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ON THE BREAKDOWN OF A LONG STREAK IN A TRANSITIONAL BOUNDARY LAYER*

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Transition in regular K-regime of boundary layer is studied. The features of the long streak that is considered as a form of soliton/like coherent structure (CS-soliton) are investigated briefly. The experiment shows that the breakdown of long streak is generated by chain of ring-like vortices.

Keywords: boundary layer transition, chain of ring-like vortices, secondary closed vortex, long streak breakdown

PACC: 4725C, 4715C, 4715F

I. INTRODUCTION

The problem of the onset of the turbulence in flat plate boundary layer has attracted the attention of investigators for more than a century. Despite its complexity, interest in laminar-turbulent transition has increased during the past decades due to its importance in both fundamental and applied aspects of fluid mechanics. In particular, a flat plate boundary layer has been used as a prototype flow. Theoretical studies in this field are discussed in the books[1,2] and the reviews in both theoretical and experimental aspects.[3−8] After the famous experiments by Schubauer and Klebanoff [9] and Klebanoff *et al.*,[10] it is well known that the nonlinear wave development at later stages further downstream is characterized by the appearance of powerful flashes of disturbances on the velocity oscilloscope traces in the specific form of narrow spikes. Other extremely careful experiments performed by Kachanov *et al.* [11] revealed the appearance of multi-spikes, which are in response to high-frequency flow structures, on the velocity oscilloscope traces.[8] The spikes are shown to be not of stochastic characters. The same topics had been also studied by other researchers.[12−14]

Lee[15−18] has proposed a new scenario for the transition, which involves the formation of both low- and high-frequency vortices. Both a large scale motion, which consists of a closed vortex and a soliton/like coherent structure (CS-soliton), and a chain of ring-like vortices were suggested in these works. The features of these three kinds of flow structures have been discussed qualitatively and quantitatively.[17,18] Another kind of long streak, which is a form of a CS-soliton,[18] in regular K-regime of boundary layer transition is different from that in turbulent boundary layer, which is considered as streamwise vortex.[19] In this paper, we try to discuss the three stages of the CS-solitons and mainly focus on the physical mechanism for the long streak breakdown which is considered as the last stage of the CS-solitons.

II. EXPERIMENTAL TECHNIQUES AND FACILITIES

A description of the experimental setup is presented in Fig.1. The experiments were conducted on a low turbulence level water channel new established at the State Key Laboratory of Turbulence Research of Peking University, at a free stream velocity U_0=17.0 cm/s with a turbulence level around 0.1% measured by several researchers from China, Japan and Russia. The size of the channel is 600mm × 400mm and the test section is about 6000mm long. A flat plate having a chord length of 1.8m, a span of 0.8m and a thickness of 15mm is used. The leading edge is composed of two semi-cycles. The plate is mounted in the test section normally with the bottom of the channel under zero degree angle of attack. The model has almost a zero streamwise and spanwise pressure gradients far enough from the leading edge. In order to make the flow more uniform, a flap is used (see Fig.1).

The disturbance generator (T-S wave generator) is a slit with a length of 150mm and a width of 1mm on the working side, through which water is pumped in and out periodically at a frequency of 2 Hz. A water box which is connected to both the slit and the two tubes is put on the opposite side. The loudspeaker

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sits on the top of a round barrel and the two tubes are mounted on the outer side of the barrel's bottom. So the instability wave has the frequency of 2Hz and the amplitude of this disturbance is 1.6% of the free stream speed if we switch on the loudspeaker and put it in proper output electric voltage. The T-S wave generator is mounted at a distance x=200mm from the leading edge of the plate. The development of the disturbances in the boundary layer and the structures of the mean flow are investigated by means of Kanomax hot wire anemometer. The hot films are made from TSI and the sensitive part of the probe is less than 2mm.

The experimental data is acquired at the positions from x=248 to 700mm. At each spatial point, three characteristics are measured: the mean values of a streamwise u-component of the mean flow velocity, the amplitude and phase of the u-component of the disturbance velocity filtered at the fundamental frequency. Distributions of all measured characteristics along the downstream(x), normal to wall (y) and spanwise(z) co-ordinates (see Fig.1) have been measured.

