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A method for testing drag-reduction on riblet surfaces based on the Spalding formula

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Abstract: This paper presents a method based on the Spalding formula for testing drag-reduction on riblet surfaces. Its advantage lies in that it is more convenient and yields more precise data compared with testing methods using instruments such as a scale. With this method, data is obtained from the velocity distribution within the inner layer, nearest the riblet surface. Precision of measurement of the velocity distribution is the key factor affecting the precision of the testing.
Keywords: Spalding formula; riblet surface; drag-reduction testing
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1 Introduction

Research of drag-reduction method about riblet surface has been developed for more than 40 years and the most explicit way to evaluate the effect is to compare the wall friction stress of riblet and smooth surface. However, how to measure the wall friction stress exactly is a topic which many experts do research on[1,2]. There are several general ways of measuring the wall friction stress such as the method of direct scale dynamometry, Stanton pipe, Preston pipe, the method of bottom clapboard and so on, the complexity of manipulating is a common defect of those ways since all of those may disrupt the flow field of surface more or less so that the authenticity, reliability and accuracy of testing may be affected.

After fitting the data of time-averaged velocity distribution by law of the wall formula of boundary layer, several parameters, for example, wall friction velocity can be obtained, so does the wall friction stress. At present, some formulas have been approved by testing, for instance, the Spalding formula, the Logarithmic Law and viscous sublayer formula and so on. Then for nearly thirty years, flow field measurement with no disturbance or little has been achieved by the popular application of Hot-wire Anemometry (HWA), Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV), which provide accurate data base for implementing the method.

Whereas, the method based on Logarithmic Law formula requires that the selected data must lie in logarithmic region[3]. For one thing, the involved data are finite, for another, the region limit is hard to be confirmed. The method based on viscous sublayer formula demands that the selected data must lie in viscous sublayer region which is very close to the wall, and it may generate several major residual, since the region is hard to measure exactly. Making use of Spalding formula will be right as long as the data lie in the inner layer, whose depth is one-fifth of the boundary layer's, consequently, the region limit is easy to be confirmed. This paper will introduce a way of drag-reduction testing method about riblet surface based on Spalding formula.

2 Drag-reduction testing method about riblet surface based on Spalding formula

2.1 Spalding formula

Spalding formula was presented by Spalding in 1961 and it had already been approved by experiment. Spalding formula represents the distribution of dimensionless time-averaged velocity, which could be applied in the inner layer of the turbulent boundary layer and defined as follows[4]:

$$y^+ = u^+ + \exp(-\kappa B)[\exp(\kappa u^+) - 1 - \kappa u^+ - \frac{(\kappa u^+)^2}{2} - \frac{(\kappa u^+)^3}{6}] \tag{1}$$

wherein,

$$y^+ = \frac{y u_\tau}{\nu} \tag{2}$$

$$u^+ = \frac{u}{u_\tau} \tag{3}$$

κ is called Karman constant which has very close relationship with the testing conditions; B represents integral constant; u_τ represents the wall friction velocity and it is measured by the unit m/s; y represents the vertical distance from the wall and it is measured by the unit m; y^+ stands for the dimensionless height from the wall; u stands for the local time-averaged velocity and it is measured by the unit m/s, u^+ stands for the

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dimensionless velocity; ν stands for the kinematic coefficient of viscosity of flow media and it is measured by the unit m^2/s.

Virtual origin is an important parameter of the riblet surface, to reflect its importance in the Spalding formula, formula (2) is modified to

$$y^+ = \frac{(y+y_0)\ u_\tau}{\nu} \tag{4}$$

Supposed y_0 is the position of virtual origin, for smooth surface, y_0=0.

2.2 The basic principle of the method

The connection between the wall friction stress τ and the wall friction velocity u_τ is represented as[5]

$$\tau = \rho (u_\tau)^2 \tag{5}$$

Consequently, after acquiring the wall friction velocity u_τ of smooth surface and that of riblet surface separately, the wall friction stress can be received respectively, sequentially, the drag reduction quantity of the riblet surface will be received.

