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The spanwise non-uniformity of nominally two-dimensional
turbulent boundary layer

(3rd Report Influence of the streamwise
vortices arising from the protrusion) *

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In this report, results of an experimental investigation which was performed to eliminate the streamwise vortices arising in a nominally two-dimensional turbulent boundary layer of which behaviour was examined in detail in the authors' previous paper, are presented. Though there may be two procedures of obliteration of streamwise vortices, the present work is concerned with the method to place the vortex generators like roughness element at the leading edge of a flat plate inducing the counter rotating vortices against pre-existing vortices in the boundary layer.

Using this set, the authors measured the downstream development and uniformization of the spatial variations of the boundary layer characteristics.

From these results, it was revealed that the streamwise vortices were extremely stable, and large vortex generators must be used to eliminate these vortices. In addition, these streamwise vortices, which disappeared once in the course of the boundary layer development, exhibited a tendency to appear again in the downstream region. And a weak variation of velocity with large wave length at the outside of the layer produced by the protuberances was observed.

1. Introduction

From the authors' preceding measurements of the mean velocity, turbulence intensity, wall shear stress and the observation by flow visualization, it was revealed that the streamwise vortices arising in a nominally two-dimensional turbulent boundary layer originated from the spatial instability of the flow through the screen with a certain open area ratio. And the relation among the velocity components of the streamwise vortices and wall shear stress became evident. Specifically speaking, these longitudinal vortices cause redistribution of streamwise momentum in the boundary layer such that the boundary layer exhibits a large variation of thickness in the spanwise direction but the local wall shear stress is not appreciably different from the one in the two-dimensional case.

There may be two procedures of obliteration of those vortices, one being the method to uniformize the main stream

completely, the other to induce the counter rotating vortices against pre-existing vortices. In order to construct a two-dimensional boundary layer perfectly, it seems that the uniform main flow with spatial stability must be produced by use of suitable screens or a honeycomb under certain circumstances. While in most cases it is very difficult to make the repair works of replacing the screens in order to remove such vortices arising in a measurement of turbulent boundary layer utilizing a large sized wind tunnel now used and the related experiment, it is easy to introduce the counter rotating longitudinal vortices. Reports of this type of research have apparently not been published to date. In addition for the practical purpose, it is very important to examine such phenomenon which is a mutual interaction of streamwise vortices distributed complicately in the boundary layer with the ones introduced artificially in order to understand the characteristics of the turbulent boundary layers.

From those points of view, we intend to compare the two methods of obliteration of longitudinal vortices and to clarify the flow fields in detail. In the first place, it was examined how to remove the pre-existing vortices by setting up the protuberances at the leading edge of a flat plate in manufacturing the experimental equipment. In this paper we describe an experimental result of the boundary layer development and uniformization of the spatial variations of those characteristics, and discuss how to describe such flow

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fields. From those experiments, it was proved that an exact two-dimensional flow could not be obtained by introducing the vortices originated from the protuberances. We shall report the results of examinations done about the method to uniformize the main flow strictly in the next paper.⁽⁷⁾

Main nomenclature and coordinate system used later are the same as in the last report and the major ones are shown in the following.

- U_i : i component of a moment velocity;
 $i = 1, 2, 3$ show x, y, z components respectively; x_i or x, y and z are used according to the circumstances.
 $\bar{U}_i$: time mean velocity component
 u_i : fluctuating velocity
 $-$: time mean operation
 $\sim$: spatial mean operation, which is performed parallel to a coordinate axis.
 $\langle \rangle$: area mean operation
 $(*)_{,x}$: differentiation by x
 S : suffix S shows the spatial variation of time mean value.

2. Experimental equipment and techniques

Measuring plate and situation of the screens used in this work are the same as those in the previous paper.⁽⁶⁾⁽²⁾ Vortex generators set up so as to obliterate the spanwise variation are placed at the leading edge of a flat plate. This equipment

Fig.1 Spectral density distribution of the shapes of protuberances

Fig.2 Variation of the velocity distribution by the protuberances ($U_e / \nu = 2.08 \times 10^6 \text{ m}^{-1}$)

