Mechanism of Momentum Exchange near a Roughness Element for Rough Wall Turbulent Boundary Layer *

(Flow Visualization of Eddy Formed in a Two-Dimensional Square Cavity)

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Abstract

Flow visualization has been performed in the vicinity of a roughness element for boundary layers developing over rough surfaces with roughness pitch ratios p of 2 and 4 at low Reynolds number. The momentum thickness Reynolds numbers at streamwise distance $x=865$ mm for $p=2$ and 4 are 300 and 500, respectively. For the rough surface of $p=2$, typical eddy structures are classified into 4 patterns that are consistent with the results of Townes et al., whereas for the rough surface of $p=4$, three patterns are recognized. As compared with the rough surface of $p=2$, the rough surface of $p=4$ takes a larger value of occurrence frequency normalized with respect to the cavity width and the friction velocity. Occurrence frequency is equal to the sum of the frequency of each pattern, and is closely related with momentum exchange. This quantitative result can suggest that the pressure drag acting on a roughness element for the rough surface of $p=4$ is larger than that of the rough surface of $p=2$.

Key words: Boundary Layer, Turbulence, Flow Visualization, Rough Wall, Low Reynolds Number

1. Introduction

For a boundary layer over a rough surface, which consists of two-dimensional square ribs placed perpendicular to the mean flow, the roughness function, which is the non-dimensional velocity deficit in the log-law region between the boundary layers over smooth and rough surfaces, is generally given as a function of the Reynolds number based on the error in origin, which is the distance from the top of roughness element to the virtual origin for logarithmic similarity profile in the mean velocity profile. Rough surfaces have been divided into two types in accordance with the characteristic of the error in origin ⁽¹⁾. One is a d-type rough surface, whose roughness pitch ratio is less than 3, and the error in origin is proportional to streamwise distance or boundary layer thickness. The other is a k-type rough surface, whose roughness pitch ratio is greater than 3. The error in origin can be expressed by a linear function of roughness height. Roughness effect and self-similarity have been investigated on mean velocity and turbulence properties in these boundary layers by many researchers ⁽²⁾⁻⁽⁸⁾. However, only a few qualitative and quantitative researches have

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discussed the relevant flow structures in the production of larger wall shear stress over the rough surfaces ⁽⁹⁾⁻⁽¹²⁾.

We have already reported that pressure drag acting on a roughness element could be scaled with the velocity and length scales of a separated free shear layer evolved from the downstream edge of the roughness element ⁽⁹⁾. Furthermore, Leonaridi et al. ⁽¹⁰⁾ and we ⁽¹¹⁾ revealed that the pressure drag would be represented as the sum of momentum fluxes of both mean flow and turbulence and viscous force obtained from an integral of the Reynolds equation in the cavity region between the roughness elements. The discussion due to the integral of the Reynolds equation clearly demonstrates that the momentum fluxes produced most of the pressure drag. However, little is known of the relation between the magnitudes of the scales for the momentum fluxes and coherent structure in the roughness sub-layer, except for the evolution of the separated free shear layer with the increment of the gap size between the roughness elements. Only Djenidi et al. ⁽¹²⁾, who investigated the turbulent boundary layer over a rough surface with a roughness pitch ratio of 2, reported that the separated free shear layer would contribute to maintain the turbulent energy in the turbulent boundary layer and would have a firm relationship with the behavior of eddies in the cavity.

In order to investigate the eddy structure in turbulent shear layers, the eddy, which has a structure that varies time-wise and spatially, was sampled with hot-wire anemometry by applying an arbitrary threshold to the signals of the instantaneous velocity, and observation of the eddies is limited to information from single-point measurement. On the other hand, flow visualization is an effective way to capture eddies in time and space. The flow visualization technique for the sampling of eddies in the vicinity of the roughness elements might be useful in understanding the role of behavior of the eddies for the fundamental dynamics in connection with the turbulence model ^{(10), (13)-(15)}. In the present study, we use flow visualization to investigate the variation, with the roughness pitch ratio, of the frequency and scale of eddies in the cavity.