The testing could survey the velocity values of different heights in the direction of vertical wall in certain position of flow field. (y_1,u_1), (y_2,u_2),… (y_n,u_n) is a set of some discrete points. Fitting the set with least square method utilizing the Spalding formula, then the values of all the parameters will be got. The specific method is as follows:

Firstly, the error function is defined as

$$f(y,u) = \lg(u^+ + \exp(-\kappa B)[\exp(\kappa u^+) - 1 - \kappa u^+ - \frac{(\kappa u^+)^2}{2} - \frac{(\kappa u^+)^3}{6}]) - \lg(y^+) \tag{6}$$

κ, B, u_τ and y_0, which come from the Spalding formula, are independent variables. For these variables, take values successively by the fixed step length in the certain range partly, then program to calculate the values of $\sum_{i=1}^{n} f^2(y_i,u_i)$. Secondly, when the minimum value of $\sum_{i=1}^{n} f^2(y_i,u_i)$ is found, the expected values of κ, B, u_τ and y_0 will be received. In view of the general conditions, in the distribution testing of the turbulent wall velocity, there are more points nearby the wall which means the value of y is minor, moreover, the errors produced by those points will account for a little in total error. Thereby, to balance the error ratio generated by each point, logarithm is applied in the expression (6).

2.3 Confirm the value of *k*

The Karman constant κ has very close relationship with the test conditions such that if the test conditions keep unvarying, κ should be constant. Therefore, in the fitting method as said above, κ is a constant. Based on this condition, for a specific testing of drag-reduction about riblet surface, a way of confirming the value of κ is conceived as follows: Firstly, test the flow field of the smooth surface in a fixed place of the flow field, only changing the velocity values of wind and keeping other conditions unvarying, then survey the velocity distribution of vertical wall direction at diverse wind speeds. So, several groups of data can be obtained. Secondly, with regard to each group of data, after fitting them by the method which is presented in section 2.2, a series of $\kappa, \kappa_1, \kappa_2, \kappa_3$…can be acquired, these values of κ should be unanimous basically (the following application has approved this point), then average these values, a new value of κ can be received, which will be used in the testing as a Karman constant.

2.4 Drag-reduction testing method about riblet surface

When the value of κ has been fixed, fit the testing data about the distribution of velocity of smooth surface another time, wherein, κ is a constant, y_0=0, u_τ and y_0 are independent variables, B and u_τ are computed by iterating. Fit the testing data about the distribution of velocity of the riblet surface through the way proposed in section 2.2, wherein, κ is a constant, B, u_τ and y_0 are independent variables. Then values of B, u_τ and y_0 that belong to the riblet surface will be computed by iterating.

The wall friction stress of riblet surface and smooth surface will be obtained through the formula (5), then the drag-reduction quantity of the riblet surface will be acquired.The whole procedure is shown in Fig. 1.

