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CFD based design and analysis of micro-structured surfaces with application to drag and noise reduction

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Abstract The micro-structured surface have the complex effects on the interface mechanics, such as the friction drag and noise reduction, which can be well integrated with sustainable design and manufacturing applied to wind turbines and aerodynamic surfaces. This paper presents the CFD (computational fluid dynamics) analysis, based on Reynolds averaged N-S equations and Realizable K- ε turbulence model, the drag reduction effects of four common configurations of micro-structured surfaces. The CFD simulations are developed focusing on the flow-field and the corresponding total pressure loss in relation to different micro-structured configurations. The evaluation of drag reduction effect is undertaken by comparing the total pressure loss between applying the micro-structured surfaces and normal smooth surfaces. Furthermore, analysis of the velocity and pressure distribution in the flow field is carried out so as to get better understanding of drag and noise reduction. Finally, design and manufacturing of the micro-structured samples are presented with optimal drag reduction effect for further experimental analysis.

Keywords: micro-structured surface; drag reduction; CFD analysis; noise reduction.

1. Introduction

The micro-structured surface is an important technical method to enhance the mechanical function of products/components, the micro structure or feature sizes are normally in 1 ~ 100 micrometers. Tiny topological structures are typically with a specific function, such as micro grooves (Riblet) array, crater (Dimple) array, and micro pyramid (Pyramid) array structure, etc. The micro structures, usually distributed on the surface in 10 ~ 1000 mm magnitude scales of machinery, can change the surface friction of parts, lubrication, adhesion, abrasion resistance and fluid physical properties such as mechanical properties, thus improve the functional characteristics of mechanical products and functional components. They are likely of the ways to move forward for future sustainable design and manufacturing of engineering products or components.

Drag reduction is a fundamental technical issue in development of large civil aircraft. The drag has been the key problem since the beginning of navigating by air. Microstructure surface has the complex effects on the Interface mechanics and has been regarded as an efficient tool to change the fluid physical mechanical properties and to reduce drag and noise. Specific functional surface structures allow for both an enhancement of product functionality [1] and an optimization of economic as well as ecologic aspects in production processes and product behaviors [2]. But in most cases there is no explicit correlation between desired surface function and required surface structure details. In fact, the development of functional surfaces in optics, tribology, fluid-dynamics and other disciplines demands for an extensive research with regard to a multitude of alternative surface structure details. In certain cases promising approaches for the realization and optimization of functional surfaces can be found in nature offering a significant commercial potential for bio-inspired structured surfaces [3]. In the past, the understanding and design of the microstructure are mostly based on bionics. Once functional structure details have been derived, suitable production processes have to be planned and realized. Due to geometrical features are mostly found in the micro-meter range, existing manufacturing technologies have to be adapted or even new technologies have to be developed to fabricate these functional surfaces. With regard to market opportunity, sophisticated combinations of a product-driven approach and a technology-driven approach are promising [4-5].

Aiming at analysing the drag reduction mechanics, this paper investigates different types of grooves, based on Reynolds averaged N-S equations and Realizable k- ε turbulence mode. The investigation also compares the total pressure loss on the micro structured plates against the normal smooth plate, and evaluates their efficiency in drag and noise reduction.

2. Analysis and design of the micro-structured surface

2.1 Geometric model and boundary conditions

This article selects the surface of horizontal layout of small rib/groove as the research object. Considering to the convenience of research, the microstructure are arranged on the flat surface, by using the numerical method to carry on the analysis. Establish the calculation domain, the computational domain and boundary conditions are set as shown in Figure 1: Inlet and outlet, respectively, using the velocity inlet and pressure outlet boundary condition. The whole computational domain size is 3.1 mm * 3 mm. The depth of every micro groove is 0.1 mm.

