Effects of Riblet Shape of Non-smooth Surface on Aerodynamic Characteristics of Vehicle

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Abstract. To reduce the aerodynamic drag of the vehicle, three kinds of riblet shape non-smooth surfaces were arranged in the tail of the Motor Industry Research Association (MIRA) stepped-back vehicle mode. The shapes of the non-smooth riblet elements are triangular, circular and rectangular. Computational fluid dynamics (CFD) method was used for numerical analysis. To verify the effectiveness of the analysis method, the analysis result of the standard MIRA stepped-back vehicle mode was compared with wind tunnel test data. The tail-flow, pressure and turbulent kinetic energy of the MIRA stepped back vehicle modes, which were arranged with riblet elements, were analyzed. The effects of riblet shape of non-smooth surfaces on the reduction of vehicle’ aerodynamic drag were compared with each other. The simulation results show that the three kinds of non-smooth surfaces have a good effect on drag reduction by reducing the negative pressure in the tail zone of the model, reduce the turbulent kinetic energy and reduce energy dissipation. The circular non-smooth surface is better than the other, with drag reduction effect of 5.53%.

1. Introduction

Global oil consumption has been increasing in recent decades. But oil is a non-renewable resources. How to effectively reduce energy consumption is a worldwide problem to be solved urgently. The total number of vehicles in the world has exceeded 1 billion in 2011. The oil is consumed by vehicles accounts for a large proportion of the world’s oil consumption. When a vehicle is driving at high speed, the output power of the engine is mainly used to overcome the air drag. Therefore, reducing the aerodynamic drag of the vehicle is beneficial to improve vehicle power and fuel economy, thus reducing oil consumption. Bionics studies have found that the surface of sharks is covered with shield scales with riblets. These shield scales can inhibit and delay the occurrence of turbulence in the fluid boundary layer of shark body surface and effectively reduce the flow drag [1]. How to apply the research results of bionics to the aerodynamic drag reduction of the vehicle body is a very interesting topic.

Walsh et al. [2] carried out turbulent drag reduction studies on fluted flat plates. Their results show that the drag reduction effect of non-smooth riblet of shield scale can reach 8% under the condition of high-speed fluid flow. Bechert et al. [3-4] proposed the calculation theory and optimization method of...
riblet section, which laid the theoretical foundation for the design and manufacture of riblet drag reduction structure.

To reduce the aerodynamic drag of the vehicle, researchers have conducted a lot of researches on aerodynamic drag reduction effect and mechanism of pit type non-smooth element [5-8, 10, 12-13]. Previous studies have shown that the arrangement of non-smooth elements in vehicle tail can achieve better drag reduction effect than other surfaces. Scholars have conducted extensive research on the plate riblet model and achieved beneficial results. Although riblet drag reduction technology has been applied in the shipbuilding industry [9], there are few studies on aerodynamic drag reduction of vehicles with non-smooth riblet structures. In this paper, three different non-smooth riblet structures are arranged at the vehicle tail. And then the influence of the shape of non-smooth elements on the aerodynamic characteristics of the vehicle is compared and analysed by Computational Fluid Dynamics (CFD, Fluent).

2. Vehicle Model And Validation

The stepped-back vehicle model given by the Motor Industry Research Association (MIRA) was selected as the research target. The MIRA model group is an internationally recognized standard model [10] and is widely used in basic research of vehicle aerodynamic characteristics. As shown in figure 1, the 3D model of MIRA stepped-back vehicle was built by UG based on the data in reference [11].

![Figure 1. MIRA stepped-back vehicle model.](image)

To ensure the accuracy of the numerical calculation, the parameters of the computational domain of Fluent are shown in table 1.

| Parameter                  | Length | Width | Height | The distance from inlet to vehicle head | The distance from vehicle tail to outlet |
|----------------------------|--------|-------|--------|----------------------------------------|----------------------------------------|
| Value                      | 10×4165| 9×1625| 5×1421 | 3×4165                                 | 4×4165                                 |

The unstructured tetrahedral mesh was used to divide the mesh. The triangular prism mesh was added to the curved surface of the vehicle body as the boundary layer for eliminating the influence of the wall function. The maximum mesh size of each part in the simulation is shown in table 2. Settings of Fluent are shown in table 3.

| Part                        | Flat surface of vehicle body | Curved surface of vehicle body | The overall basin | The basin around vehicle body | The basin around vehicle tail |
|-----------------------------|------------------------------|-------------------------------|------------------|-------------------------------|-------------------------------|
| Value                       | 32                           | 16                            | 8                | 512                           | 64                            |
### Table 3. Settings of Fluent (unit: mm).

| Object             | Setting value | Object             | Setting value |
|--------------------|---------------|--------------------|---------------|
| Solver             | Pressure-Based| Ground             | Slip wall     |
| Turbulence model   | Realizable k-ε| Other wall surface | No-slip wall  |
| Inlet              | Velocity inlet| Temperature        | 15°C          |
| Out let            | Pressure outlet| Residuals         | 0.000001      |
| Vehicle body       | No-slip wall  | Iteration steps    | 3000          |

The aerodynamic drag coefficient of the stepped-back vehicle model (smooth body) of MIRA is 0.3257 through numerical calculation.

To verify the accuracy and reliability of the simulation model and method, the simulation data of MIRA stepped-back vehicle model was compared with the measured wind drag data of HD-2 wind tunnel in Hunan University and IVK wind tunnel in Stuttgart [12].