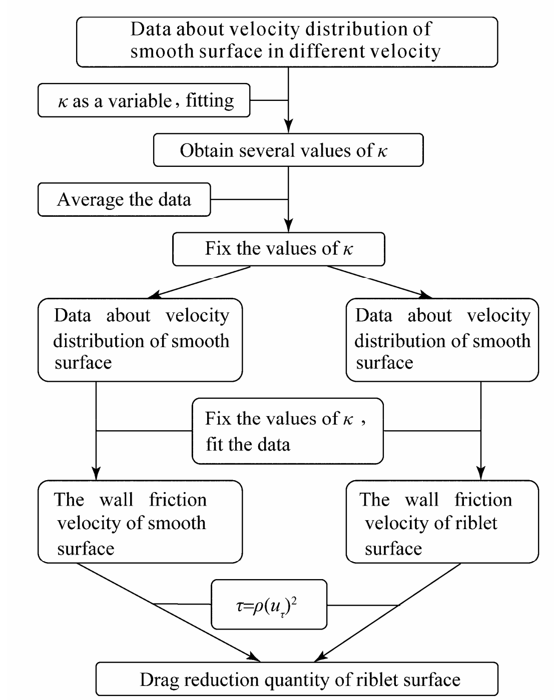

Fig.1 The procedure of the method

3 Applications

3.1 Experimental instrument and method

The testing has been done in small suction type low speed wind tunnel; the wind speed may vary between 0 m/s and 15 m/s successively. The distribution of the flow speed and statistics' average quantity in flow field could be surveyed by hot-wire anemometer in the experiment which was produced by TSI company. Smooth plate and five plates with symmetry V style riblet structure are the testing objects. The depth of riblet structure is represented by h and width denoted by s and the values of them are equal, that is $h/s=1$. The sizes of the five riblet structures are 0.5 mm, 0.65 mm, 0.8 mm, 0.9 mm and 1.0 mm respectively.

The velocity distributions of smooth surface and riblet surface are measured at the same position. The hot wire measuring position is selected on the center line of wind tunnel so as to reduce the boundary constraint influence as far as possible. The surveyed position is 300m far away from the leading end of testing plate represented as L_1 and 4300m far away from the leading end of wind tunnel development segment represented as L_2 (shown in Fig.2). The 32 points with unequal intervals between 0.3 mm and 50 mm (the center of wind tunnel) apart from the testing plate surface (top of riblet structure) are measured. The flow speeds are 4 m/s, 5 m/s and 6 m/s respectively in the experiment.

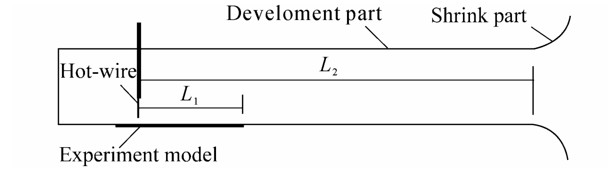

Fig.2 The survey position in the wind tunnel

3.2 Processing the experimental results

In the experiment, the velocity distribution of smooth surface at six different wind speeds is measured firstly. The wind speeds are 4 m/s, 4.5 m/s, 5 m/s, 5.5 m/s, 6 m/s, 7 m/s, respectively. Secondly, after fitting separately, the values of κ are acquired, which are 0.67, 0.63, 0.69, 0.65, 0.6 and 0.64 respectively. At last, average the data, the value of κ in the experiment is confirmed as 0.65. The received results utilizing the way as said above are shown in Table 1.

The dimensionless velocity distribution curves of each riblet surface and that of smooth surface at 4m/s wind speed are shown from Fig.3 to Fig.8 as well as the Spalding curves, so the comparison of the two kinds of curves can be seen directly. On the whole, the fitting effect is satisfying, therefore the accuracy of the method proposed in this paper is confirmed.

Table 1 Results of fitting the experimental data

Velocity /m·s^{-1}	Parameter	Smooth plate	Riblet structure sizes / mm				
			0.5	0.65	0.8	0.9	1.0
4	u_τ /m·s^{-1}	0.223	0.226	0.219	0.212	0.209	0.208
	B	6.64	6.87	7.4	7.89	8.44	7.87
	y_0 /mm	0	0.14	0.08	0.21	0.19	0.22
	drag reduction quantity / %	—	-2.71	3.56	9.62	12.16	13.00
5	u_τ /m·s^{-1}	0.296	0.29	0.279	0.275	0.276	0.27
	B	5.66	5.8	6.9	7.0	6.97	7.16
	y_0 /mm	0	0.1	0.08	0.2	0.07	0.17
	drag reduction quantity / %	—	4.01	11.16	13.69	13.05	16.8
6	u_τ /m·s^{-1}	0.327	0.315	0.305	0.303	0.32	0.33
	B	6.53	6.56	7.48	7.4	6.87	6.0
	y_0 /mm	0	0.07	0.1	0.29	0.01	0.13
	drag reduction quantity / %	—	7.2	13	14.14	4.23	-1.84

