Analysis of the influence of transverse groove structure on the flow of a flat-plate surface based on Liutex parameters

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\textbf{ABSTRACT}

Research on turbulent drag reduction has been limited owing to the limitations of existing parameters used for the identification of vortex structures. As a new and more suitable vortex parameter, Liutex provides a novel research method for turbulence control. We used a channel with a transverse groove structure as the research model and employed large-eddy simulation method based on Liutex to study the influence and mechanism of the transverse groove structure on the watershed. The analysis revealed that the transverse groove structure significantly inhibited the vortex intensity, and this effect diminished with the increase of the normal height. Moreover, the transverse groove structure could maintain the stability of the flow vortex and restrain the hairpin vortex. The fundamental action mechanism of the groove structure pertained to slip condition of the bottom surface along the flow direction, which was essential for conveying the bottom fluid. Furthermore, the transverse groove structure could significantly reduce the overall increase in the vortex intensity in the transition layer, and the fluctuation of the vortex intensity in the logarithmic layer was lower under the action of the groove structure. This case can guide the application of the new vortex identification method in turbulence drag reduction.

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\section*{Introduction}

In recent years, the rapid development of computer technology has opened new avenues for the development of computational fluid dynamics (CFD). Consequently, the calculation model and method have been significantly improved. For instance, certain real-life case studies involving the application of CFD models have been reported (Ghalandari et al., 2019; Salih et al., 2019); these studies proposed novel approach and methods based on CFD, such as turbulence control and vortex structure.

Since Walsh (1982) concluded that symmetrical V-grooves along the flow direction offer the largest drag reduction effect, most researchers have focused on this aspect. Presently, symmetrical two-dimensional grooves with serrated, fan-shaped, and blade cross-sections have been extensively studied. In addition, the continuous exploration of the groove structure shows that the drag reduction effect of sinusoidal groove is more significant (Sasamori et al., 2014; W. Wang et al., 2014). Several studies investigated the structure as well as mechanism of grooves. Currently, the action mechanism of grooves can be categorized into two types: transverse and longitudinal.

The primary action theories for describing longitudinal grooves are the ‘protruding height theory’ (P Luchini et al., 1992) and ‘secondary vortex group theory’ (Lee & Lee, 2001); however, these theories have not achieved a scientific consensus. In the ‘theory of secondary vortices’, the grooves control the flow vortices formed in the turbulence. The axial rotation of these vortices along the average velocity direction causes ejection and sweep motion, in which the high-speed fluid mixing with the low-speed fluid near the wall creates regions of high shear stress and resistance (Martin & Bhushan, 2016). The selection of the appropriate groove spacing according to the inherent vortex size in the basin can raise these vortices from the surface, thus reducing the area exposed to high shear stress and thereby reducing the resistance (Choi et al., 1993; Martin & Bhushan, 2014). The function of the longitudinal groove is to generate a flow vortex and fix it at the tip of the groove (Goldstein & Tuan, 1998). In the ‘protruding height theory’, the groove surface is compared to a smooth surface with a virtual origin (Luchini et al., 1991), and the position of origin, i.e. vertical height, depends on the direction of the flow. Moreover, the virtual origin is closer to the top of the groove in the case...
of a lateral flow on the groove. The height difference between the transverse and longitudinal flows is termed as the ‘prominent height difference’ (Hage et al., 2000). Subsequently, several studies have attempted to alleviate the difference between the virtual origin and protruding height.

Furthermore, Cui et al. (2017) determined that the groove direction poses a significant influence on the flow of the working fluid. In addition, the convergence groove increased the intensity and number of the vortex structures, whereas the divergent groove reduced the turbulent fluctuation, which garnered considerable scholarly attention. Since then, several scholars have studied the extreme cases of divergent grooves, that is, the arrangement of transverse grooves (Z. Liu et al., 2009; S. Wang et al., 2016).

Although transverse grooves affect the normal flow of fluid, they are different from longitudinal grooves. The characteristics of their lateral arrangement prevent momentum transfer along the flow direction and increase the lateral exchange of momentum. Mariotti et al. (2017) reported that the action mechanism of transverse grooves involves the relaxation of the no-slip boundary condition in the flow surrounding the recirculation regions. Lang et al. (2017) reported the same mechanism and stated that the variation in the boundary layer in the trench basin weakened the low-velocity band and delayed the flow separation. Moreover, Ranjan et al. (2011) suggested that reducing the distance between the two grooves reduces the overall effect of the grooves and impacts the overshoot and undershoot of the fluid. In the laminar sub-layer, the average velocity and turbulence intensity does not significantly differ between the smooth and groove walls. Furthermore, Sutardi and Widodo (2016) analyzed the energy spectrum from the perspective of energy and determined that the energy spectrum of a flat plate with grooves was significantly lower than that of a smooth plate. The vortex structure generates a relative velocity near the wall and reduces the velocity gradient, thus reducing the viscous resistance (B. Wang et al., 2014). However, it produces an additional pressure resistance owing to its structural characteristics. Therefore, the actual scenario is a consequence of the overall effect, and it produces the influence of drag reduction for a large gain (Ahmadi-Baloutaki et al., 2013). Nevertheless, the burst frequency and shear stress distributions did not considerably vary in the downstream for grooves with various shapes (Sutardi & Ching, 2003).

Prior research indicated that the generation of high friction resistance in the turbulence is closely related to the internal coherent structure (Kravchenko et al., 1993), which is mainly embodied in the large and small vortex structures. Moreover, the intensity of these vortex structures poses a significant influence on the flow (Ke et al., 2009). Thus, this is important to exploring the mechanism of drag reduction in groove based on the evolution of a turbulent coherent structure. However, traditional vorticity parameters cannot appropriately represent the real vortex structure. Robinson (1991) found that the correlation between the high vorticity region and the actual fluid rotation was very low. Y. Wang et al. (2017) found in the direct numerical simulation results that not only the vorticity and the direction of the vorticity were completely separated from the darts, but there was also a region with strong rotation but small vorticity, and the vorticity was large in the non-rotating area.