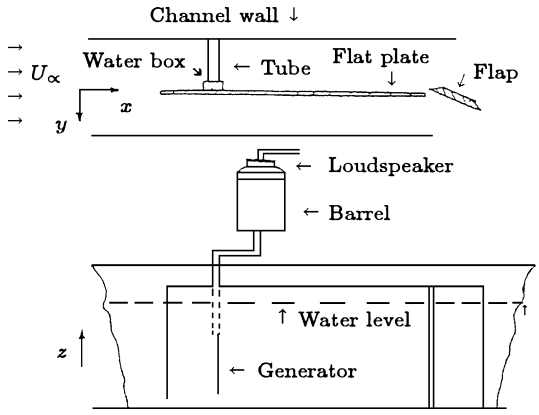


Fig.1. Sketch of water channel, experimental model, and disturbance source.

The hydrogen bubble technique is used to visualize the flow structures very clearly. In order to make a throughout visualization of the flow structure, the hydrogen bubble wire is placed at positions from x=250 to 700mm with a step of 50mm and from y=0.5 to 6mm with a step of 0.5mm.

The temperature of the water during test is about 20°C. In order to obtain a constant water temperature, the water channel has been switched on for more than 9h before test. The kinematic viscosity is $1.01 \times 10^{-6}\mathrm{m}^2/\mathrm{s}$ and the Reynolds number per meter is 1.7×10^5.

Ⅲ. EXPERIMENTAL RESULTS

A. Physical mechanism for the CS-soliton formation

Receptivity is defined as a mechanism by which disturbances enter the boundary layer and create the initial conditions for unstable waves. Which kinds of unstable waves can generate the rhombus-like CS-solitons in plan-view?

The wave resonant (WR) concept has been suggested[8] on the basis of a detailed analysis of experiments by Kachanov and Levchenko,[20] as well as of the theoretical results by Crack,[21] Zelman and Maslennikova,[22] Nayfeh and Bozetli,[23] Herbert[4] and others. The results obtained by Borodulin and Kachanov [24] show that the system of the parametric subharmonic resonance, postulated within the framework of the WR concept, is actually observed in the K-regime of breakdown at the stage of spike formation. Simulations of oblique wave interactions in a Blasius boundary layer were performed by Joslin, Streett and Chang.[25] The simulations show that the oblique wave interaction generates a strong spanwise-dependent mean-flow distortion. No two-dimensional (2D) T-S wave takes part in this process. The CS-solitons can generate this kind of strong spanwise-dependent mean-flow distortion. In the results of Williamson[26] and Williamson and Prasad,[27] they found a honeycomb pattern which is considered as the direct results of an interaction between oblique shedding vortices and 2D large-scale waves that grow in far wake. One possible physical reason for it is that the CS-solitons are generated by the interaction between two oblique waves. Does the 2D T-S wave have effects on the formation of the CS-solitons? A theoretical approach called Phase-locked in by Wu *et al.*[28] shows that the 2D T-S wave has the catalytic effect on the 3D structure formation. The results presented in Fig.2 show that these two kinds of effects are quite possible.

Some scientists believed that CS-solitons are the secondary structures which are generated by the Λ-structures. No direct evidence in Fig.2 shows that the Λ-structures are formed before the formation of the CS-soliton. The moving pictures from video and films show that the CS-solitons are formed slightly earlier than the Λ-structures. This evolution is very similar to the process suggested in works of Lee.[15−18]

Generally, it is proposed that CS-solitons are the direct results of interaction between two oblique waves, and the 2D T-S wave

has the catalytic effects on their formation.