As shown in table 4, the error between the numerical simulation value and the typical wind tunnel test value is small. It means that the numerical simulation method adopted in this paper has high reliability and accuracy.

### Table 4. Comparison between simulation and test.

| Wind tunnel | Test data | error |
|-------------|-----------|-------|
| HD-2        | 0.3225    | 0.99  |
| IVK         | 0.3204    | 1.65  |

3. Riblet Shapes And Parameters

As shown in figure 2, non-smooth riblet structures such as triangle, circular arc and rectangle were selected to be arranged at the tail of MIRA stepped-back vehicle model.

Previous studies have shown that the non-smooth surface morphology can change the boundary layer flow field structure, control the surface flow field and reduce aerodynamic drag. Therefore, the dimension of the non-smooth riblet can be chosen according to the thickness of the boundary layer at the tail of the vehicle. The selection of riblet element size should consider making the riblet depth less than the thickness of the boundary layer. Reference [13] shows that the thickness of the tail boundary layer of MIRA stepped back model is 4.13mm. Therefore, the non-smooth riblet structure depth h is set as 4mm. In this study, L=30mm, k=8mm, r=k/2.

Bionic studies have shown that the parallel arrangement of the riblets and the incoming flow is better than the vertical arrangement of the drag reduction. In this study, the riblets were arranged along the flow direction, as shown in figure 3.
4. Effect of Riblet Shape on Drag Reduction Performance
The MIRA stepped-back vehicle model with three types of riblets at the tail was analysed by the method given in section 2. Due to the size of the tablet is too small, the riblet surface is encrypted (maximum size 2mm) in the meshing process to obtain more accurate flow field information.

4.1. Effect of Riblet Shape on Wind Drag Coefficient
Drag reduction rate \( k \) was used as the evaluation index of drag reduction effect.

\[
k = \frac{C_{d_a} - C_{d_b}}{C_{d_b}}
\]

where \( C_{d_a} \) is the aerodynamic drag coefficient of smooth vehicle body, and \( C_{d_b} \) is the aerodynamic drag coefficient of non-smooth vehicle body.

From table 5, it can be seen that the non-smooth riblet structure at the tail of the MIRA stepped-back vehicle model can effectively reduce the wind drag coefficient of the vehicle, and the circular riblet has the most obvious drag reduction effect.

| Shape     | Drag coefficient | \( k \) |
|-----------|------------------|--------|
| Triangular| 0.3119           | 4.24%  |
| Circular  | 0.3077           | 5.53%  |
| Rectangular| 0.3099          | 4.85%  |

4.2. Effect of Riblet Shape on Wake Flow
It can be seen from figure 4 that after the non-smooth riblet elements are arranged at the tail of the MIRA model, the shape of the wake flow becomes narrow and the center of the wake vortex is farther from the tail. It indicates that the tail of the vehicle is less affected by the low-pressure region of the wake flow after the non-smooth riblet elements are arranged, and the effect of differential pressure drag is reduced.

![Figure 4. Wake flow field maps of longitudinal symmetry plane.](image)
4.3. Effect of Riblet Shape on Pressure

The pressure drag accounts for about 50\%~60\% of the total aerodynamic drag of the vehicle. To reduce the pressure drag, the positive pressure area at the front of the vehicle and the negative pressure area at the tail of the vehicle should be reduced [10]. This paper mainly focuses on the influence of the riblet shape of non-smooth surface on the vehicle tail on the aerodynamic characteristics of the vehicle. Therefore, the pressure distribution in the front area of each model is the same, and the pressure drag of the vehicle is determined in the tail wake flow region.

It can be seen from figure 5 that the negative pressure region of the vehicle tail was reduced after the non-smooth riblet element was arranged at the tail. It indicates that the pressure at the tail of the model was increased, and the pressure drag was reduced. It also can be seen from figure 5 that the surface of the circular riblet have the most obvious influence on the pressure drag.

![Figure 5. Pressure maps of longitudinal symmetry plane.](image)

(a) Smooth model  (b) Triangular riblet  (c) Circular riblet  (d) Rectangular riblet

4.4. Effect of Riblet Shape on Turbulent Kinetic Energy

Figure 6 shows the comparison of turbulent kinetic energy in the 400mm plane at the rear of each model. As shown in figure 6, the turbulent kinetic energy in the tail region of the model can be effectively reduced by adding non-smooth riblet elements in the vehicle tail. The smaller the turbulent kinetic energy is, the less energy will be dissipated when the air flows over the vehicle surface. The circular riblet element has the best effect among several shapes.

![Figure 6. Cloud of turbulent kinetic energy.](image)

(a) Smooth model  (b) Triangular riblet  (c) Circular riblet  (d) Rectangular riblet

5. Equations and Mathematics

In this paper, the computational fluid dynamics method was used to evaluate the influence of riblet shape on the aerodynamic characteristics of the vehicle body. The main conclusions, which can be drawn from the conducted simulations, are as follows:

1) By adding non-smooth riblet elements on the vehicle tail, the aerodynamic drag of the vehicle can be reduced significantly. The circular riblet has the largest amount of drag reduction, which is up to 5.53\%.

2) Three kinds of riblet shape can effectively reduce the negative pressure at the vehicle tail, and reduce the pressure drag, turbulent kinetic energy and energy dissipation.
In this paper, non-smooth riblet element surface is only arranged on the vehicle tail, and no other surface is involved. At the same time, the relationship between the geometry of non-smooth riblet and the aerodynamic drag reduction of the vehicle body needs to be further studied.

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