Fig.3 Changes in the spanwise velocity distributions in the downstream direction ($\bar{y}_+ = 393, U_e / \nu = 2.08 \times 10^6 \text{ m}^{-1}$)

made of oil clay forms a rectangular prism on whose upper surface the sand paper is attached. This shape is shown on the left hand side in Fig.3 and the spectral density distribution obtained from the spanwise distribution of heights of the protuberances is shown in Fig.1. The x direction length of the protuberances is about 100mm. The distribution of the vortex generators was decided after hard work. On that occasion, trial and error method was done on the bases of the way of thinking mentioned later. That is, it may be expected that the mean velocity at each z position increases or decreases by the streamwise vortices induced by the protuberances in the direction of a thick arrow as shown in Fig.2. Accordingly, it is assumed that the spanwise variations of the boundary layer characteristics disappear when the spanwise distribution of the vortex generator shapes is set inversely corresponding to the spanwise velocity distribution, U/U_e . After all, this is equivalent to use of a negative wake effect. The way of thinking mentioned above is considered when the variations of the spanwise velocity distribution are compared with the main arrangement of the protuberances before and after the vortex generators are provided.

Although at the beginning, we set about to attach only a thin scotch tape or a sandpaper irregularly, as shown in Fig.3 finally a large equipment was required in order to remove the pre-existing vortices because those vortices were extremely stable. The variation of the spanwise velocity distribution under examination was investigated in the section of $x = 2490\text{mm}$. It could be considered that the two-dimensionality of the flow, for example, re-

quired to determine the wall shear stress by means of the floating element device, was almost obtained at the stage where the maximum variation of U/U_e was about 2.5%. The distribution of the protuberances in that situation was determined as the final shape. The streamwise variation of the characteristics of the flow field is studied in the condition mentioned above.

Measurement of the spanwise distribution of the mean velocities and wall shear stresses is made by traversing a pitot tube or a Preston tube respectively at 11 cross sections of $x = 580$ to 3075 mm in the range of $-300 \leq z \leq 300$ with the pressure gradient along a flat plate being kept about zero. At 5 locations in the x direction the direction of flow is measured by means of a two-holes pitot tube and the z component of the mean velocity is obtained on the basis of those results. Turbulence intensity is measured at 3 cross sections of $x = 760$, 1305 and 2490 mm and also the direct measurement of wall shear stress by means of the floating element equipment is done. The value of U_e/ν was kept equal to $2.08 \times 10^6 \text{ m}^{-1}$. The property of the flow field did not change within the range of $U_e/\nu = 1.03 \times 10^6$ to $2.75 \times 10^6 \text{ m}^{-1}$.

3. Experimental results and discussion

($U_e/\nu = 2.08 \times 10^6 \text{ m}^{-1}$, $\tilde{y}_+ = 786$)

Fig.4 Spanwise distribution of U/U_e for the upstream ranges

($x = 2490 \text{ mm}$; $U_e/\nu = 2.08 \times 10^6 \text{ m}^{-1}$)

Fig.5 Velocity distribution in the boundary layer

3-1. Change of the variations in the spanwise distributions in the downstream direction

It is described how the spanwise distribution of the boundary layer characteristics changes in the downstream direction when the streamwise vortices are introduced by the vortex generators. Fig.3 shows the spanwise distribution of U/U_e at $\tilde{y}_+ = \tilde{u}_T y/\nu = 393$ (where $\tilde{u}_T$ is the spatial mean friction velocity) in the 11 cross sections of $x = 580 \sim 3075$ mm. The patterns of variations remain fixed in the downstream direction, and their magnitude decreases with x and finally settles to about 2.5% at $x = 2730$ mm. Thus, the magnitude of the spanwise variation decreases with an increasing distance for the region where the law of the wall is established. The patterns of the variations are also maintained over the upstream range more than $x = 1305$ mm, where the spanwise distribution varies remarkably and there the vortices caused by the spatial instability of main flow through the screen are complicatedly mixed with the ones introduced by the protuberances. Fig.4 shows the spanwise distribution of U/U_e at $\tilde{y}_+ = 786$ in that mixing region. Main pattern of the variation is reverse to the one of the vortex generators installed at the leading edge of a flat plate. As shown in the figure, the magnitude of U/U_e is reversed for the region between $x = 735$ mm and 875 mm. The reason can be explained as follows; In this region the flow separated by the protuberances is reattached and recovered to the flat plate flow. The spanwise distribution of U/U_e at $x = 2490$ mm in the boundary layer is shown in Fig.5. As described above, the spanwise variation is small in the region where the wall law is applicable. But, in the outer region a spanwise variation with a long period exists and the maximum difference of boundary layer thickness amounts to 30 mm, because of the direct effects of the induced streamwise vortices by the vortex generators. In addition the pattern