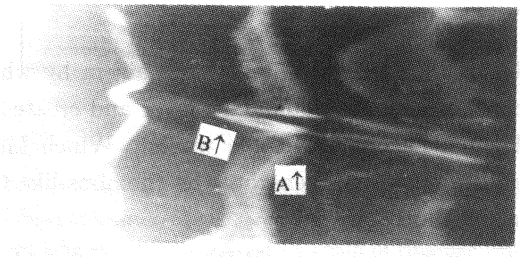


Fig.2. A (Λ-structure(A↑) and a CS-soliton(B↑) which is independent of Λ-structure (Ratio 1:4 and x from 280mm).

B. Long streak in transitional boundary layers

A long streak is present in Fig.3 obtained with the cathode-wire positioned at x=350mm and y=0.5mm. The structure is modulated in time with the fundamental frequency. This kind of long streak has never been observed experimentally in the two known "normal" regimes of the boundary layer transition, neither in K-regime nor in N-regime.

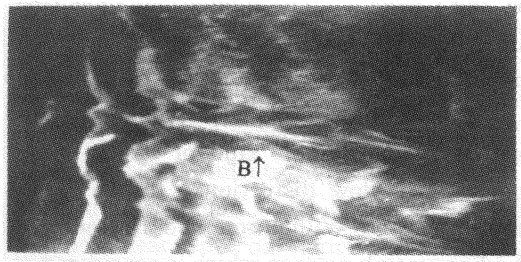


Fig.3. Long streak(B↑) in a transitional boundary layer. (Ratio 1:5; x from 350mm and y=0.5mm).

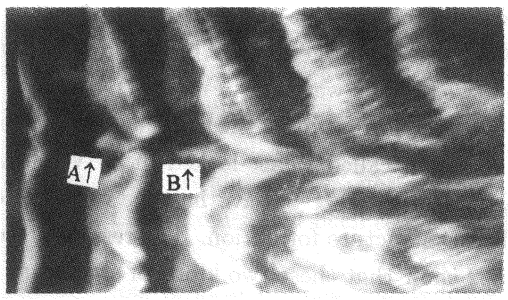


Fig.4. From a CS-soliton(A↑) to a long streak (B↑). (Ratio 1:2.6; x from 350mm and y=1mm).

The long streak (See Fig.3) in transitional boundary layer is different from that in developed turbulent boundary layer[19,29] in some aspects: Firstly, the long streak in transitional boundary layer is present in the near wall region in the "peak position". But in the developed turbulent boundary layer they appear both in the region where the interface often appears[19] and in the near wall region. [29] Secondly, the long streak in the transitional boundary layer represents the features of CS-solitons, but in the developed turbulent boundary layer it represents the streamwise vortex.[19] The direct evidence showing the formation of the long-streak in the region near to the wall is given in Fig.4. The arrows A and B indicate the evolution of the form of CS-solitons into a long-streak, which still has the features of CS-soliton. The reason for the long-streak having the features of the CS-solitons is not difficult to explain. In the near-wall region the fact of the fluctuations of u-component of velocity at low frequency and high amplitude makes the streak here longer. In other words, the streak has not only a convection velocity but also an oscillatory velocity at high amplitude.[15−18] Then the streak should spread both upstream and downstream and the long streak should form. The formation of this streamwise long streak shows that it is a typical phenomenon of turbulent slug which has been described by Linden.[30,31]

C. Breakdown of the long streak

Streaky structures elongated in the streamwise direction play a fundamental role in the sustainment of turbulence in wall-bounded shear flows,[19,29,32] and much work has been done on the origin and breakdown of these structures in the turbulent regime. A theoretical analysis of the streak breakdown in channel flow is present in recent papers on near wall turbulence.[33−36] In the model considered in these papers, streak breakdown is one phase of self-sustaining cycle in turbulent flow, which includes streak formation, streak breakdown, and streamwise vortex regeneration from the direct nonlinear interaction of the streak instability eigenmode.

Dauchot and Daviaud[37] investigated the evolution of the streamwise vortices in Couette flow by placing a wire in a flow. They found that the Reynolds number is above 160, streamwise vortices are continuously shed from the wire and create streaks.