2. Experimental instrument and conditions

2.1 Rough surfaces and flow field

The rough surfaces were selected from two roughness types; a d-type rough surface consisting of two-dimensional square ribs arranged with a roughness pitch ratio $p=2$, and a k-type rough surface with $p=4$. The roughness pitch ratio is given as $p=(b+w)/k$. The roughness element is 10 mm in height and 10 mm in width. The test plate has an upstream edge milled into a hemicylindrical shape (R 10 mm) and has a smooth portion of 50 mm length. Flow visualization and LDV measurement were performed in a water open

Figure 1 Schematic flow field, coordinate system and nomenclature.

Table 1 Experimental conditions at $x=865$ mm.

p	U_1 (m/s)	$R_\theta (=U_1 \theta / \nu)$	$k^+ (=u_\tau k / \nu)$	k / δ	$K (= \frac{\nu}{U_1^2} \frac{dU_1}{dx})$	c_f
2	0.0689	300	30	0.165	5.4×10^{-10}	7.32×10^{-3}
4	0.0694	500	47	0.156	7.4×10^{-10}	13.9×10^{-3}

channel with a closed circuit, which has a test section of 1.86 m in length, 0.4 m in width, and 0.4 m in height (0.325 m water depth).

Figure 1 shows the flow field, nomenclature, and the coordinate system. In the coordinate system, x is the streamwise distance measured from the upstream edge of the surface, and y_T is normal height from the top of the roughness element. Furthermore, x_{RE} is used as the streamwise distance measured from the downstream edge of the roughness element. The two-dimensionality of the flow was corroborated by checking the spanwise variation of the streamwise mean velocity and turbulent intensity within $z=-180$ mm to 180 mm at $x=865$ mm. Under these conditions, the spanwise maximum variation to the spatial mean values was less than 1 %.

2.2 Experimental condition and measurement

Table 1 shows the flow conditions for both boundary layers over the rough surfaces with $p=2$ and 4. The values of the non-dimensional pressure gradient $K (= \nu / U_1^2 \cdot dU_1 / dx)$, ν is kinematic viscosity and U_1 is freestream velocity) for both boundary layers are slightly positive, so that the boundary layers are imposed on favorable pressure gradient. However, these values fall within the conditions of weak pressure gradient according to the definition proposed by Kline et al. ⁽¹⁶⁾. The momentum thickness Reynolds numbers $R_\theta (=U_1 \theta / \nu)$, θ is momentum thickness) are close to the lower limit at which the wake region of the turbulent boundary layer disappears ⁽¹⁷⁾, and the roughness Reynolds number $k^+ (=u_\tau k / \nu)$, u_τ is friction velocity) indicates that the present rough condition is a traditional rough regime. The relative roughness height k / δ is almost the same for both boundary layers. The local skin friction coefficient c_f was estimated by the momentum integral equation (1) neglecting the integral of the differential values of the Reynolds stresses with respect to the streamwise direction throughout the layer. Usually, the integrated effect to the local skin friction coefficient is less than 5 % ⁽⁶⁾.

$$c_f = 2 \frac{d\theta}{dx} + \frac{2\theta}{U_1} \frac{dU_1}{dx} (H + 2) \quad (1),$$

where, H is shape parameter $(= \delta^* / \theta)$, δ^* is displacement thickness.). Although the present experiments involve weak pressure gradient, the contribution of the second term to local skin friction is 16% for $p=2$ and 19% for $p=4$.

Mean velocity measurement was performed with the LDV system (IFA-750, 4-W Ar-Ion). Focal length is 350 mm, and the measurement volume for the cross part of laser beams is 0.09 mm x 0.09 mm x 0.13 mm. Tracer particles of white poster color (mean diameter 0.3 μm and specific gravity 1.135) were mixed at a volume ratio of 1 ppm. The data rate was 500-1500 Hz, and the data number was 100 thousand for each measurement point.