($U_e/\nu = 2.08 \times 10^6 \text{ m}^{-1}$, at $y = 5 \text{ mm}$)

Fig.6 Spectral density distribution of the spanwise distributions of U/U_e

(a) comparison with Klebanoff's data

(b) spanwise distribution of turbulence intensities

Fig.7 Spanwise turbulence intensity distribution

(a) ($x = 760 \text{ mm}$; $U_e / \nu = 2.08 \times 10^6 \text{ m}^{-1}$) (b) ($x = 2490 \text{ mm}$; $U_e / \nu = 2.08 \times 10^6 \text{ m}^{-1}$)

Fig.8 Flow direction

of the variation is roughly inclined to the distribution of the protuberances in the outer region. Fig.6 shows the spectral density distribution obtained from the spanwise velocity distribution at $y = 5 \text{ mm}$ in the section of $x = 760 \text{ mm}$ and 2490 mm . In comparison of the present results with the ones of Fig.14 in the previous paper¹⁾, it is found that the spectral density with wave number of about 1 cm^{-1} caused by the instability of flow through the screen is reduced in magnitude by the vortices introduced by the vortex generators. The reason is as follows; from the comparison with Fig.1 the vortices with the spectral density of about $k = 1 \text{ cm}^{-1}$ and 2 cm^{-1} indicating a rough shape of the protuberances are mixed with the one originated from the flow instability and they compensated each other. Nevertheless, the components with small wave numbers, for example $k < 0.5 \text{ cm}^{-1}$, don't yet disappear. Fig.7(a) and (b) show the turbulence intensity distributions at $x = 2490 \text{ mm}$. As shown in Fig.7(a), the values of u'/U_e are larger than Klebanoff's data³⁾ over the range from outer region to external region. The spanwise distribution of u'/U_e is changed such as to have a negative correlation with the spanwise distribution of U/U_e as shown in Fig.7(b). In addition, it is seen that the magnitude of variation of the turbulence intensity decreases downstream in the region where wall law can be applied and a variation with a large period, similar to the distribution of protuberances, is caused over the range from outer region to external region.

Subsequently, the local variation of flow direction in the boundary layer and outside the layer was investigated respectively. Fig.8(a) and (b) show the flow direction within $z \approx \pm 100 \text{ mm}$ in the section

($U_e / \nu = 2.08 \times 10^6 \text{ m}^{-1}$)

Fig.9 Polar diagrams

of $x = 760\text{mm}$ and 2490mm . Measurement of flow direction is made at $x = 760\text{mm}$ in more detail because of the large change of flow field at the place. Therefore, results in the limited region of $z = \pm 50\text{mm}$ are shown in Fig.8(a). The directional angle α is expressed in values relative to the standard one at $y \doteq 158\text{mm}$. The directional angle near the wall is about 2° to 3° at the section of $x = 760\text{mm}$ and its value decreases by less than 1° at downstream section of $x = 2490\text{mm}$. The directional angle over the region where wall law is established, that is, at nearly $y = 20\text{mm}$, disappears in downstream section. Therefore, it may be considered that the variation originated from the streamwise vortices caused by the screen is removed. The directional angle, in the range from the outer region to external region, that is the range of $y = 20$ to 80mm , is nearly constant at all sections in the streamwise direction, but its value is different at different sections of z . Accordingly, it can be inferred that a spanwise variation with a long wave length is produced at the place. Furthermore, in the range of $y > 80\text{mm}$ the directional angle is changed slowly and reversed in the sign of its value, approaching zero asymptotically. From those results, it is assumed that the streamwise vortices with a large wave length are caused again over the range from outside the boundary layer to nearly $y = 150\text{mm}$ as a result of interaction of the streamwise vortices caused by the screen with the ones caused by the protuberances. Fig.9 shows the polar diagrams of the mean velocity vectors at $x = 2490\text{mm}$. W/U_e is smaller than 0.01 in almost all y - z sections. W/U_e is, however, changed considerably by more than 0.01 in the region of nearly $U/U_e = 1$, that is the one from outside the boundary layer to external region. Result mentioned above indicates that there exists the streamwise vortices in that region.