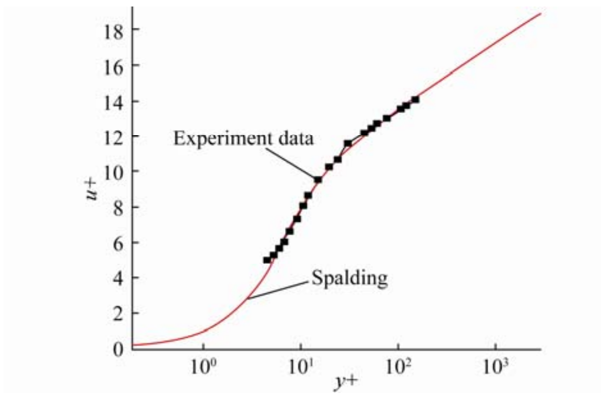

Fig.3 Velocity distribution of smooth surface at 4m/s

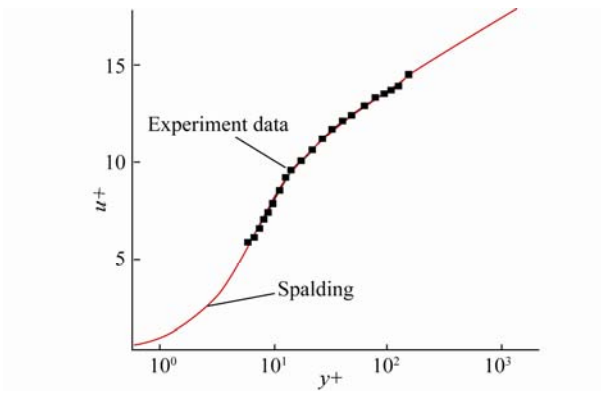

Fig.4 Velocity distribution of riblet surface at 4m/s (*s*=0.5mm)

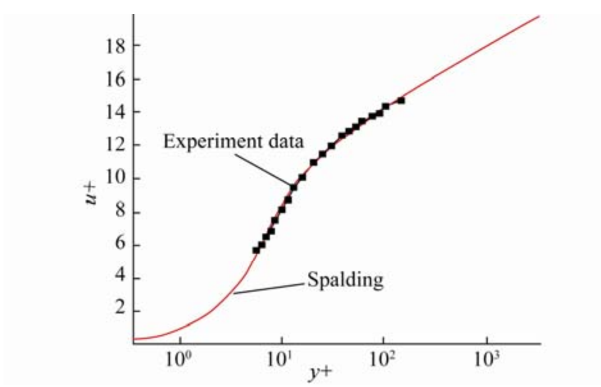

Fig.5 Velocity distribution of riblet surface at 4m/s (s=0.65mm)

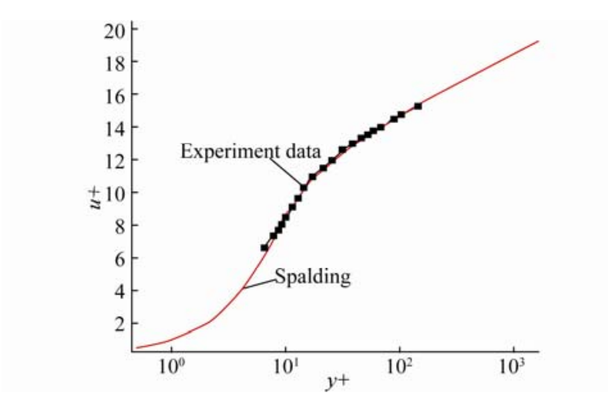

Fig.6 Velocity distribution of riblet surface at 4m/s (s=0.8mm)