Flow visualization in the vicinity of the roughness element was carried out in the cavity region between the roughness elements at $x=865$ mm. Dye injection holes were placed at $x_{RE}=2$ mm, which is on the bottom surface, and at $x_{RE}=-2$ mm, which is on the top surface of the roughness element. In each surface, 10 holes were provided at 10 mm intervals in the spanwise direction. Hole diameter d_D is 0.6 mm, and Reynolds number

Figure 2 Streamwise mean velocity profiles.

($=u_{\tau} d_D / \nu$) based on the diameter is less than 3; therefore, the holes have a negligible effect on the flow. The selected dye was fluorescein-sodium solution. A laser slit measuring 8 mm in width was used to visualize the flow in the cavity. The flow was photographed with a digital camera (Nikon COOLPIX990). Shutter speed, stop, and exposure were fixed at 1/8, 2.5, and +2.0, respectively.

3. Experimental Results and consideration

3.1 Characteristics of mean velocity profiles

To confirm that the flows over both rough surfaces are turbulent boundary layers, mean velocity profiles were measured over the cavity at $x=865$ mm. Figure 2 gives the mean velocity profiles normalized with respect to the outer variables (free stream velocity U_1 and boundary layer thickness δ). Also, Fig. 2 shows the data over the rough surfaces of $p=2$ ($R_0=800$, $k^+=60$, and $k/\delta=0.147$) and $p=4$ ($R_0=1060$, $k^+=77$, and $k/\delta=0.132$) obtained by Liu et al.⁽¹⁸⁾ and a smooth surface ($R_0=860$) measured by Osaka et al.⁽¹⁹⁾. Here, the origin of the normal height for the smooth surface is placed on the surface. The data contained in the figure are for $R_0>500$, where the wake region of the turbulent boundary layer exists under a zero pressure gradient⁽¹⁷⁾, except for the present data.

First, we discuss the mean velocity profiles for each roughness pitch ratio. For $p=4$, the present profile is in close agreement with that of Liu et al., but for $p=2$ the velocity profile is more filled in shape. The difference between the present data and that of Liu et al. for $p=2$ may be caused by the experimental conditions. Under the present conditions, Reynolds number R_0 is lower and is subject to the weak favorable pressure gradient. Here, we will discuss the effect of Reynolds number. Osaka et al.⁽⁴⁾ reported that the local skin friction coefficient c_f of the turbulent boundary layer over $p=2$ is equal to that over the smooth surface at $R_0=800$ and $k^+=30$. Then, we can expect that the mean velocity profiles of both surface conditions become similar within the ranges of $R_0 \leq 800$ and $k^+ \leq 30$. Therefore, when we compare the mean velocity profiles, these profiles are consistent near the wall region ($y_T/\delta < 0.2$), but in the outer region ($y_T/\delta > 0.2$) the value of normalized velocity of $p=2$ is slightly larger than that of the smooth surface, due to the weak favorable pressure gradient.

Next, we will examine the difference in mean velocity profiles between $p=2$ and 4. Throughout the layer, the mean velocity profile of $p=4$ has a large deficit compared with that of $p=2$. Correspondingly, the local skin friction coefficient c_f of $p=4$ takes a remarkably large value in comparison with that of $p=2$ shown in Table 1. The reason for

Figure 3 Patterns of eddy structures near a roughness element.

(Flow left to right)

the remarkable increase is the increase in the contribution of the averaged Reynolds shear stress $\langle -uv \rangle$ per roughness pitch length, which is produced by the momentum exchange between the cavity flow and the flow over the cavity, to the pressure drag acting on the roughness element, as reported in Ref. (11). In the following section, in addition to discussing the qualitative results, we investigate the coherent structure in the cavity by flow visualization in order to consider the momentum exchange kinematically.