In almost all the previous studies, long streak is considered to be a form of streamwise vortex. The long streak herein is a form of the CS-soliton instead of streamwise vortex.

Figure 5 shows the regular breakdown of the long streak at x=675mm. Two kinds of flow structures, involving a closed vortex and a chain of ring-like vortices at the same x- and z- position, probably have effects on its breakdown. The closed vortex becomes very

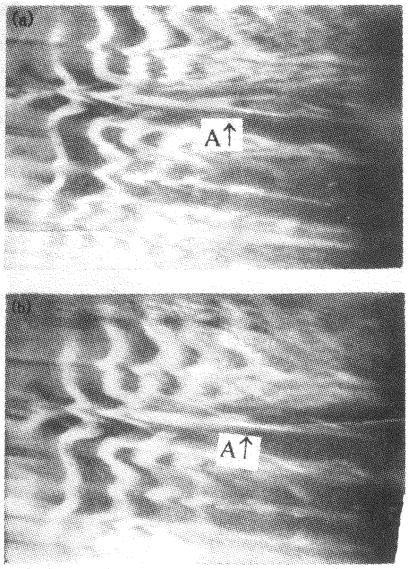


Fig.5. Breakdown of a long streak at x=675mm (A↑). (a) Start to breakdown; (b) after breakdown.

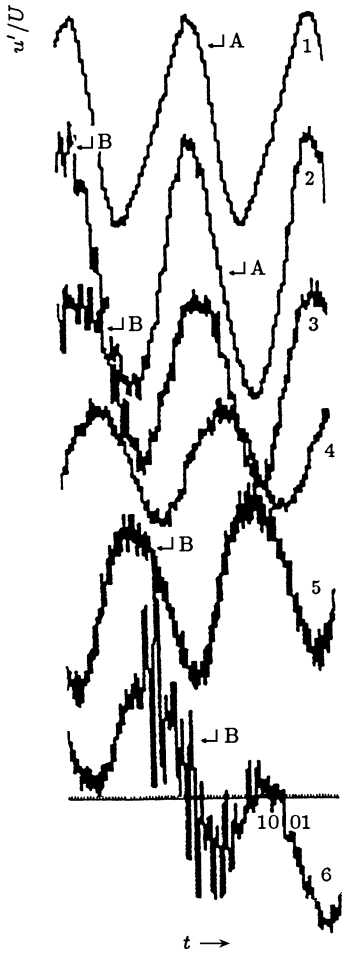


Fig.6. The u-components of velocity fluctuations and the breakdown of a long streak occurs at x=675mm. The arrow A points out the traces of the CS-solitons and the arrow B points out the traces of the chain of ring-like vortices.1,2,..., 6 curves are for x=248mm, y=0.4mm; x=300mm, y=0.46mm; x=400mm, y=0.8mm; x=500mm, y=1.02mm; x=600mm, y=1.2mm; x=675mm, y=1.6mm and z=0 for all.

weak at the position of x >550mm.[15−18] The chain of ring-like vortices represents the process from their formation at x=420mm to the position of the long streak breakdown. Three stages of their formation and evolution are found.[18] First, they are formed along the borders of the CS-solitons and then separated from the CS-solitons one by one. Second, they meet the head of Λ-vortex which is part of the closed vortex, and their rotation speed become large which is induced by Λ-vortex. Because the convection velocity of the chain of ring like vortices is higher than that of the closed vortex, the chain of ring-like vortices are separated from the Λ-vortex one by one. Third, the angles between the plane where the vortices exist and the flat plate change quickly to nearly 90° and the vortices propagate downstream at a speed of about 0.9 times of the free stream velocity. They are visible even at the very late stage when the boundary layer becomes turbulence. They have strong effects not only in the outerlayer but also in the near wall region.

Besides the main fluctuations at low frequency and high amplitude in the near-wall region, which is generated by the CS-solitons, as shown in Fig.6, additional spikes (see arrows) are also present on the time traces, which are generated by some of the chain of ring-like vortices. The breakdown occurs at the position of x=675mm. We can not find the obvious increase of the streak amplitude at this time, which is considered to be the necessary condition for its breakdown (Fig.7).