3-2. Wall shear stress

Fig.10 shows the spanwise distribution of τ_0 obtained using the Preston tube at the 11 positions of $x = 580\text{mm}$ to 3075mm . This distribution of τ_0 makes a spanwise variation corresponding to the velocity distribution and its magnitude of variation

Fig.10 Changes in the spanwise wall shear stress distribution in the downstream direction ($U_e/\nu = 2.08 \times 10^6 \text{ m}^{-1}$)

decreases downstream. Value of maximum variation of this distribution is about 25 % at $x = 580\text{mm}$, 10 % at $x = 1305\text{mm}$ and under 3 % at $x = 2730\text{mm}$ and becomes one of the allowable values⁽⁶⁾ being obtained for the two-dimensionality. In the following, the result of wall shear stress measured by means of the floating element wall shear stress meter, described in the previous paper, at $x = 2490\text{mm}$ is shown. Fig.11 shows the local skin friction coefficient C_f versus $R_\theta = U_e \theta / \nu$. Results fully agree with the Karman-Schoenherr⁽⁵⁾ equation in the range of $5 \times 10^3 \leq R_\theta \leq 10^4$. Accordingly it seems to be quite all right to consider that the spatial variation of boundary layer characteristics is considerably small and that in regard to the wall shear stress it is nearly two-dimensional.

3-3. Expression using the spatial mean

As is evident from the experimental results described so far, the flow field in the series of our experiments shows a quasi-periodic spanwise variation. Although it can be considered that expression split into a spatial mean part and a fluctuating part of time mean velocity facilitates understanding of the whole flow field, this type of illustrations has not apparently been published to date. So, how to make use of this expression is investigated. The instantaneous velocity u_i is split, such that

$$u_i(x, y, z, t) = \bar{u}_i(x, y) + u_i^s(x, y, z) \quad \text{-----(1)}$$

We interpret $\bar{u}_i$ as a spatial average, defined by

$$\bar{u}_i(x, y) = \lim_{l \rightarrow \infty} \int_{-l}^l u_i(x, y, z) \cdot dz / 2l \quad \text{-----(2)}$$

and also u_i^s as a fluctuating part of time mean given by

$$u_i^s(x, y, z) = u_i(x, y, z) - \bar{u}_i(x, y), \quad (\bar{u}_i^s = 0) \quad \text{-----(3)}$$

Reynolds equation is then given by, with ordinary tensor notations

$$(\bar{u}_i + u_i^s)_{,t} + \{(\bar{u}_i + u_i^s)(\bar{u}_j + u_j^s)\}_{,j} = -\frac{1}{\rho}(\bar{P} + P')_{,i} + \nu \nabla^2(\bar{u}_i + u_i^s) - (\bar{u}_i \bar{u}_j + \bar{u}_i u_j^s)_{,j} \quad \text{-----(4)}$$

Fig.11 Local skin friction coefficient by direct measurement

Here, from a practical point of view Reynolds stress is split into spatial averages and fluctuations. Spatial average of equation (4) is

$$\bar{U}_{i,t} + (\bar{U}_i \bar{U}_{i,\alpha})_{,\alpha} = -\frac{1}{\rho} \bar{P}_{,i} + \nu \nabla^2 \bar{U}_i - (\bar{u_i u_i} + \bar{U_i^2})_{,\alpha} \quad (5)$$

Spatial derivatives are, of course, zero by definition and $\bar{U}_{i,\alpha} = 0$, therefore $\bar{U}_{i,\alpha} = 0$. From this point of view mentioned above, it is assumed that a spatial fluctuating Reynolds stress $\rho \bar{U_i^2} \bar{U_j^2}$ is produced newly by the spatial non-uniformity of time mean flow.