3.2 Flow pattern in the x - y_T plane

Although turbulent flow is inherently three dimensional and unsteady, in the preliminary experiment the flows in the cavity beneath the turbulent boundary layers over $p=2$ and 4 were observed to have the following features.

(1) The behavior of the flow in the cavity consists of formation, growth, and decay of the eddy.

(2) Each pattern of formation, growth and decay has a duration time on the order of one second.

(3) Each of the patterns occurs repeatedly at irregular intervals.

In the present study, we define a third feature as a quasi-periodic occurrence of the pattern, and focus on the patterns of eddy structures as a low-frequency component that can be followed with the eyes. In flow visualization, the patterns were classified according to observations of whether the streak line flows into the cavity or out of the cavity. These flow patterns can be related with the momentum exchange through the open face between the roughness elements. The height of the observation area is limited to the region of $y_T/k < 2$, where the statistics on the streamwise velocity depend on the relative position to the roughness height in the streamwise direction⁽⁹⁾.

Figure 3 shows the typical patterns of eddy structures for $p=2$ and 4. The flow direction is from the left to the right. For $p=2$ shown in Fig. 3(a), there are 4 patterns similar to those observed by Townes et al.⁽²⁰⁾ and Djenidi et al.⁽¹²⁾; (i) Strong outflow, (ii) Weak outflow, (iii) Inflow, and (iv) Divided flow. The strong outflow pattern produces outflow of the fluid in the cavity extensively after decay of the eddy in the cavity accompanied with the disappearance of spanwise vorticity. For the weak outflow pattern, the degrees of the outflow from the cavity and decay of the eddy are weaker than those of the strong outflow pattern. The inflow pattern forms the eddy in the cavity due to inflow of the fluid from the downstream edge of the cavity, and it is strengthened. In the divided pattern the fluids inside and outside the cavity never interact, and therefore the eddy in the cavity maintains its strength. The 4 typical patterns seldom appear in the order mentioned above.

For $p=4$ shown in Fig. 3(b), there are 3 patterns; (v) Strong outflow, (vi) Outflow from the downstream cavity edge, and (vii) Inflow. The strong outflow is similar to that of $p=2$, but the outflow angle is approximately perpendicular to the wall. The outflow from the downstream cavity edge is such that the fluid flowing from upstream of the cavity undergoes both inflow and outflow simultaneously near the downstream edge, and the shape of the streak line is bent downward. The inflow pattern is the same as that of $p=2$. These observed flow patterns seldom repeat regularity in the order given.

Next, we estimate the frequency f_n (1/s) of each pattern in order to discuss the stability of the separated free shear layer originated from the roughness element. The frequency f_n was calculated by counting the number of occurrence of each pattern per 600 s. The subscript n corresponds to the pattern number (i to vii). Table 2 gives the frequencies of the patterns of eddy structures. Also, in the table, inflow and outflow are represented as sweep and ejection, respectively, to connect with the momentum transport. Now, we consider representative scales for frequency. The momentum exchange at the open face between the roughness elements can be related to the pressure drag acting on the cavity⁽¹¹⁾. Therefore, we attempt to determine the representative scale in consideration of pressure drag. In Ref. (9), we reported that the pressure drag c_D could be estimated from the representative scales of the separated free shear layer as equation (2).

$$c_{DP} = O \left[\frac{(u_{rms})_s}{U_1^2} \frac{L_s}{k} \times \frac{k}{\lambda} \right] \quad (2)$$

$(u_{rms})_s$ is streamwise turbulent intensity in the separated free shear layer, L_s is the width defined as the height between $1/2 U_s$ and $3/2 U_s$ (U_s is the value of the mean velocity at the inflectional point in mean velocity profile.) and λ is the roughness pitch length. The width L_s increases with the cavity width b , and $(u_{rms})_s$ is scaled with the friction velocity u_τ . Therefore, the time scale is represented as b/u_τ . Table 2 includes the frequency f_n scaled with the time scale. Also, $f_t b/u_\tau$ in the sixth column of the table gives non-dimensional frequency, where the frequency f_t is the total frequency of all the

