fluids Eng. 1994, vol.116, pp.228-232.
14. Silveira Neto A., Grand D., Metais O., Lesieur M. *A Numerical Investigation of the Coherent Vortices in Turbulence behind a Backward-Facing Step*. J.Fluid Mech. 1993, vol.256, pp.1-25.
15. Arnal M., Friedrich R. *Large-Eddy Simulation of a Turbulent Flow with Separation*. Turbulent Shear Flows 8. 1992, pp.169-187.
16. Le H., Moin P., Kim J. *Direct Numerical Simulation of Turbulent Flow over a Backward-Facing Step*. J.Fluid Mech. 1997, vol.330, pp.349-374.
17. Manhart M., Friedrich R. *DNS of a Turbulent Boundary Layer with Separation*. Int. J. Heat Fluid Flow. 2002, vol.23, pp.572-581.
18. Adrian R.J. *New Methodologies for Experimental Flow Engineering*. Proc. Int. Conf. Fluid Eng. Tokyo, Japan, July 13-16, 1997, pp.23-29.
19. Kiya M., Sasaki K. *Structure of a Turbulent Separation Bubble*. J. Fluid Mech. 1983, vol.137, pp.83-113.
20. Dianat M., Castro I.P. *Turbulence in a Separated Boundary Layer*. J. Fluid Mech. 1991, vol.226, pp.91-123.
21. Furuichi N., Kumada M. *Spanwise Structure around a Reattachment Region of a Two-Dimensional Backward-Facing Step Flow*. 2nd International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering (2 ISUD), September 20-22, 1999, pp.25-28.
22. Kiya M., Shimizu M., Mochizuki O. *Sinusoidal Forcing of a Turbulent Separation Bubble*. J. Fluid Mech. 1997, vol.342, pp.119-139.
23. Pronchick S., Kline S. *An Experimental Investigation of the Structure of a Turbulent Reattaching Flow behind a Backward-Facing Step*. Technical Report MD-42, Stanford University. 1983.
24. Robinson S.K. *Coherent Motions in the Turbulent Boundary Layer*. Annu. Rev. Fluid Mech. 1991, vol. 23, pp.601-639.
25. Sullivan P., Pollard A. *Coherent Structure Identification from the Analysis of Hot-Wire Data*. Meas. Sci. Technol. 1996, vol.7, no.10, pp.1498-1516.
26. Raiesi H., Piomelli U., Pollard A. *Evaluation of Turbulence Models Using Direct Numerical and Large-Eddy Simulation Data*. J. Fluids Eng. 2011, vol.133, 10 p.
27. Keating A., Piomelli U., Bremhorst K., Nesic S. *Large-Eddy Simulation of Heat Transfer Downstream of a Backward-Facing Step*. J. Turbul., vol.5, pp.1-27.
28. Lund T.S., Wu X., Squires K.D. *Generation of Inflow Data for Spatially-Developing Boundary Layer Simulations*. J. Comput. Phys. 1998, vol.140, pp.233-258.
29. Na Y., Moin P. *Direct Numerical Simulation of a Separated Turbulent Boundary Layer*. J. Fluid Mech. 1998, vol.370, pp.175-201.
30. Orlanski I. *A Simple Boundary Condition for Unbounded Hyperbolic Flows*. J. Comput. Phys. 1976, vol.21, pp.251-269.