As the antisymmetric tensor or vorticity cannot be utilized to measure the vortices, researchers have proposed vortex identification methods based on the eigenvalues of the velocity gradient tensor, such as Q criterion, the Δ criterion, the $\lambda_{ci}$ criterion and the $\lambda_{ci}$ criterion. Q is the second Galilean invariant of the velocity gradient tensor. A region with $Q > 0$ can be thought as a vortex (Hunt et al., 1988). Chong et al. (1990) defined a vortex core to be the region where the velocity gradient tensor has complex eigenvalues. The discriminant for the characteristic equation for the velocity gradient tensor is $\Delta$. When the velocity gradient tensor has two conjugate complex eigenvalues, the imaginary part of the complex value $\lambda_{ci}$ is called swirling strength (Zhou et al., 1999). Jeong and Hussain (1995) defined the vortex core as a connected region with two negative eigenvalues of the symmetric tensor $A^2 + B^2 = -\nabla(\nabla \rho/\rho) (A, B$ are the symmetric and antisymmetric parts of the velocity gradient tensor, $\rho$ is the pressure). If the eigenvalues of the tensor $A^2 + B^2$ are ordered as $\lambda_1 \geq \lambda_2 \geq \lambda_3$, this definition is equivalent to the requirement that $\lambda_2 < 0$.

Although significant progress has been achieved in the field of vortex identification, these methods pose limitations from various aspects (C. Liu, 2020) such as inappropriate representation of the vortex direction, unclear physical meaning, existence of shear or tensile-compression pollution, threshold sensitivity, and limited selection owing to empirical and subjective factors. Moreover, a majority of these identification methods require supplementation with additional variables, which increases the workload and difficulty of analysis. Recently, Gao and Liu (2018), C. Liu (2018), and C. Liu et al. (2018) further decomposed the vorticity into rotating and non-rotating parts. Subsequently, they proposed the extraction of the rigid rotation part from fluid motion and named it the Rortex vector, which was later renamed as Liutex. Furthermore, Liu suggested the Omega criterion (Dong et al., 2018; C. Liu et al., 2016; C. Liu et al., 2019) that separates the rotation from the vorticity and removes the shear deformation, which can
more accurately represent the vortex structure. The vortex structure can be accurately captured when omega has a value of 0.52, which represents an approximate definition of the vortex boundary quantity.

The definition and identification method of vortex is of considerable significance to the study of turbulence. However, due to the limitation of traditional vortex identification methods, the vortex structure in turbulence cannot be analyzed accurately and quantitatively. The definition and identification method of the third-generation vortex based on the Liutex vector has obvious advantages for the quantitative study of turbulence. Therefore, this study aims to quantitatively analyze the effect of transverse grooves on the vortex structure in turbulence.

This study used the ANSYS FLUENT numerical calculation software for adopting the new vortex intensity parameter Liutex as well as the omega vortex identification criteria to explore the turbulence control and turbulence drag reduction of the transverse groove structure. The Liutex parameter distribution and the evolution of the vortex structure in the flat and grooved watersheds were compared to characterize the influence of the lateral grooves on turbulent structure accurately and quantitatively and verify the drag reduction mechanism of the lateral grooves.

### Calculation model and numerical calculation method

**Groove structure setting**

Prior research has primarily focused on the drag reduction of longitudinal grooves, but the transverse groove size parameters are still not clearly understood with relation to the drag reduction effect. However, in the previous research on groove size (Lang et al., 2017; Sutardi & Ching, 2003; S. Sutardi & Widodo, 2016), an adequate drag reduction effect is realized when the dimensionless groove width $s^+ < 50$ and dimensionless groove height $h^+ < 30$. In this study, a V-shaped symmetrical groove was adopted, and the actual size of the transverse groove was adjusted according to the flow state; the final parameters were then determined based on comprehensive consideration.

The wall friction velocity was defined as

$$u_T = \sqrt{\frac{\tau_w}{\rho}},$$

where $\tau_w$ denotes the wall shear stress and $\rho$ represents the working medium density.

The characteristic length of wall viscosity scale can be defined as

$$\delta_v = \frac{\nu}{u_T},$$

where $\nu$ denotes the coefficient of viscosity of motion.

Additionally, the dimensionless grooves dimensions can be expressed as

$$h^+ = \frac{h}{\delta_v},$$

$$s^+ = \frac{s}{\delta_v}.$$

Moreover, the groove size was confirmed by simulating the flow of the flat plate, and the empirical formula was determined as follows.

$$\tau_w = 0.0225\rho U^2 \left( \frac{\nu}{U \delta} \right)^{0.25},$$

$$\delta = 0.37 \left( \frac{\nu}{U \delta} \right)^{0.2} = 0.37 \times Re^{-0.2},$$

where $U$ represents the flow rate of working fluid and $Re$ is the Reynolds number.

Equations (1) and (5) can be rewritten as

$$\tau_w = 0.029\rho U^2 Re^{-0.2},$$

$$u_T = 0.17 U Re^{-0.1}.$$

The specific expressions of Equations (3) and (4) can be written as

$$h^+ = \frac{0.17 U Re^{-0.1}}{\nu},$$

$$s^+ = \frac{0.17 U Re^{-0.1}}{\nu}.$$

Under the simulated conditions, the temperature was 20°C. The working fluid parameters at atmospheric pressure are listed in Table 1.

In this study, the mainstream speeds in the simulated data were 30, 40, 50, and 60 m/s. The dimensionless grooves dimensions were initially defined as $s^+ = 40$ and $h^+ = 20$. The calculations of the specific parameters are presented in Table 2.

Based on the above data, the specific groove size was determined as 0.2 and 0.1 mm.