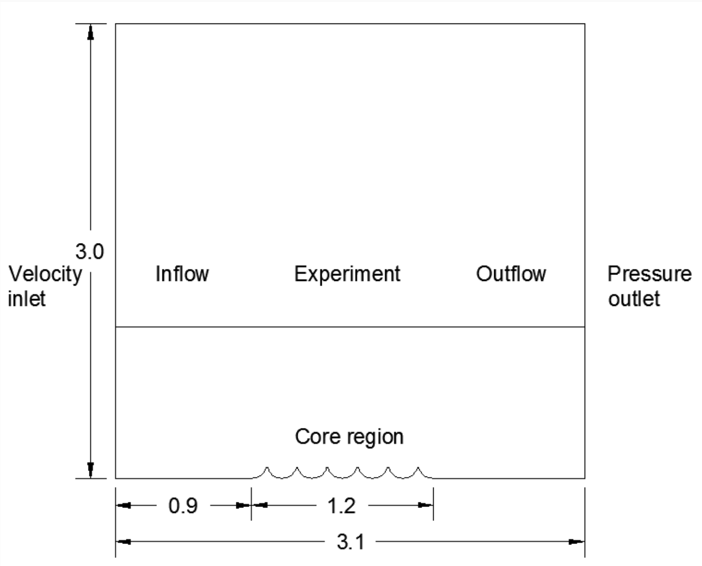

Figure 1. The computational domain

Before processing: the computational domain is divided into three parts which are inflow, experiment and outflow segment. In order to control the grid number and achieve high quality of the grid, the flow sections are meshed separately; Experimental section shield is the core region with complex imbricate structure, which is important to divide the grid, the microstructure is complicated, used to adapt to the complex shapes of unstructured grid area which are dispersed in the experimental section. by setting the rate of change size and initial size to realize the grid scale which is near the core region is small enough and reasonable distribution density; Inflow and outflow section adopt quadrilateral grid, the grid size from far to near the experimental section is gradually from large to small, the grid size of closing to the experimental section and that of the experimental period is nearly the same, enables the flow field to transition smooth cohesion, and reduce the numerical discretization error. After the grid independence test and verify, Selects the proper grid type and mesh density to analyse the model.

2.2. Realizable $k-\varepsilon$ turbulence model and its numerical method

Realizable k-ε model equation:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho C_1 S\varepsilon-\rho C_2\frac{\varepsilon^2}{k+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon \quad (2)$$

$$C_1=\max\left[0.43,\frac{\eta}{\eta+5}\right] \quad (3)$$

$$\eta=S\frac{k}{\varepsilon} \quad (4)$$

In the equation, G_k is generated by the laminar velocity gradient and the turbulence kinetic energy, the G_b is produced by buoyancy and turbulent kinetic energy, Y_M is the volatility cause by the excessive spread in impressible turbulent flow. C_1, $C_{1\varepsilon}$ is constant, σ k and σ is the turbulent Prandtl Number of k equation and e equation , S_k and S_ε are defined by users.

Realizable k- ε model and RNG k- ε model have better performance than the standard k- ε model in strong streamline curvature, vortex and rotation. Because Realizable k- ε model is a new model, so there is no conclusive evidence that it has better performance than RNG k- ε model. But the original study that Realizable k -

ε model has a good effect both in flow separation of k - ε model and complex second order flow.[6]

3. Flow field analysis

Based on the simulation model established in the previous section, studied the influence of different geometric configurations on wall friction resistance, choose the rectangular groove, V groove, U groove and Space-V groove as the research objects.

3.1. Simulation results and analysis

Simulate the air flow through the plates with different types of micro structure in different velocity. Area-weighted average the distribution of the inlet and outlet total pressure, get the average total pressure of inlet and outlet.

Compare the total pressures of inlet and outlet. Then do subtraction and gain the total pressure loss relative to the entrance and outlet. By comparing the total pressure loss in micro structure plates and that in the smooth plate, Figure 2 lists total pressure loss of different micro-structured surfaces, the flow velocity of flow field is from 0.3 to 0.9 Mach number.

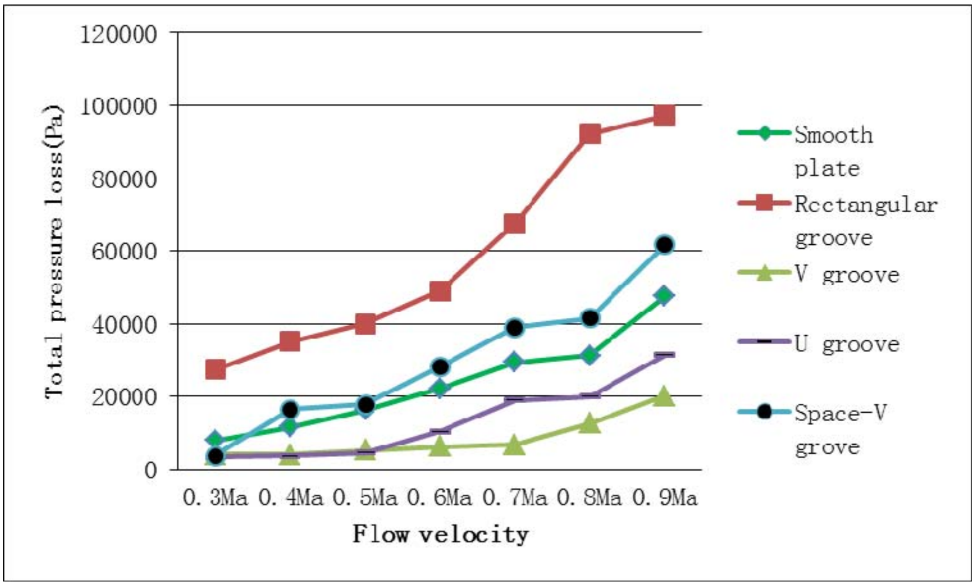

Figure 2. Total pressure loss of different micro-structured surfaces in the velocity of 0.3-0.9 Mach