The boundary layer equations for the case that flow is steady are in the x, y and z directions respectively as follows.

$$\left. \begin{aligned} \bar{U} \bar{U}_x + \bar{V} \bar{U}_y &= -\frac{1}{\rho} \bar{P}_x - (\bar{u^2} + \bar{U^2})_y + \nu \bar{U}_{yy} \\ 0 &= -\frac{1}{\rho} \bar{P}_y + \{ \bar{v^2} + (\bar{V^2}) \}_y \\ 0 &= (\bar{w^2} + \bar{V^2} \bar{W^2})_y \end{aligned} \right\} \quad (6)$$

In comparison with a strictly two-dimensional case, a spatial fluctuating Reynolds stress $\rho \bar{U^2} \bar{V^2}$ is added to the streamwise mean flow equation. A momentum integral equation is given by $d\bar{\theta}/d\chi = \bar{\tau}_0 / \rho U_e^2$ in this experiment because the pressure gradient is nearly zero. The energy of spatial variations can be assumed from these variations of time mean value. The change of the energy of spatial fluctuating parts is important in the same manner as the energy of time fluctuating parts in considering the boundary layer development. Setting up the equations for the momentum tensor $\rho \bar{U_i} \bar{U_j}$, $\rho \bar{U_i^2} \bar{U_j^2}$ and $\rho \bar{u_i} \bar{u_j}$ and contracting those equations, the energy equations of the spatial mean part of time average motion, the spatial fluctuating part and the time fluctuating motion may be written respectively

$$\left. \begin{aligned} \left\{ \frac{1}{2} \rho \bar{Q^2} \bar{U}_\alpha + \rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha + \bar{P} \bar{U}_\alpha - \sum_{\alpha\beta} \bar{U}_\alpha \bar{U}_\beta + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha \right\}_{,\alpha} \\ = - \sum_{\alpha\beta} \bar{U}_\alpha \bar{U}_\beta + \rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha \\ \left\{ \frac{1}{2} \rho \bar{Q^2} \bar{U}_\alpha + \frac{1}{2} \rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha + \bar{P} \bar{U}_\alpha - \sum_{\alpha\beta} \bar{U}_\alpha \bar{U}_\beta + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha \right\}_{,\alpha} \\ = - \sum_{\alpha\beta} \bar{U}_\alpha \bar{U}_\beta - \rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha \\ \left\{ \frac{1}{2} \rho \bar{Q^2} \bar{U}_\alpha + \frac{1}{2} \rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha + \frac{1}{2} \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha + \bar{P} \bar{U}_\alpha - \bar{G}_{\alpha\beta} \bar{U}_\beta \right\}_{,\alpha} \\ = - \bar{G}_{\alpha\beta} \bar{U}_\beta + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha + \rho \bar{u_i} \bar{u_j} \bar{U}_\alpha \end{aligned} \right\} \quad (7)$$

Where $\bar{Q^2} = \bar{U}_\alpha \bar{U}_\alpha$, $\bar{Q^2} = \bar{U}_\alpha \bar{U}_\alpha$ and $\bar{Q^2} = \bar{u_i} \bar{u_i}$ and $\sum_{\alpha\beta}$ and $\bar{G}_{\alpha\beta}$ denote the time mean and fluctuating parts of the viscous stress

Fig.12 Spatial averaged values of the boundary layer thickness, displacement thickness and momentum thickness

respectively. As is evident from the equation described above, the energy exchange between $(1/2)\rho \bar{Q^2}$ and $(1/2)\rho \bar{Q^2}$ is made by $\rho \bar{U_i^2} \bar{U_j^2} \bar{U}_\alpha$, the production term of the spatial fluctuating energy and between those two energies and $\frac{1}{2} \rho \bar{Q^2}$ by the terms of $\rho \bar{u_i} \bar{u_j} \bar{U}_\alpha$ and $\rho \bar{u_i} \bar{u_j} \bar{U}_\alpha$ simultaneously and still energy budget per unit volume is established by the direct viscous dissipation term and advection term extracted from each energy.

As it is difficult to investigate this energy budget in detail, we try to discuss the results under consideration from the standpoint of the spatial average. The streamwise variations of the spatial average of boundary layer thickness (value of y where U/U_e equal to 0.995), displacement thickness and momentum thickness ($\bar{\delta}$, $\bar{\delta}^*$ and $\bar{\theta}$ respectively) are shown in Fig.12. As is evident from this figure, $\bar{\delta}$ develops almost uniformly in the streamwise direction in spite of the large spanwise variation of $\bar{\delta}$. Identically, $\bar{\delta}^*$ and $\bar{\theta}$ also develop in almost the same way. However, the relation between $\bar{\theta}$ and x obtained from the present experiment is slightly smaller in degree of development than the following relation; for example, $\bar{\theta}$ is proportional to $x^{4/5}$ assuming that one seventh power law of the velocity distribution is valid from the leading edge of the flat plate in the two dimensional turbulent boundary layer. It can be considered that this phenomenon is caused by an active mixing as the result of introducing the streamwise vortices originated from the protuberances. In addition, it is suggested from small degree of the development for the boundary layer characteristics that the spatial fluctuating Reynolds stresses appearing in equation(6) have the effect of accelerating the flow. Fig.13 shows the state of change of the spatial average of $\bar{\tau}_0$ in the downstream direction. In spite of the development of the value of $\bar{\theta}$ etc., $\bar{\tau}_0$ decreases monotonously in the section