**Table 1. Working substance parameters.**

| Working substance | $\rho$(m$^3$/kg) | $\nu$(m$^2$/s) |
|-------------------|-----------------|----------------|
| Air               | 1.225           | $1.4607 \times 10^{-5}$ |

**Table 2. Groove structure parameters.**

| $U$(m/s) | Re | $s^+ = 1$(m) | $h^+ = 1$(m) | $s^+ = 40$(m) | $h^+ = 20$(m) |
|----------|----|--------------|--------------|--------------|--------------|
| 30       | 16,430 | 0.0075606 | 0.0075606 | 0.298 | 0.149 |
| 40       | 21,907 | 0.0058359 | 0.0058359 | 0.233 | 0.117 |
| 50       | 27,383 | 0.0047741 | 0.0047741 | 0.191 | 0.096 |
| 60       | 32,860 | 0.0040516 | 0.0040516 | 0.162 | 0.081 |
Figure 1. (a) Three-dimensional perspective of computational domain; (b) cross-sectional view of riblet configuration.

**Numerical model**

The calculation model is illustrated in Figure 1, wherein the simulation adopted a calculation model of $40s \times 15s \times 50s$ ($s = 0.2 \text{ mm}$). The distance between the grooves was 0.2 mm, the height was 0.1 mm, and the top angle was 90°. Additionally, the wall conditions were as follows: the groove structure arranged at the bottom and the smooth surface set at the top. Moreover, the basin was set as a periodic boundary condition in the flow direction and expansion to ensure the complete development of turbulence along the flow direction and avoid the interference of the two sides with the basin.

**Numerical method**

In this study, large-eddy simulations (LES) were used to evaluate the channel watershed. The numerical calculation was primarily based on the pressure-velocity coupling of the SIMPLEC algorithm; the finite volume method was used for spatial discretization, and the second-order upwind difference method was employed to utilize the $N$–$S$ equation. Initially, the RNG $k$–$\varepsilon$ model was used to iterate, and the standard wall function was reviewed during simulation. The model performed a rotation correction, and the wall function could modify the boundary layer to a certain extent. Subsequently, the simulation results were used as the initial field of LES in accordance with the characteristics of stable turbulence. Moreover, the LES was used for unsteady calculations with the Smagorinsky subgrid filter model; the time step was considered as $10^{-5}$ s, and the residual was set to $10^{-5}$.

Overall, a structured hexahedral grid was used in the computational domain mesh. Owing to the normal symmetry of the computing region, we meshed only the half of the slots, and the location of the grid points in the remaining half were obtained using symmetry. The LES has highly strict requirements for the grid, because the grid in vicinity of the wall poses an important influence on capturing the small-scale vortex structure. Thus, the dimensionless normal distance $y^+ \leq 1$ is essential for evaluation ($y^+$ denotes the dimensionless wall distance, and wall viscosity length scale $\delta_v = v/\nu_f$, where $v$ represents the fluid motion viscosity coefficient and $\nu_f$ indicates the wall friction velocity). In this study, the grid near the upper and lower walls was refined, i.e. a non-uniform grid was used in the normal direction with a
grid growth rate of 1.03. In addition, the flow and spread directions were incorporated in uniform grids. In particular, the grid number was initially set to 3.16 million, which was gradually raised to 3.45, 3.74, and 4.03 million. Ultimately, a numerical simulation was conducted at various flow rates. The $y^+$ value of the first wall are presented in Figure 2.

As can be observed from Figure 2, the grid number of LES does not satisfy the requirement of LES until it is at least 4.03 million. Thus, the irrelevance of the grid was verified, and the grid was encrypted to 4.32 million. Moreover, the comprehensive turbulence in the boundary layer was calculated under identical conditions, and the results are presented in Figure 3. As the comprehensive turbulence did not vary significantly upon grid encryption, its irrelevance with the grid can be verified at this instance. A local grid diagram is depicted in Figure 4.

The accuracy of the numerical simulation results was verified with comparative analysis based on the pulsating velocity experimental data of Kim (Kim et al., 1987), which are listed in Table 3. The comparative analysis revealed a strong correlation between the stated results with an $<2\%$ error, which sufficiently proves the accuracy of the model.

### Large-eddy simulation and common recognition criterion

The LES directly simulated the large-scale vortices, whereas the small-scale vortices were filtered and replaced following alternative methods. Additionally, the LES used the scale of the inertial sub-region to employ the basic equation, and a new $N$–$S$ equation was derived post processing.

$$\frac{\partial \vec{u}_i}{\partial x_i} = 0, \quad (11)$$

$$\frac{\partial \vec{u}_i}{\partial t} + \frac{\partial (\vec{u}_i \vec{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \vec{p}}{\partial x_i} + \nu \frac{\partial^2 \vec{u}_i}{\partial x_j \partial x_j} - \frac{\partial Q_{ij}}{\partial x_i}, \quad (12)$$

where

$$Q_{ij} = \vec{u}_i \vec{u}_j - \delta_{ij} \frac{1}{3} Q_{kk} = -2 \nu_T \vec{S}_{ij}, \quad (13)$$

Using the Smagorinsky–Lilly model, we obtain

$$\tau_{ij} = Q_{ij} - \frac{\delta_{ij}}{3} Q_{kk} = -2 \nu_T \vec{S}_{ij}, \quad (14)$$

$$\vec{S}_{ij} = \frac{1}{2} \left( \frac{\partial \vec{u}_i}{\partial x_j} + \frac{\partial \vec{u}_j}{\partial x_i} \right), \quad (15)$$

$$\nu_T = (C_s \Delta t_s)^2 |\overline{S}|, \quad (16)$$

$$|\overline{S}| = \sqrt{\overline{S}_{ij} \overline{S}_{ij}}, \quad (17)$$

In the above-mentioned equations, $\Delta$ denotes the filtering function and $C_s$ represents the Smagorinsky coefficient with a value of 0.1.