According to the results of simulation, with the increase of flow velocity, for all of the surfaces, the total pressure losses are on the rise. For each case of flow field, the total pressure loss of the rectangular groove are always the biggest, do not have the effect on drag reduction. When the flow velocity is less than Ma 0.4, the total pressure losses of V groove, the U groove and Space-V groove are less than that of smooth plate, illustrate that, all of these three kinds of microstructure has the drag reduction effect in this flow velocity, and the drag reduction effect of three kinds of microstructure is very little different. In the flow velocity for Ma 0.4 to Ma 0.5, the total pressure loss of Space-V groove start to be greater than that of the smooth plate. When the velocity is less than Ma 0.6, the total pressure loss of U groove of is the smallest, and very close to V groove. After the flow velocity is greater than Ma 0.6, the total pressure loss of U groove of begin to more than V groove, V groove has the best drag reduction effect.

Above all, in these four kinds of microstructure, when the flow velocity is less than Ma 0.6, the drag reduction effect of U groove is best. Otherwise, V groove has the best drag reduction effect. Space-V groove has the function of drag reduction effect in flow velocity less than Ma 0.4, when the flow velocity is larger, it did not have the effect of drag reduction. Rectangular groove has the effect on adding drag reduction.

3.2 Pressure and velocity changes on the micro-structured surface

For the micro groove induced vortex flow, in the windward side of groove form high pressure area, in the leeward side form the low pressure area, due to the pressure. As shown in Figure 3, for Ma 0.8, the stress field in the four types of groove profile, the surface pressure is different in the windward side and the leeward side of the groove. The difference of pressure forms the additional pressure drag in direction of velocity.

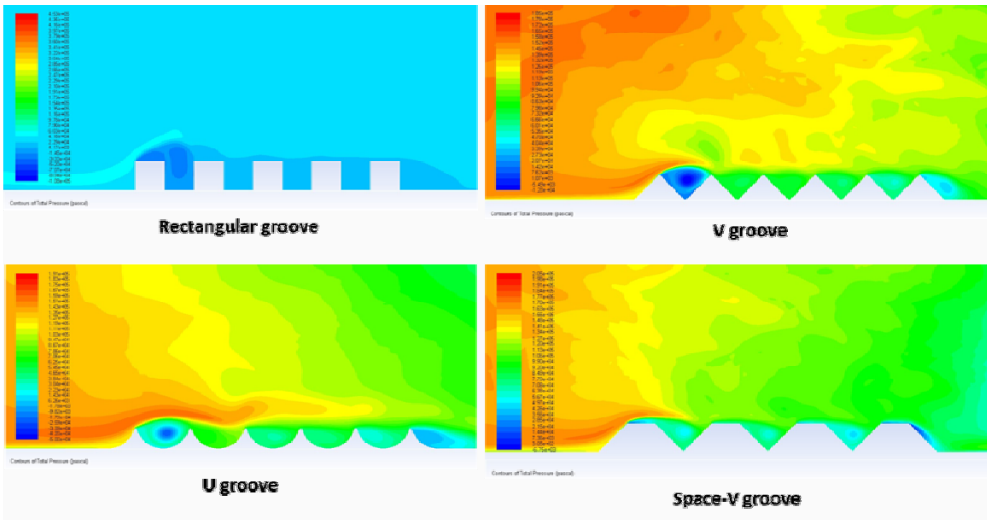

Figure 3. Pressure contours on the four micro-structured surfaces (Mach=0.8)

In high-speed airflow, grooved surface induced the second order micro vortex flow is the main reason for the wall friction resistance reducing [7], impacting the velocity field and pressure field distribution near wall viscous sub-layer [8-9]. As seen from Figure 4, there are some micro vortexes in the groove velocity vectors.