Table 2 Frequency on each pattern.

p	Patterns	Momentum exchange	Frequency f_n (1/s)	$f_n b/u_\tau$	Total $f_t b/u_\tau$
2	(i)Strong outflow	Ejection	0.007	0.019	0.90
	(ii)Weak outflow	Ejection	0.147	0.392	
	(iii)Inflow	Sweep	0.145	0.387	
	(iv)Divide	—	0.038	0.101	
4	(v) Strong outflow	Ejection	0.120	0.623	1.98
	(vi)Outflow from downstream cavity edge	Ejection+Sweep	0.088	0.457	
	(vii) Inflow	Sweep	0.173	0.898	

patterns for each rough surface. The value of $f_t b/u_\tau$ for $p=4$ is about two times that of $p=2$, indicating that the flow of the separated free shear layer may be more unstable for $p=4$. Here, comparing $f_t b/u_\tau$ of $p=2$ for the present rough surface and the results of Townes et al. ⁽²⁰⁾, both of which have an aspect ratio $b/k=1$, the present value ($f_t b/u_\tau=0.90$ at $k^+=30$) is 0.53 times that ($f_t b/u_\tau=1.70$ at $k^+=26$) of Townes et al. As previously reported in Ref. (21), the strength and frequency of sweep and ejection events calculated by means of the four-quadrant method on the Reynolds shear stress increase with increasing roughness density $\lambda_s (=b/(b+w))$. In this case, λ_s of the present rough surface and that of Townes et al. are 0.5 and 0.67, respectively. Accordingly, it seems that the values of $f_t b/u_\tau$ increases with increasing the roughness density.

3.3 Consideration on the momentum exchange

In this sub-section, we discuss the degree of momentum exchange through the open face between the roughness elements and the ordered motions of the eddy in the cavity. Then, we define the frequency f_m of the momentum exchange from the patterns of eddy structures. Although the patterns appear with quasi-periodicity in the spanwise direction, the value of f_m at any position in spanwise direction can be considered a typical one, because velocity measurement confirms that the statistics of velocities are two-dimensional. Furthermore, the patterns never occur in the sequence shown in Fig. 3; therefore, we define f_m as the sum of the respective patterns related with momentum exchange, as below.

$$\text{For } p=2, f_m = f_i + f_{ii} + f_{iii} \quad (3)$$

$$\text{For } p=4, f_m = f_v + f_{vi} + f_{vii} \quad (4)$$

In the case where f_m is normalized with respect to the scales on the pressure drag discussed in sub-section 3.2, we can expect that the degree of the momentum exchange is the same for both $p=2$ and 4 if the non-dimensional frequency $f_m b/u_\tau$ is independent of the roughness pitch ratio p . The value of $f_m b/u_\tau$ for $p=2$ is 0.80 and that for $p=4$ is 1.98, or 2.5 times the corresponding value for $p=2$. The result suggests that the frequency for the momentum exchange through the open face, which is equivalent to the repeating frequency of the random formation, growth, and decay of the eddy, is higher for $p=4$ than for $p=2$. This can interpret as variation in the ratio of the pressure drag coefficient to the local skin friction coefficient. In fact, a wind tunnel experiment shows that the ratios for $p=2$ and 4 are 54% and 93%, respectively ⁽⁹⁾.