Liu Chaoqun et al. (Dong et al., 2018) proposed a new vortex identification criterion – the omega criterion, which represents the proportion of rotation. The general value of omega is 0.52, and values greater than 0.5 indicate rotation. The criterion is derived from the velocity gradient tensor.

$$\nabla V = \frac{1}{2} (\nabla V + \nabla V^T) + \frac{1}{2} (\nabla V - \nabla V^T) = A + B, \quad (18)$$

| $y^+$ | Kim experimental data | LES simulated data | Error |
|-------|-----------------------|--------------------|-------|
| 10    | 2.733                 | 2.736              | 1.10% |
| 20    | 2.665                 | 2.663              | 0.75% |
| 30    | 2.254                 | 2.251              | 1.13% |
| 40    | 2.015                 | 2.012              | 1.49% |
| 50    | 1.852                 | 1.855              | 1.62% |
| 60    | 1.727                 | 1.724              | 1.73% |
Figure 4. Partial schematic of grid.

\[ a = \text{trace}(A^T A) = \sum_{i=1}^{3} \sum_{j=1}^{3} (A_{ij})^2, \quad (19) \]

\[ b = \text{trace}(B^T B) = \sum_{i=1}^{3} \sum_{j=1}^{3} (B_{ij})^2. \quad (20) \]

The mathematical definition of this omega criterion is presented as follows:

\[ \Omega = \frac{b}{a + b + \varepsilon}. \quad (21) \]

Similar to vorticity, Liutex can be derived from the velocity gradient; this parameter is a vector and conforms to the right-hand rule (Gao & Liu, 2018; C. Liu et al., 2018). The Liutex vector represents the rigid rotation part of the local fluid motion in the flow field, and its direction denotes the real eigenvector of the velocity gradient tensor, which represents the local rotation axis. Moreover, its magnitude corresponds to the angular velocity of the rigid rotation (C. Liu, 2018).

The Liutex vector can be defined as follows, with the explicit expressions presented in Equation (26).

\[ R = 2(\beta - \alpha), \beta^2 > \alpha^2, \quad (22) \]

\[ R = 0, \alpha^2 \geq \beta^2, \quad (23) \]

\[ \alpha = \frac{1}{2} \sqrt{\left( \frac{\partial V}{\partial Y} - \frac{\partial U}{\partial X} \right)^2 + \left( \frac{\partial V}{\partial X} + \frac{\partial U}{\partial Y} \right)^2}, \quad (24) \]

\[ \beta = \frac{1}{2} \left( \frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y} \right), \quad (25) \]

\[ \bar{R} = R \bar{r}. \quad (26) \]

**Numerical result analysis**

In the mathematical expression of the vortex, the magnitude of Liutex represents the intensity of the vortex, and the direction corresponds to that of the rotation axis. As a vector parameter, Liutex exhibits three-dimensional characteristics and conforms to the right-hand rule. In particular, Liutex-x, Liutex-y, and Liutex-z are the three components of Liutex in the Cartesian coordinate system. Thus, the distribution of this parameter is essential to be explored in the boundary layer.

**Comparative analysis of Liutex parameters in watershed**

**Comparison of Liutex in near-wall area of flat plate and groove**

Figure 5 presents the Liutex distribution of the smooth surface and groove surface at the \( y^+ = 5 \) position. The Liutex distribution on the upper side of the plate is scattered, as portrayed in Figure 5(a,c,e,g). The values of Liutex-x and Liutex-y were both positive and negative. According to the right-hand rule, the rotation direction was out of order. In addition, most of the Liutex-z values in the flat basin were positive. In the flat plate, the direction of rotation of the upper part of the vortex was opposite to the flow direction, which reduced the velocity of the fluid in the upper portion. However, Liutex-z is not the only component in the tablet that determines the macroscopic outcome. In contrast to the components of the groove surface, the Liutex-x and Liutex-z components of the plate surface were larger, but the Liutex in the \( x \)-direction was larger, whereas the Liutex in the \( y \)-direction was the smallest. Moreover, the vector sum of the three vectors determined the macroscopic results. The results revealed that the rotation axis of the vortex structure in the vicinity of the plate wall was greater in the \( x-z \) plane than that in the vertical direction.

As observed from Figure 5(b,d), the vortex structure in the vicinity of the groove wall was more regular and orderly, and there was a positive and negative mutual modification process for the Liutex vectors in the \( x \)- and \( y \)-directions, which was potentially caused by the reverse force. Based on the angle of the vortex structure, there existed a hairpin vortex structure above the 0.004 position, and the two sides of the vortex head progressed in two opposite directions with alternating vortex intensity near the wall. However, the values in the \( x \)- and \( y \)-directions were much smaller than those in the flat region. Furthermore, the macrostructure was influenced by a large component, and the vortices in the
Figure 5. Liutex distribution of smooth plate and grooved plate at $y^+ = 5$. (a) Smooth plate Liutex-x. (b) Grooved plate Liutex-x. (c) Smooth plate Liutex-y. (d) Grooved plate Liutex-y. (e) Smooth plate Liutex-z. (f) Grooved plate Liutex-z. (g) Smooth plate Liutex-m. (h) Grooved plate Liutex-m.
$x$- and $y$-directions were easily eliminated by those in the $z$-direction as the principal axis. Consequently, all the values of $Liutex$ components were negative in the vicinity of the grooves in the $z$-direction, and there was no positive or negative transition process. Based on the right-hand rule, the $Liutex$ direction indicates that only a single vortex structure rotated along the groove flow direction, which was essential for a ‘rolling bearing’. Thus, the groove essentially hindered the momentum exchange in the $x$- and $y$-directions on the wall. Consequently, the $Liutex$-x and $Liutex$-y components became smaller, and the $Liutex$-z component was limited to the interior of the groove. Owing to the pressure gradient, the rotation direction altered, and the transverse vortex structure near the groove acted as a ‘rolling bearing’.

The $Liutex$-m on the groove surface exhibited a similar trend to that of $Liutex$-z. Based on the influence of the large-scale vortex structure on the $Liutex$ in the groove, the distribution of $Liutex$-m can be used to deduce the existence of the card vortex structure. The probability of large-scale vortex motion was relatively high at the peak of the $Liutex$-m curve. Upon analyzing the internal flow field of the groove, the external flow field can be speculated and judged only by the $Liutex$ vector.

**Figure 6. $Liutex$ distribution in vertical direction of the grooved plate.** (a) $Liutex$-x. (b) $Liutex$-y. (c) $Liutex$-z. (d) $Liutex$-m.