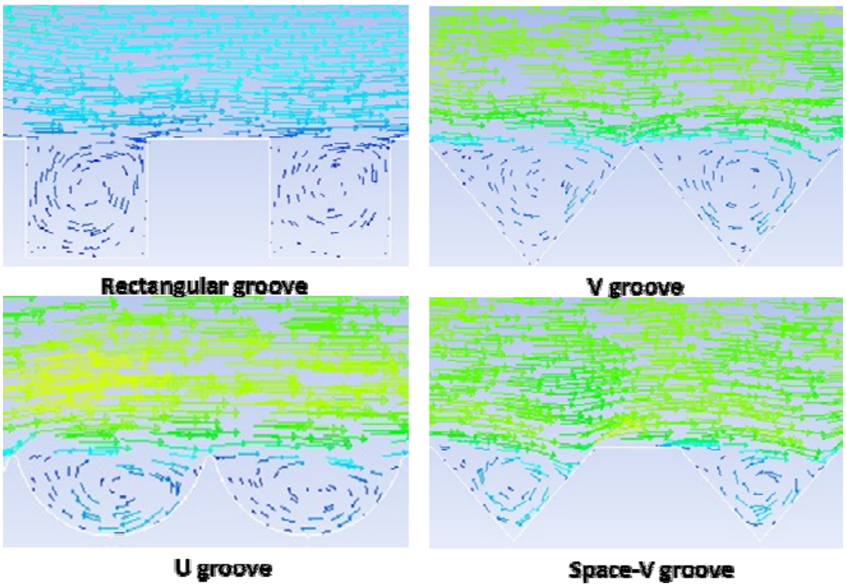

Figure 4. Velocity vectors on the four micro-structured surfaces (Mach=0.8)

Adverse pressure gradient and eddy current result in differential pressure resistance. But at the same time, the existence of the eddy current reduces friction between small ribs at the top of the fluid, and the reverse flow of the vortex at the bottom gives the wall of a forward friction. Offset some the wall friction of the fluid, therefore, viscous resistance reduced[9]. When the reduction of viscous resistance is greater than the increment of the differential pressure resistance, the micro surface performs the function of drag reduction.

This identification process requires the experiments to confirm. Some micro grooves are already manufactured by Kern EVO five-axis milling machine, such as V grooves with the slope angle of 45 degrees and 30 degrees, U grooves and Space-V grooves with 0.1 mm depth as illustrated in Figure 5. Through the image processing technology, the processing quality of the micro-structured surfaces can be texted. The subsequent experiments are prepared to test the drag reduction effect of these micro-structured surfaces.

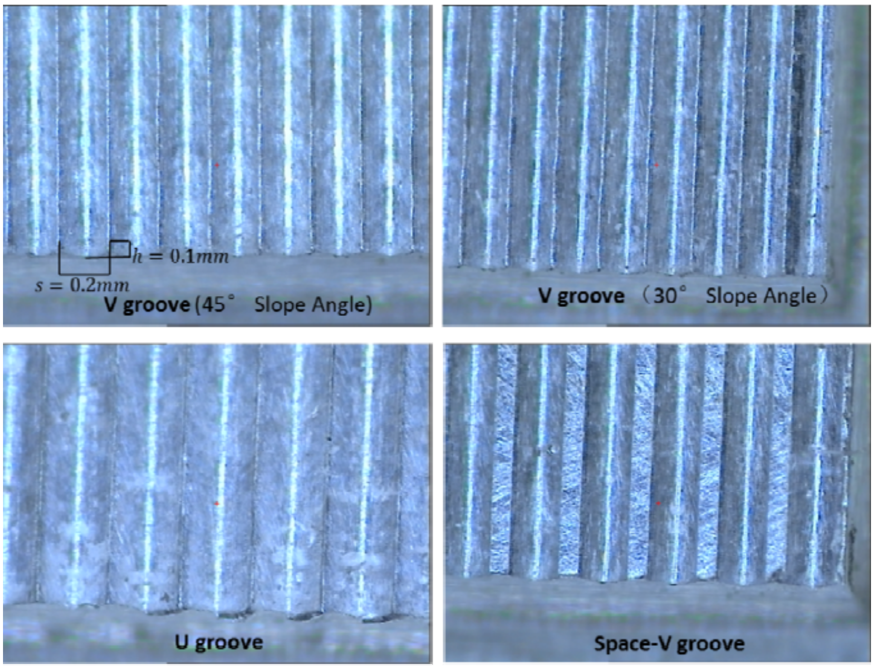

Figure 5. The micro-groove processed by Kern EVO Five-axis milling machine

4. Conclusions

In this paper, four different configurations of micro-structured surfaces are investigated particularly focusing on their drag reduction effect and their potential use in sustainable design and manufacturing of engineering products and components. Above all, when the flow velocity is less than Ma 0.6, the drag reduction effect of the U groove is the best. Otherwise, V groove has the best drag reduction effect. Through the flow field analysis, the second order micro vortex flow which is induced in grooved surface can describe the reason for the wall friction resistance reducing. The drag reduction performed when the reduction of viscous resistance is greater than the increment of the differential pressure resistance. The analysis can be used in the further study and optimizing other configurations of micro-structured surfaces.

The most important factor to design of a micro-structured surface with a good drag reduction effect is to determine the accurate geometric parameters, including configuration, size, shape, location and distribution density. Through the simulation research and statistical rule, the influence factors on the flow field can be gained. The key factors can be identified so as to optimize a micro-structured surface with the best drag reduction function. An effective and efficient evaluation method is needed on the functionality of engineering products or components with micro-structured surfaces.

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