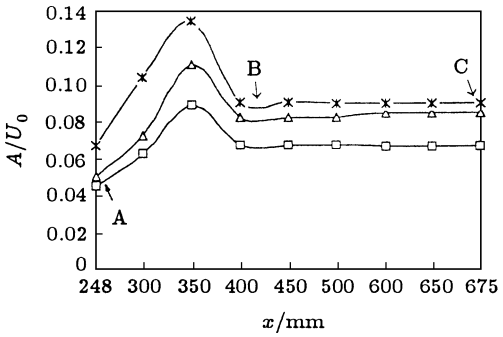


Fig.7. Amplitude distributions in x-direction. The symbols ∗, Δ and □ for y=0.6, 1.2 and 1.8mm.

IV.DISCUSSION

Almost all the pervious theoretical studies are focused on the linear approach. Both the theoretical

and experimental results show that the breakdown scenario are described by:

streamwise vortices ⇒ streamwise streaks ⇒ streak breakdown.

The present physical process for the breakdown of a long streak has never been suggested before. The event happens after the breakdown of the Λ-structure when the chain of ring-like vortices are formed.[18] The long streak is considered to be a form of the CS-soliton which is a 3D wave packet. The scenario is described as:

$$\text{oblique waves} \Rightarrow \text{CS} - \text{solitons} \Rightarrow \begin{cases} \text{long streak} \\ \text{closed vortex} \Rightarrow \text{secondary closed vortex} \Rightarrow \text{CRV} \end{cases}$$
$$\Rightarrow \text{long streak breakdown}$$
$$\Rightarrow \text{transition.}$$

V. Conclusions

Based on the above experimental observations, it is concluded that the breakdown of the long streak is generated by the chain of ring like vortices.

Appendix A

The chain which contains 4 vortices appears periodically associated with each Λ-structure. The detailed description for the different stages of these vortices has been discussed in our previous works.[15,18] In order to obtain the total information of the flow structures, the process for the formation of ring-like vortices is given in Figs. 8 and 9. The visual results in these two figures show that the CRV are the direct results of the breaking and the reconnection of the vortex filaments from both the Λ-vortex and the secondary closed vortex.

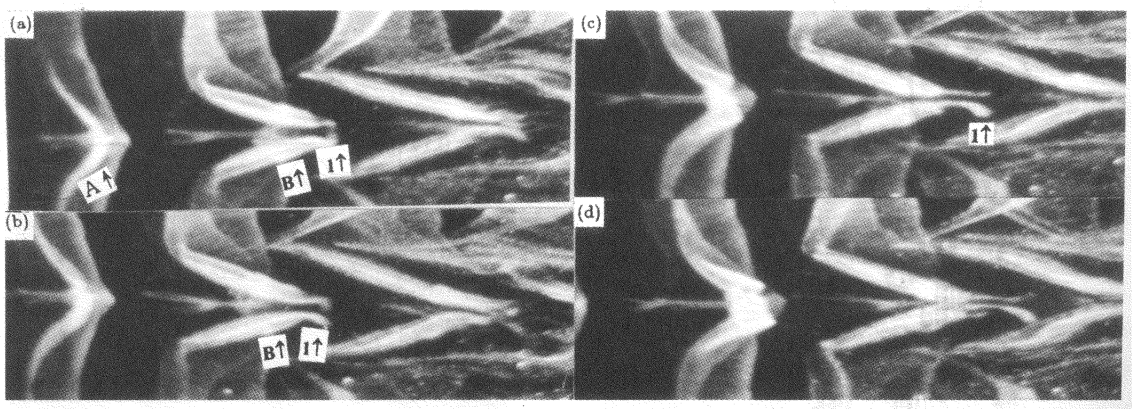


Fig.8. Generation of the first ring-like vortex(1↑) by the interaction between the secondary closed vortex (B↑) and the Λ-vortex (A↑). The vortex is cut by the secondary closed vortex from the head part of the closed vortex called Λ-vortex. The time interval between successive pictures is $\frac{1}{12}$s.