**Liutex distribution in vertical direction of trench**

Figure 6 displays the influence of groove on the upper region, where $y = 0$ m denotes the bottom position of the groove, and $y = 0.0001$ m represents the top of the groove, i.e. the flat wall. As can be observed, the $Liutex$ component decreased significantly from all directions, and the fluctuation amplitude decreased as well. Additionally, the $Liutex$-m evidently decreased from the maximum value of 12,000 s$^{-1}$ to approximately 6000 s$^{-1}$.
Liutex-z altered the direction of the vector, and the values of the smooth flat basin were positive, whereas those of the flat plate with grooves were negative. However, the value of Liutex-z in the groove interior was approximately 3000 s$^{-1}$, and its fluctuation range above the top of the groove was less than 1000 s$^{-1}$, which was significantly lower than that of the flat plate. Moreover, the maximum value of Liutex-\(x\) was only 200 s$^{-1}$. As compared with the components in other directions, the value was exceedingly small and posed a slight influence on the overall flow field.

Overall, the influence of the grooves on the reduction of the height below 0.001 m near the wall was considerably significant, and its effect decreased gradually with the increase of normal height. This could be potentially related to the decrease in the upper vortex structure. Moreover, the Liutex was almost zero at a height of 0.002 m for the upper part of the smooth plate. Additionally, the vortex structure existed only near the wall, and the vortex structure was weak farther away from the wall.

Regardless of the average value or the maximum value, all the Liutex components at the plate wall were larger than the Liutex components on the groove surface; the results are presented in Figure 7. For the average value, the groove structure suppressed the generation of the Liutex component in all directions. The Liutex-\(x\) component almost disappeared with the generation of the vortex, and the remaining Liutex-\(z\) component was limited to the inner region of the groove, thus forming a stable secondary vortex structure along the flow direction and reducing both the velocity gradient and viscous resistance. A similar trend of the maximum value was observed. The Liutex-\(x\) with a maximum value of nearly 70,000 s$^{-1}$ was prominently reduced to less than 5000 s$^{-1}$, indicating the evident influence of the groove structure on the near wall. Moreover, the chaotic vortex structure became orderly through the guiding action of the groove.

If all the other Liutex components near the wall could be converted into Liutex-\(z\) components, the influence of groove drag reduction would be more evident. However, an exceedingly large groove structure would increase the internal turbulence dissipation, which is not favorable for the formation of a larger vortex in the groove. Thus, the combination of the two may yield superior optimization results.

**Liutex distribution in inner region of trench**

Figure 8 presents the Liutex distribution at various grooves, considering the positions as a series of points along the \(y\)-direction at the groove center. As observed, there were prominent characteristics in the groove interior. Specifically, the Liutex parameter values in the flow and normal directions were not large; the Liutex-\(z\) component was negative, and the curve displayed a concave trend followed by recovery. The minimum and maximum values were approximately \(-25,000\) and 25,000 s$^{-1}$, respectively. Moreover, the values of Liutex-\(z\) and Liutex-\(m\) exhibited similar variation trends in the groove with similar values. Therefore, the Liutex vector in the groove primarily existed in the \(z\)-direction, and the Liutex-\(z\) component contributed to a major proportion of the Liutex values in the groove. Based on the right-handed rule, the vortex column rotated along the flow direction, but the vortex with other directions as the principal axis is not evident. The rotation direction in the transverse groove
was the same as that of the flow direction in the upper region of the vortex, which is consistent with the phenomenon of ‘rolling bearing’ in the previous study (B. Wang et al., 2014).

**Analysis of evolution of vortex structure in basin**

**Vortex evolution process of flat plate and groove surface**

Figure 9 illustrates the time evolution of the plate surface and groove portion for an omega value of 0.55. There existed numerous scattered vortex structures along with six stable hairpin vortices on the flat plate surface, whereas there was only one hairpin vortex on the groove surface. Generally, the hairpin vortex structure was located in the logarithmic region and had a large structure, thus its effect was over a large space. However, the existence of this structure disturbed the surrounding area, and the inner side of the hairpin vortex rose higher as the outer side of the hairpin vortex moved down, which is an essential coherent structure of turbulence.

The main vortex structure type and the characteristics of the two basins were mainly affected. In comparison to the flat basin, the disordered vortex structure on the groove surface disappeared, as depicted in Figure 9(b,d,f,h). Additionally, the vortex in the vicinity of the groove surface existed mainly in the form of a downstream vortex, and the flow scale and spread width were large. This indicated that the groove structure was able to integrate the small vortex structure near the wall, which was stretched or integrated into a regular flow vortex. As the small vortex structure was the primary source of energy dissipation, the groove structure was effective in reducing energy dissipation. With the evolution and
The development of the flow vortex on the groove surface, the flow vortex maintained adequate stability along the flow direction and did not yield a hairpin vortex structure. This result implied a low correlation between the spreading direction and the normal phase of the vortex structure in the trench basin. As the hairpin vortex comprised adequately strong reverse-rotating flow vortex pairs, a bow-shaped vortex head was formed under the action of tension and torsion, which further overlapped. Therefore, one of the objectives of the groove structure is to restrain the spreading direction and normal upward disturbance in the near-wall region. Moreover, the significant reduction of hairpin vortices suggested that the grooves effectively reduced the instability of flow vortices and strip structures owing to torsion and tension in the process of evolution. Regardless of the number of hairpin vortices or disorder, the groove surface was significantly improved, and the overall disturbance became evidently smaller.

The migration velocity and uplift height of the vortex structure evidently varied between the flat and groove basins. The flow velocity distribution of the vortex structure is presented in Figure 9. It can be seen that both the migration velocity and normal lifting height of the
vortex structure on the groove surface are low, which reduce the influence range of the vortex structure. Moreover, the velocity distribution of the vortex structure was uniform on the groove surface, and the shear stress in the flow was significantly reduced; thus, the fragmentation of the vortex structure reduced, thereby reducing the turbulent burst and turbulent dissipation. As observed from Figure 9(b,d,f,h), a uniform transverse vortex column was formed at the bottom of the groove, which was essential for the transverse groove structure (verifying the Liutex direction analysis in the previous sections). The stated figure clearly depicts the flow direction of the transverse vortex column at the bottom, where the sliding friction near the wall converted into rolling friction, and the slip conditions of the bottom surface improved. This is one of the primary reasons for the drag reduction in the transverse grooves. Furthermore, this secondary vortex structure did not vary significantly with time, and it continuously acted as a stable ‘rolling bearing’.