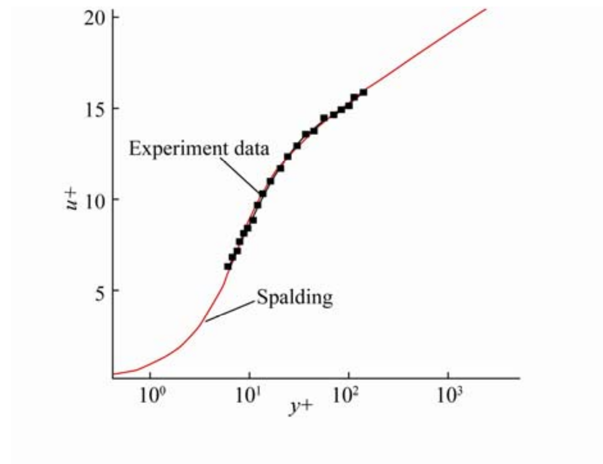

Fig.7 Velocity distribution of riblet surface at 4m/s (*s*=0.9mm)

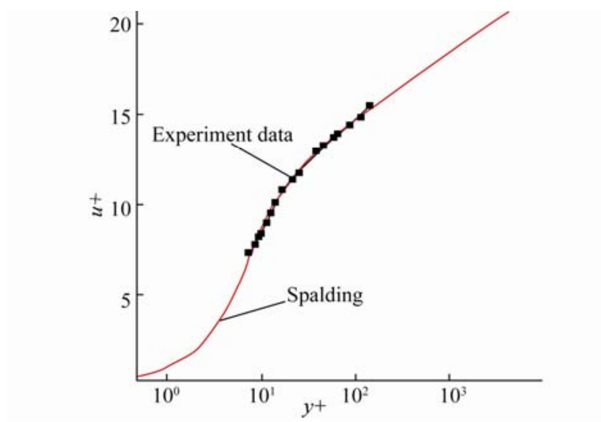

Fig.8 Velocity distribution of riblet surface at 4 m/s (*s*=1.0 mm)

According to the fitting results, the relationship between the dimensionless size of riblet structure and drag reduction quantity of that can be obtained, which is shown in Fig.9. It's clear in the figure that when the value of s^+ arrives at 15, the drag reduction effect is the best and the quantity of that can reach to 14%, which is identical with the conclusion of Walsh and other scholars.

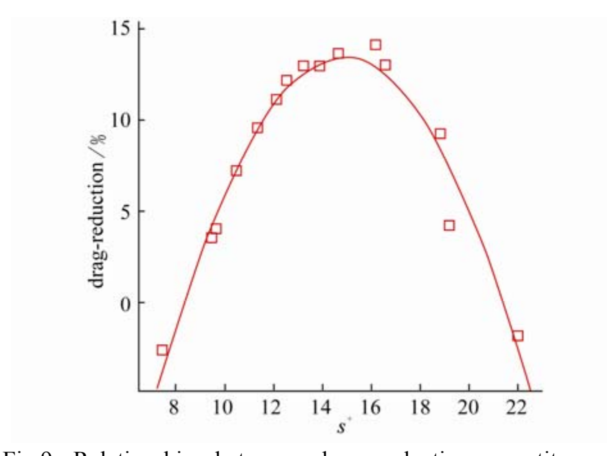

Fig.9 Relationship between drag reduction quantity and dimensionless size

4 Conclusions

This paper presents a new way of testing drag reduction of riblet surface, which only needs the velocity distribution of boundary layer. After fitting by Spalding formula, the wall friction stress can be obtained. Compared with the way of testing by other equipments such as scale, this method is simple, convenient and practical. In the fitting progress, a way of confirming the values of parameter κ is proposed and its better reliability has been proved in the example.

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基于 Spalding 公式的脊状表面减阻测试方法研究

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摘　要：介绍了一种基于 Spalding 公式拟合的脊状表面减阻测试方法，相比于用天平等测力设备测试的方法，其优点在于简便实用，从应用实例来看，准确性也是令人满意的. 由于该方法依靠的数据基础是壁面边界层内层速度分布，因此，速度分布测量的准确程度是影响该方法测试结果准确与否的决定因素.

关键词：Spalding 公式；脊状表面；减阻测试