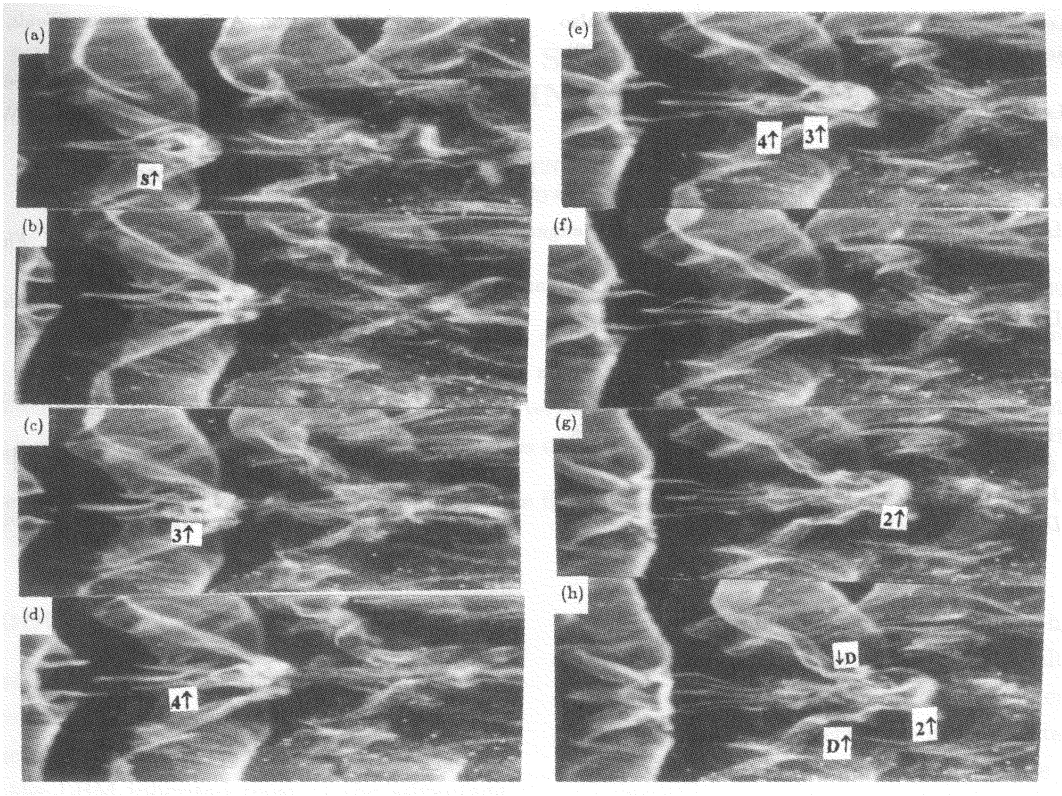


Fig.9. Formation of the second (2↑), third (3↑) and fourth (4↑) ring-like vortices in a chain of ring-like vortices. The time interval between successive pictures is 1/12s. Figures.9(a)–(d) show the breaking and reconnection of the two symmetric filaments with two narrow necks from the Λ-vortex inside the secondary closed vortex (S↑), and the third ring-like vortex is clearly formed. In Fig.9(e), the fourth ring-like vortex appears. Three ring-like vortices appear clearly in Figs.9(f), (g) and (h). On the two side of these three vortices, two streamwise vortices appear (see arrows D).

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REFERENCES

[1] A. D. D. Craik, Wave Interactions and Fluid Flows Cambridge, *Cambridge Univ. Press.*,1985.

[2] V. N. Zhigulyov, A. M. Tumin, Novosibrisk, Origin of Turbulence *Nauka Publ., Sib. Div.* (1987),**p.282** (in Russian).

[3] A. H. Nayfeh, AIAA paper, No.87-0044(1987).

[4] T. Herbert, *Annu. Rev. Fluid Mech.,* **20** (1988), 487.