**Variation of vortex structure in transition layer**

Figure 10 displays the temporal variation in Liutex-m in the transition layer. The parameter Liutex-m is the scalar sum of Liutex components in the basin, which represents the existence of the entire vortex structure to a certain extent. The time-value started at the instant a hairpin vortex entered the left-hand side and ended as the structure flowed out from the right-hand side.

As can be observed from Figure 10(a,b), the vortex intensity of the trench basin was higher than that of the flat basin for $y^+ = 5$. However, with increasing height, the vortex intensity of the flat basin increased sharply but that of the groove basin exhibited extremely slow variation. Moreover, the fluctuation of the vortex intensity of the groove basin was smaller than that of the flat basin at each layer height. The previous sections of the analysis signified that the transverse vortex column at the bottom of the trench basin increased the fluid momentum at the bottom of the trench and strengthened the disturbance. Lang et al. (2017) reported that enhancing the fluid mixing or momentum near the wall aided in controlling the flow separation. In addition, the transport in the upper portion of the secondary vortex reduced the normal gradient, weakened the viscous shear stress, and reduced the fluid turbulence and vortex intensity in the middle and upper regions of the transition zone. As compared with the flat basin and groove basin, the vortex intensity was approximately 3300 s$^{-1}$ at the groove basin $y^+ = 5$ and only around 4500 s$^{-1}$ at the top $y^+ = 30$. Furthermore, the fluctuation range of the entire transition layer
was approximately 1200 s$^{-1}$, accounting for only 13% of the overall variation of 9300 s$^{-1}$ in the flat basin. Although the value of Liutex-$m$ (4500 s$^{-1}$) at the position of $y^+ = 30$ in the trench basin was 60% lesser than that in the flat basin (11,000 s$^{-1}$). The effect of groove on vortex intensity reduction was very significant. In addition, the vortex growth rate of the flat plate reached 240% and 50% from the height of $y^+ = 5$ to $y^+ = 13$ and 21, respectively, which were significantly higher than those observed at the trench basin. Therefore, the main impact of the groove structure in the transition layer reflected the growth rate and magnitude of reducing the vortex intensity of the transition layer, and the groove structure more appropriately stabilized the activity of the transition layer.

Variation of vortex structure in logarithmic layer

Figure 11 depicts the temporal variation in Liutex-$m$ in the logarithmic layer with $y^+ = 70$. Regardless of flat watersheds or trench basins, the Liutex does not increase as much as that for $y^+ = 30$. Liutex-$m$ decreased with increasing height, indicating that the intensity of the vortex decreased. Similarly, the intensity of the vortex decreased significantly in the trench basin in the logarithmic layer. First, the overall intensity of the vertex in the upper region of the flat basin was 3–4 times stronger than that in the trench basin. The maximum value of the flat watershed was 10,743 s$^{-1}$ at $y^+ = 70$, whereas that of the trench watershed was only 3762 s$^{-1}$, and the maximum value decreased significantly. The Liutex-$m$ values of the plate and groove at $y^+ = 200$ were 2279 and 300 s$^{-1}$, respectively; this result indicates that as the height continued to increase, the intensity range of the high vortex was smaller in the trench basin than that in the plate.

In the process of flow evolution, the vortex fluctuations varied with the heights of the plate and groove, and the fluctuation of the vortex intensity became more intense with increasing height. The fluctuation intensities of 70, 100, 150, and 200 flat watersheds were 3%, 23%, 18%, and 58%, respectively. In contrast, the fluctuation intensity was significantly suppressed at varying heights of the trench basin, and the fluctuation intensities were 2%, 4%, 2%, and 26%. In the position of the top layer of the logarithmic layer of the trench, Liutex-$m$ value was approximately 300 s$^{-1}$ with less vortex intensity, and the enhancement of volatility has a slight influence on the watershed.

The value of Liutex-$m$ of the groove varied similarly with that of the plate, which decreased with the increasing $y^+$. However, the fluctuation range of the logarithmic layer was smaller in the basin with a grooved structure, indicating that the stability of each layer in the logarithmic layer was higher, which was advantageous.
for reducing the normal momentum exchange between fluids.

The maximum decrease in the transition layer and logarithmic layer watershed was evident, and the fluctuation range significantly improved as well. Therefore, the vortex intensity and fluctuation amplitude of both the local position and entire region were obviously reduced with a considerable impact, but the influence of the groove structure on the basin varied. In particular, new pressure resistance was added after introducing this structure. Therefore, the drag reduction effect was insignificant.

**Conclusion**

As a mathematical form of a vortex, \( \text{Liutex} \) represented the intensity of the vortex, and its direction corresponded to the direction of the rotation axis. Thus, the determination of distribution of this parameter in the boundary layer is essential. Consequently, the evolution law of the bionic groove structure was explored in terms of a coherent structure, which provided a theoretical basis for the passive control of turbulence. The main conclusions were as follows.

The rotation axis of the vortex structure near the wall surface of the flat plate was more concentrated in the \( x-z \) plane at \( y^+ \sim 5 \), whereas the vortex structure near the wall surface of the groove was stronger with the \( z \)-axis as the rotation axis. The vortex structure with the \( z \)-axis as the rotation axis was mainly a downstream vortex structure (\( \text{Liutex}-z \) is negative), which was opposite to that of the flat-plate basin. Additionally, the groove posed a significant influence on the reduction of the vortex intensity within the basin range below 0.001 m (\( y^+ = 83 \)). However, this influence gradually decreased as the height increased. At 0.00225 m (\( y^+ = 190 \)), the \( \text{Liutex} \) was almost zero in the basin, and both the average and maximum values of the vortex intensity near the wall of the groove structure were significantly reduced. Moreover, the \( \text{Liutex} \) vector inside the groove was dominated by the negative \( \text{Liutex}-z \) component, which verified the existence of the ‘rolling bearing’.