Fig.13 Spatial averaged value of the wall shear stress and its coefficient of variation

Fig.14 Logarithmic velocity distribution

of x larger than 875mm but upstream from that place this value is reversed. That place corresponds to the one at the velocity distribution shown in Fig.4. The value of τ_t/τ_0 shown in the same figure decreases monotonously in the downstream direction. τ_t/τ_0 however, becomes slightly large at $x = 3075\text{mm}$ which is the most downstream place. Comparing this phenomenon with the one indicated later, it can be assumed that the variation will slowly increase from now. Therefore, it is not likely that the variation of the boundary layer characteristics caused by the effect of the vortex pairs existing in the main flow can be obliterated by introducing the vortices originated from the protuberances over the whole region. The logarithmic velocity profile is shown with use of the spatial mean value in Fig.14. The results in the three sections of $x = 760, 1531$ and 2490mm are shown respectively and the full line indicates the equation

$$\bar{U}/\bar{u}_\tau = 5.5 \log(\bar{u}_\tau y/\nu) + 5.4$$

making use of Sarnecki's constant.⁽⁶⁾ $\bar{u}_\tau$ is the spatial mean of friction velocity calculated from τ_0 measured by means of a Preston tube. As it is clear from the figure there exists a linear range and its gradient is in agreement with the one in the two-dimensional case and the results under consideration almost coincide with the full line at every section. This means that the law of the wall is established from the point of view of the spatial mean value as well as the local standpoint clarified by the authors' previous paper.⁽²⁾ The

$$(U_e/\nu = 2.08 \times 10^6 \text{ m}^{-1})$$

Fig.15 Spatial fluctuating intensity distribution

spatial average value of the boundary layer characteristics for various values of x is shown in the figure. The velocity distribution in the outer layer becomes different under the effect of protuberances from those of the flat plate turbulent boundary layer with zero pressure gradient. A detailed discussion is made in the following paper⁽⁷⁾ as to this subject.

Fig.15 shows the spatial fluctuating intensity distribution, $\sqrt{(u')^2}/U_e$ and $\sqrt{(w')^2}/U_e$ all over the range of boundary layer. $\sqrt{(v')^2}/U_e$ is not measured because this value is about 1/10 times the magnitude of fluctuations mentioned above. The standard value is taken at $y = 158\text{mm}$ and shown in the figure. The value of $\sqrt{(u')^2}/U_e$ is 1 to 2% near the wall and takes the maximum one of 2 to 5% near the positions of y/δ being 1/2 to 2/3 at all of six sections, $x = 760$ to 2730mm . This value reaches minimum near the positions of $y = 60$ to 70mm and maximum again at y still larger and finally decreases to the standard value at $y = 158\text{mm}$ as shown by the dotted line in figure. The value of $\sqrt{(w')^2}/U_e$ is 1 to 2% close to the wall and reaches minimum at about $y = 5\text{mm}$. This value increases in the range from the position of y about 5mm to the one where $\sqrt{(u')^2}/U_e$ takes the maximum value and settles nearly to a constant value in the still larger region and, of course, finally approaches the standard value, zero, with an increasing y as shown by the dotted line in the figure. In this figure the dotted line right to the abscissa drawn near the positions of y being $30 \sim 60\text{mm}$ shows the value of δ . From the same figure it is seen that the influence of the protuberances is exerted up to the outer part of the spatial mean value of the boundary layer. The position of y where the value of $\sqrt{(u')^2}/U_e$ has a maximum value, moves from the one of y/δ being about 1/2 to 2/3 as a boundary layer develops. The magnitudes of $\sqrt{(u')^2}/U_e$ and $\sqrt{(w')^2}/U_e$ are seen to decrease with the distance increasing in the downstream direction within the boundary layer. There exists a spatial fluctuating intensity in

Fig.16 Cross section area averaged value of spatial fluctuating energy

the outer part of the boundary layer for the reason that the spatial variation with a large periodic still remains.