Finally, we consider what factor the frequency f_m is affected by. The behavior of the eddy (formation, growth, and decay) in the cavity is affected strongly by the characteristics of both the boundary layer over the rough surface ⁽²²⁾ and the separated free shear layer originated from the roughness element ^{(9), (23)}. In the present experiment, the characteristics of the boundary layers over the rough surfaces have little effect on the behavior of the eddy,

Figure 4 Non-dimensional frequency of momentum exchange.

because, as shown in Table 1, the relative roughness height k/δ is almost the same for both cases. Defining the convective time scale b/u_τ as the characteristic of the separated free shear layer, we investigate the relation between the non-dimensional frequency $f_m b/u_\tau$ scaled with the time scale and the roughness pitch ratio p . Here, the convective velocity is scaled with the friction velocity u_τ , because the mean velocity in the separated free shear layer is of the same order as the friction velocity⁽⁹⁾. Figure 4 gives the variation of the non-dimensional frequency $f_m b/u_\tau$ with the roughness pitch ratio p . The value of $f_m b/u_\tau$ may increase with increasing p , so that the momentum exchange accompanied with the quasi-periodicity of patterns of eddy structures will depend on the increase of the convective time scale. On the other hand, it is interesting that for the flow passing over a single cavity, Rockwell et al.⁽²⁴⁾ reported that the dominant frequency, estimated from the power spectrum of pressure fluctuation at the downstream sidewall in the cavity, varies with b/k .

4. Conclusions

Flow visualization was performed in the cavity between roughness elements for the boundary layer over the rough surfaces of $p=2$ and 4. The behavior of the eddy in the cavity was kinematically related with the momentum exchange in the separated free shear layer originated from the roughness element. Four patterns of eddy structures, which are (i) Strong outflow, (ii) Weak outflow, (iii) Inflow, and (iv) Divided flow, were observed for $p=2$, and the three patterns of (v) Strong outflow, (vi) Outflow from downstream cavity edge, and (vii) Inflow were observed for $p=4$. For $p=4$, the non-dimensional frequency on the momentum exchange using the scales estimated from the pressure drag acting on the cavity takes a value of 2.5 times that for $p=2$. The degree of the quasi-periodicity of the flow patterns may be related to the increase in convective time in the separated free shear layer behind the roughness element.

References

- (1) Perry A.E., Schofield W.H. and Joubert P.N., Rough Wall Turbulent Boundary Layers, *J. Fluid Mech.*, Vol.37, Part.2 (1969), 383-413.
- (2) Dvorak F.A., Calculations of Turbulent Boundary Layers on Rough Surfaces in Pressure Gradient, *AIAA Journal*, Vol.7, No.9 (1969), 1752-1759.
- (3) Wood D.H. and Antonia R.A., Measurements in a Turbulent Boundary Layer over a d-type Surface Roughness, *Trans. ASME, Series E*, Vol. 42, No.3 (1975), 591-597.
- (4) Osaka H, Nakamura I. and Kageyama Y, Characteristics of Mean Flow Quantities for Turbulent Boundary Layer over a d-type Rough Wall, *Trans. JSME, Series B*, Vol.50, No.458 (1984), 2299-2306, in Japanese.
- (5) Tani I., Turbulent Boundary Layer Development over Rough Surfaces, *Perspective in Turbulence Studies* (1987), Meier H.U. and Bradshaw P. (Eds.), Springer-Verlag, 223-249.
- (6) Antonia R.A. and Luxton R.E., The Response of a Turbulent Boundary Layer to a Step