[5] H. L. Reed, W. S. Saric, *Annu. Rev. Fluid Mech.,* **21** (1990), 235.

[6] H. Fasel, Laminar Turbulent Transition (Springer-Verlag, 1990), p.587.

[7] L. Kleiser, T. A. Zang, *Annu. Rev. Fluid Mech.,* **23** (1991), 495.

[8] Yu. S. Kachanov, *Annu. Rev. Fluid Mech.,* **26**(1994),411.

[9] G. B. Schubauer, P. S. Klebanoff, *NACA Rep.,* (1289)(1956).

[10] P. S. Klebanoff, K. D. Tidstrom, L. M. Sargent, *J. Fluid Mech.,* **12**(1962),1.

[11] Y. S. Kachanov, V. V. Koznov, V. Y. Levchenko, M. P. Ramazanov, *Transl. Sov. J. Appl. Phys.,* **4**(1990), 124.

[12] D. R.Williams, H. Fasel. F. R. Hama, *J. Fluid Mech.,* **149**(1984),179.

[13] M. Nishioka, M. Asai, S. Iida, Laminar-Turbulent Transition (Springer-Verlag, 1980), p.37.

[14] M. Asai, M. Nishioka, *J. Fluid Mech.,* **208**(1989),1.

[15] C. B. Lee, *Chinese J. Atmospheric Sci.,* **23**(1999),227; also *Chinese J. Atmospheric Sci.*(*English Version*), **23** (1999), 55.

[16] C. B. Lee, *Chinese J. Exp. and Measurements in Fluids.,* **12** (1998), 8.

[17] C. B. Lee, *Phys. Letts.,* **A247**(1998), 397.

[18] C. B. Lee, *Exps. in Fluids.,* **28**(2000),234.

[19] Q. X. Lian, *J. Fluid Mech.,* **215**(1990), 101.

[20] Y. S. Kachanov, V. Y. Levchenko, *J. Fluid Mech.,* **138**(1984),209.

[21] A. D. D. Craik, *J. Fluid Mech.,* **50**(1971), 393.

[22] M. B. Zelman, I. I. Maslennikova, *J. Fluid Mech.,* **252**(1993),499.

[23] A. H. Nayfeh, A. N. Bozatli, *Phys. Fluids,* **22**(1979), 805.

[24] V. I. Borodulin, Y. S. Kachanov, *Simulation in Mech.,* **3**(20), (1989), 38 (in Russian).

[25] R. D. Joslin, C. R. Streett, C. L. Chang, *Theor. Comput. Fluid Dyn.,* **4**(1993),271.

[26] C. H. K. Williamson, *J. Fluid Mech.,* **243**(1992),393.

[27] C. H. K. Williamson, A. Prasad, *Phys. Fluids,* **5** (1993), 12854.

[28] X.Wu, P. A. Stewart, *J. Fluid Mech.,* **316**(1996),335.

[29] S. J. Kline, W. C. Reynolds, F. A. Schraub, W. P. Runstaller, *J. Fluid Mech.,* **30**(1967), 741.

[30] E. R. Linden, *Ark. Fys.,* **15**(1959),97.

[31] E. R. Linden, *Ark. Fys.,* **15**(1959),503.

[32] H. Kim, S. J. Kline, W. C. Reynolds, *J. Fluid Mech.,* **50**(1971),133.

[33] J. M. Hamilton, J. Kim, F. Waleffe, *J. Fluid Mech.,* **287**(1995),317.

[34] F. Waleffe, *Phys. Fluids,* **A7**(1995), 3060.

[35] L. N. Trefethen, A. E. Thefethen, S. C. Reddy, T. A. Driscoll, *Science,* **261**(1993), 578.

[36] S. C. Reddy, P. J. Schmid, J. S. Baggett, D. S. Henningson, *J. Fluid Mech.,* **365**(1998),269.

[37] O. Dauchot, F. Daviaud, *Phys. Fluids,* **A7**(1995), 335.