In the evolution of the vortex structure, the groove structure could considerably improve the disordered vortex structure on the plate surface, primarily to eliminate the small vortex structure, promote the formation of the flow vortex, and maintain the stability of the flow vortex, thus restraining the formation of the hairpin vortex. Furthermore, the groove structure reduced the lifting height and migration velocity of the surface vortex structure, thus breaking the vortex structure and weakening the turbulent dissipation.

The fundamental action mechanism of the transverse groove was to form a clockwise rotating transverse vortex column in the groove, wherein the upper rotating direction was the same as the main flow direction. This secondary vortex acted as a ‘rolling bearing’ at the bottom; thus, the groove wall exhibited a sliding condition along the flow direction and could transport the low-speed fluid on the surface.

As compared with the vortex intensities of the transition layers and logarithmic layers of the flat grooves in various watersheds, the groove structure significantly reduced the vortex intensities in the two regions. For the transition layer, the lateral grooves reduced the growth rate of the vortex intensity in the entire transition layer and stabilized the activity of the transition layer. One of the primary characteristics of the transition layer was that the secondary vortex inside the groove affected the watershed, making the vortex at the bottom stronger than the flat plate. In the logarithmic layer, the groove reduced the fluctuation range of the vortex intensity in each height layer and increased the stability of each layer of fluid.

This study utilized the new \( \text{Liutex} \) parameters to explore the drag reduction mechanism of the trench in an attempt to inspire future research on wall turbulence drag reduction. Owing to the limitations of LES, several aspects of the current study still require improvement. The groove drag reduction mechanism was studied based on the working conditions in a completely developed turbulent state, and the working conditions were found to be relatively simple. Therefore, a further development could combine the new turbulence model for studying the evolution of the \( \text{Liutex} \) parameters on the groove surface under various Reynolds numbers to enrich the existing theoretical system, such as the transition section from laminar flow to turbulent flow. Future research can employ the proposed third-generation vortex identification method to explore the influences of groove structure in various fluid machinery for creating a reasonable layout from the evolution of the vortex structure.

**Disclosure statement**

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References

Ahmadi-Baloutaki, M., Carriveau, R., & Ting, S. K. (2013). Effect of free-stream turbulence on flow characteristics over a transversely-grooved surface. Experimental Thermal and Fluid Science, 51, 56–70. https://doi.org/10.1016/j.expthermflusci.2013.07.001

Choi, H., Moin, P., & Kim, J. (1993). Direct numerical simulation of turbulent flow over riblets. Journal of Fluid Mechanics, 255(–1), 503–539. https://doi.org/10.1017/S0022112093002575

Chong, M. S., Perry, A. E., & Cantwell, B. J. (1990). A general classification of three-dimensional flow fields. Physics of Fluids A: Fluid Dynamics, 2(5), 765–777. https://doi.org/10.1063/1.857730

Cui, G., Pan, C., Gao, Q., Rinoshika, A., & Jinjun, W. (2017). Flow structure in the turbulent boundary layer over directional riblets surfaces. Chinese Journal of Theoretical and Applied Mechanics, 49(6), 1201–1212. https://doi.org/10.6052/0459-1879-17-252

Dong, X., Wang, Y. Q., Chen, X., Dong, Y., Zhang, Y., & Liu, C. (2018). Determination of epsilon for omega vortex identification method. Journal of Hydromechanics, 30(4), 541–548. https://doi.org/10.15705/s42241-018-0066-x

Gao, Y., & Liu, C. (2018). Rortex and comparison with eigenvalue-based vortex identification criteria. Physics of Fluids, 30(8), 085107. https://doi.org/10.1063/1.5040112

Ghalandari, M., Bornassi, S., Shamsirband, S., Mosavi, A., & Chau, K. W. (2019). Investigation of submerged structures’ flexibility on sloshing frequency using a boundary element method and finite element analysis. Engineering Applications of Computational Fluid Mechanics, 13(1), 519–528. https://doi.org/10.1080/19492060.2019.1619197

Goldstein, D. B., & Tuan, T. C. (1998). Secondary flow induced by riblets. Journal of Fluid Mechanics, 363, 115–151. https://doi.org/10.1017/S0022112098008921

Hage, W., Bechert, D. W., & Bruse, M. (2000). Artificial shark skin on its way to technical application. In A. Gyr, P. D. Koumoutsakos, & U. Burr (Eds.), Science and art symposium (pp.169–175). Springer.

Hunt, J. C. R., Wray, A. A., & Moin, P. (1988). Eddies, streams, and convergence zones in turbulent flows. In Studying turbulence using numerical simulation databases (pp. 193–208). Center for Turbulence Research.

Jeong, J. J. I., & Hussain, F. (1995). On the identification of a vortex. Journal of Fluid Mechanics, 285(1), 69–94. https://doi.org/10.1017/S0022112095000462

Ke, G., Pan, G., Huang, Q., Hu, H., & Liu, Z. (2009). Reviews of underwater drag reduction technology. Advances in Mechanics, 39(5), 546–554. https://doi.org/10.6052/1000-0992-2009-5-J2008-171

Kim, J., Moin, P., & Moser, R. (1987). Turbulence statistics in fully developed channel flow at low Reynolds number. Journal of Fluid Mechanics, 177(–1), 133. https://doi.org/10.1017/ S0022112087000892

Kravchenko, A. G., Choi, H., & Moin, P. (1993). On the relation of near-wall streamwise vortices to wall skin friction in turbulent boundary layers. Physics of Fluids A: Fluid Dynamics, 5(12), 3307–3309. https://doi.org/10.1063/1.858692

Lang, A. W., Jones, E. M., & Afroz, F. (2017). Separation control over a grooved surface inspired by dolphin skin. Bioinspiration & Biomimetics, 12(2), 026005. https://doi.org/10.1088/1748-3190/aa5770