- Change in Surface Roughness Part.1 Smooth to Rough, *J. Fluid Mech.*, Vol.48, Part 4(1971), 721-761.
- (7) Pineau F., Nguyen V.D., Dickinson J. and Belanger J., Study of Flow over a Rough Surface with Passive Boundary Layer Manipulator and Direct Wall Drag Measurements, *AIAA Paper*, No.87-0357 (1987).
- (8) Osaka H., Kameda T. and Mochizuki S., Mean Flow Quantities for the Turbulent Boundary Layer over a k-type Rough Wall, *Trans. JSME, Series B*, Vol.64, No.619 (1998), 709-716, in Japanese.
- (9) Kameda T., Osaka H. and Mochizuki S., Turbulent Structure in the Vicinity of a Roughness Element for the Boundary Layer over a k-type Rough Wall, *Trans. JSME, Series B*, Vol.66, No.646 (2000), 1347-1355, in Japanese.
- (10) Leonardi S., Orlandi P., Smalley R. J., Djenidi L. and Antonia R. A., Direct Numerical Simulations of Turbulent Channel Flow with Transverse Square Bars on One Wall, *J. Fluid Mech.*, Vol.491 (2003), 229-238.
- (11) Kameda T., Osaka H. and Mochizuki S., Turbulent Structure in the Vicinity of a Roughness Element for the Boundary Layer over a k-type Rough Wall in Low-Reynolds-Number (Measurement of the Flow Interaction in the Open-face between Roughness Elements and a Flow-Pattern in a Groove), *Trans. JSME, Series B*, Vol.68, No.673 (2002), 2467-2474, in Japanese.
- (12) Djenidi L., Elaverasan R. and Antonia R.A., The Turbulent Boundary Layer over Transverse Square Cavities, *J. Fluid Mech.*, Vol.395 (1999), 271-294.
- (13) Miyake Y. and Tsujimoto K. and Agata Y., A DNS of a Turbulent Flow in a Channel with a Rough Wall, *Trans. JSME, Series B*, Vol.65, No.633 (1999), 1613-1620, in Japanese.
- (14) Yamamoto M., Proposal of a RANS Model to Predict both k- and d-Type Roughness, *Proceeding of ASME FEDSM'03*, CD-ROM: FEDSM2003-45349 (2003), 4th ASME/JSME Joint Fluid Engineering Conference.
- (15) Belcher S. E., Jerram N. and Hunt J. C. R., Adjustment of a Turbulent Boundary Layer to a Canopy of Roughness Elements, *J. Fluid Mech.*, Vol.488 (2003), 369-398.
- (16) Kline S. J., Reynolds W. C., Schraub F. A. and Runstadler P. W., The Structure of Turbulent Boundary Layers, *J. Fluid Mech.*, Vol.30, No.4 (1967), 741-773.
- (17) Purtell L.P., Klebanoff P.S. and Buckley F.T., Turbulent Boundary Layer at Low Reynolds Number, *Phys. Fluids*, Vol.24, No.5 (1981), 802-811.
- (18) Liu C.K., Kline S.J. and Johnston J.P., An Experimental Study of Turbulent Boundary Layer on Rough Walls, *Rep. MD-15* (1966), Stanford Univ. Mech. Eng.
- (19) Osaka H., Kameda T. and Mochizuki S., Re-examination of the Reynolds-Number-Effect on the Mean Flow Quantities in a Smooth Wall Turbulent Boundary Layer, *JSME Int. J., Series B*, Vol.41, No.1 (1998), 123-129.
- (20) Townes H.W. and Sabersky R.H., Experiments on the Flow over a Rough Surface, *Int. Heat Mass Transfer*, Vol.9, No.8 (1966), 729-738.
- (21) Kameda T. Osaka H. and Mochizuki S., Turbulent Transport Mechanism in the Vicinity of a Roughness Element for the Boundary Layer over k-type Rough Wall, *Trans. JSME, Series B*, Vol.69, No.686 (2003), 2260-2267, in Japanese.
- (22) Townsend A.A., *The Structure of Turbulent Shear Flow*, 2nd ed., (1976), 142, Cambridge Univ. Press.
- (23) Furuya Y. and Fujita H., Problem of Surface Roughness and Flow Resistance, *J. JSME*, Vol.71, No.588 (1968), 131-137, in Japanese.
- (24) Rockwell D. and Naudascher E., Review-Self-Sustaining Oscillations of Flow Past Cavities, *Trans. ASME, J. Fluids Eng.*, Vol.100 (1978), 152-165.