Within each energy described in the beginning of this section, a detailed investigation is made about the spatial turbulent fluctuating energy. Fig.16(a), (b) and (c) show the distribution of

$$\frac{1}{2} \overline{Q_s^2} = \frac{1}{2} \langle (U^*)^2 + (W^*)^2 \rangle.$$

In this figure, symbol $\langle \rangle_i$ indicates the quantity distributed within the boundary layer δ that is the region obtained from the definition described above. As is evident from the upper diagram (a), the value of the spatial fluctuating energy has a tendency to decrease in the downstream direction, and decreases with vibration, without the monotony. Diagram (b) indicates the rate occupied by the quantities of $\langle (U^*)^2 \rangle$ and $\langle (W^*)^2 \rangle$ respectively in all of those energies. The values of $\langle (U^*)^2 \rangle$ and $\langle (W^*)^2 \rangle$ are in the same order, and $\langle (U^*)^2 \rangle$ decreases gradually changing more or less, but $\langle (W^*)^2 \rangle$ decreases with large vibration. As the energy quantity distributed without the boundary layer δ is determined from interpolating the region close to the maximum outer portion, this tendency of the variation has a qualitative property. Diagram (c) shows the quantity distributed within the boundary layer δ . In contrast with the total value of $(1/2) \overline{Q_s^2}$ which has a tendency of decreasing with large change, the value of $(1/2) \overline{Q_s^2}$ distributed within δ decreases with gradual change. In this figure it is seen that the value of $(1/2) \langle (U^*)^2 \rangle_i$ is greater than the one of $(1/2) \langle (W^*)^2 \rangle_i$ and that both have a tendency of decreasing by degrees in the downstream direction. This value, however, becomes large slightly at the section of $x = 2730\text{mm}$. This means that the value can be assumed to increase henceforth again, as we have described in discussion of the variation coefficient. Therefore, it can be concluded that the spanwise variation of the boundary layer characteristics may not be obliterated by making use of the negative wake effect of the vortex generators, and that a closed two-dimen-

sional flow is produced by making the main flow stable and uniform entirely.

4. Conclusions

The variation of the flow field was investigated experimentally in full detail by attaching the protuberances at the leading edge of a flat plate in order to obliterate the pre-existing streamwise vortices originated from the least non-uniformity of main flow. From these results the following have been revealed.

(1) The streamwise vortices in the turbulent boundary layer originated from the spatial instability of the main flow are extremely stable. Accordingly, large protuberances must be provided in order to obliterate such vortices even in a partial region. In this study, the height of the protuberances is about 20mm.

(2) By setting up those vortex generators, a two-dimensional flow could be produced near the wall far downstream from those protuberances. From this it follows that the boundary layer thickness changes largely in the spanwise direction and that the influence of the protuberances is exerted up to the outer part of the boundary layer from usual point of view. Even in the region near the wall where the flow field once became two-dimensional, the spatial variation of this flow field indicated a tendency of increasing again far downstream.

(3) The change of the spatial fluctuating energy was determined from the investigation of flow field by splitting it into the spatial average part and the fluctuating part of the boundary layer characteristics.

(4) From those experiments, it was proved that an exact two-dimensional flow could not be obtained by introducing the vortices arising from the protrusion into the turbulent boundary layer with spanwise non-uniformity. Therefore, the main flow must be uniformized strictly.

References

- (1) Furuya, Y. & Osaka, H., Bulletin of the JSME., vol.18, No.121 (1975-7), 664.
- (2) Furuya, Y., et al., Bulletin of the JSME., vol.18, No.121 (1975-7), 673.
- (3) Klebanoff, P.S., NACA Rep., No.1247 (1955).
- (4) Bradshaw, P., J.Fluid Mech., 22-4 (1965-8), 679.
- (5) Schoenherr, K.E., (see, Hopkins, E.J., & Inouye, M., AIAA J., 9-6 (1971-6), 993.)
- (6) Sarnecki, A.J., (see, Thompson, B.G.J., Rep. & Mem., Aeron.Res. Council, No.3463 (1965).)
- (7) Osaka, H., et al., Preprint of Japan Soc.Mech.Engrs.(in Japanese) No.740-9 (1974-8), 9.