Lee, S. J., & Lee, S. H. (2001). Flow field analysis of a turbulent boundary layer over a riblet surface. Experiments in Fluids, 30(2), 153–166. https://doi.org/10.1007/s003480000150

Liu, C. (2018). Letter: Galilean invariance of Rortex. Physic of Fluids, 30(11), 111701. https://doi.org/10.1063/1.5058939

Liu, C. (2020). Liutex-third generation of vortex definition and identification methods. Acta Aerodynamica Sinica, 38(03), 15–33 + 80. https://doi.org/CNKI:SUN:KQDX.0.2020-03-002

Liu, C., Gao, Y., Tian, S., & Dong, X. (2018). Rortex—A new vortex vector definition and vorticity tensor and vector decompositions. Physics of Fluids, 30, 035103. https://doi.org/10.1063/1.5023001

Liu, C., Wang, Y., Yang, Y., & Duan, Z. (2016). New omega vortex identification method. Science China Physics, Mechanics & Astronomy, 59(8), 684711. https://doi.org/10.1007/s11433-016-0022-6

Liu, Z., Hu, H., Song, B., & Huang, Q. (2009). Numerical simulation research about riblet surface with different. Journal of System Simulation, 21(19), 6025–6028. https://doi.org/CNKI:SUN:XTFZ.0.2009-19-017

Liu, C., Gao, Y. S., Dong, X., Wang, Y., Liu, J., Zhang, Y., Cai, X., & Gui, N. (2019). Third generation of vortex identification methods: Omega and Liutex/Rortex based systems. Journal of Hydromechanics, 31(2), 205–223. https://doi.org/10.1007/s42241-019-0022-4

Luchini, P., Manzo, F., & Pozzi, A. (1991). Resistance of a grooved surface to parallel flow and cross-flow. Journal of Fluid Mechanics Digital Archive, 228(228), 87–109. https://doi.org/10.1017/S0022112091002641

Luchini, P., Manzo, F., & Pozzi, A. (1992). Viscous eddies over a grooved surface computed by a Gaussian-integration Galerkin boundary-element method. AIAA Journal, 30(8), 2168–2170. https://doi.org/10.2514/3.11200

Mariotti, A., Buresti, G., Gaggini, G., & Salvetti, M. V. (2017). Separation control and drag reduction for boat-tailed axi-symmetric bodies through contoured transverse grooves. Journal of Fluid Mechanics, 832, 514–549. https://doi.org/10.1017/jfm.2017.676

Martin, S., & Bhushan, B. (2014). Fluid flow analysis of a shark-inspired microstructure. Journal of Fluid Mechanics, 756, 5–29. https://doi.org/10.1017/jfm.2014.447

Martin, S., & Bhushan, B. (2016). Modeling and optimization of shark-inspired riblet geometries for low drag applications. Journal of Colloid & Interface Science, 474, 206–215. https://doi.org/10.1016/j.jcis.2016.04.019

Ranjan, P., Ranjan, A. R., & Singh, A. P. (2011). Computational analysis of frictional drag over transverse grooved flat plates. International Journal of Engineering, Science and Technology, 3(2), 247–254. https://doi.org/10.4314/ijest.v3i2.68680

Robinson, S. K. (1991). Coherent motions in the turbulent boundary layer. Annual Review of Fluid Mechanics, 23(1), 601–639. https://doi.org/10.1146/annurev.fl.23.010191.003125

Salih, S. Q., Suliman, M., Rasani, M. R., Ariffin, A. K., & Yaseen, Z. M. (2019). Thin and sharp edges bodies-fluid interaction simulation using cut-cell immersed boundary method.
Sasamori, M., Mamori, H., Iwamoto, K., & Murata, A. (2014). Experimental study on drag-reduction effect due to sinusoidal riblets in turbulent channel flow. *Experiments in Fluids, 55*(10), 1828. https://doi.org/10.1007/s00348-014-1828-z

Sutardi, S., & Widodo, W. A. (2016). Analysis of turbulence characteristics in the laminar sub-layer region of a perturbed turbulent boundary layer. *Applied Mechanics and Materials Applied Mechanics & Materials, 836*, 115–120. https://doi.org/10.4028/www.scientific.net/AMM.836.115

Sutardi, & Ching, C. Y. (2003). The response of a turbulent boundary layer to different shaped transverse grooves. *Experiments in Fluids, 35*(4), 325–337. https://doi.org/10.1007/s00348-003-0653-6

Walsh, M. (1982). *Turbulent boundary layer drag reduction using riblets*. 20th Aerospace Sciences Meeting. https://doi.org/10.2514/6.1982-169

Wang, B., Wang, J., Zhou, G., & Chen, D. (2014). Drag reduction by microvortexes in transverse microgrooves. *Advances in Mechanical Engineering, 6*(5-6), 734012. https://doi.org/10.1155/2014/734012

Wang, S., Deng, Y., Wu, Z., Li, Z., & Hao, X. (2016). Study on influence of riblet structure of flat surface on local turbulence characteristics. *Journal of North China Electric Power University(Natural Science Edition), 43*(5), 68–74. https://doi.org/10.3969/j.ISSN.1007-2691.2016.05.11

Wang, W., Guan, X.-L., & Jiang, N. (2014). TRPIV investigation of space-time correlation in turbulent flows over flat and wavy walls. *Acta Mechanica Sinica, 30*(4), 468–479. https://doi.org/10.1007/s10409-014-0060-7

Wang, Y., Yang, Y., Yang, G., & Liu, C. (2017). DNS study on vortex and vorticity in late boundary layer transition. *Communications in Computational Physics, 22*(02), 441–459. https://doi.org/10.4208/cicp.OA-2016-0183

Zhou, J., Adrian, R. J., Balachandar, S., & Kendall, T. M. (1999). Mechanisms for generating coherent packets of hairpin vortices in channel flow. *Journal of Fluid Mechanics, 387*, 353–396. https://doi.org/10.1017/S002211209900467X