

# Research of Boundary Layer Transition characteristics Induced by Three-Dimensional Discrete Roughness

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**Abstract:** Roughness strip is a necessary technology for wind tunnel experiment. In order to improve the accuracy and reliability of transition simulation, a new fixed transition technology based on the three-dimensional discrete roughness elements has been established. The configuration parameters of roughness elements are calculated theoretically and the formula and manufacturing processes of roughness elements are developed. Using two-dimensional airfoil and three-dimensional combination models, the transition and additional resistance characteristics of discrete roughness elements are studied. Finally, the scale effect of roughness elements is analyzed and the influence laws of height, diameter, and spacing on transition characteristics have been obtained through numerical calculation. The results of this study indicate that this new discrete roughness is better in transition and additional resistance performance than conventional grit roughness. The results obtained in this paper has created a more reliable and accurate fixed transition technology for wind tunnel experiment and provided some reference for cross-flow transition mechanism.

## 1 Introduction

The boundary layer fixed transition technology has an important significance on the accuracy of wind tunnel experiment results. However, in high dynamic experimental environment, roughness strip may be damaged or grit is blown off, which leads to the failure of the experiment consequentially. The thickness of adhesive and emery grit is not easy to be held, so the height of roughness strip cannot be precisely controlled. The selection of dimensions and installation position of roughness strip lacks scientific reference standards in different flow conditions.

Discrete roughness strip is a three-dimensional boundary layer transition technology. the ability to resist air impact of discrete roughness is higher than emery strip. Secondly, the discrete roughness may exert a three-dimensional perturbation on the boundary layer. In addition, dimensions of roughness elements can be precisely controlled by special mould.

Huang Yong<sup>1</sup> proved the feasibility of this new fixed transition technology. Li Yueli<sup>2</sup> explored the influence of roughness elements on the standing wave of 3D boundary layer. Li Yiming<sup>3</sup> and Juillen<sup>4</sup> found that single roughness element can promote transition by accelerating the T-S wave. Radeztsky's research<sup>5</sup> indicated that cross flow boundary layer transition is more sensitive to three dimensional roughness elements. Muller<sup>6</sup> confirmed that the surface roughness is the most effective means of exciting cross flow vortex. Researches of Deyhle<sup>7</sup> and Reibert<sup>8</sup> also indicated that roughness elements aligned horizontally can stimulate the cross flow wave of corresponding wavelength. Collis<sup>9</sup>

found that the increase of height of roughness elements can enhance the sensitivity of cross flow vortex. Robert's research<sup>10</sup> indicated that the effect of transition induction is more prominent when the Reynolds number enters the critical region. Nathaniel<sup>11</sup> discovered the influence of the distance between hemispherical roughness elements on the boundary layer flow. According to the Marxen's study<sup>12</sup>, blunt and sharp roughness elements can induce transition and the surface curvature has little effect on the transition characteristics. Chan<sup>13</sup> found convective instability disturbed by discrete roughness elements is the main reason for the transition of the supersonic boundary layer. As shown by Plogmann<sup>15</sup>, when the height of roughness elements is taken as 30% ~ 50% of boundary layer displacement thickness, transition effect is best.

## 2 Theoretical calculation of the height of roughness elements

The configuration parameters of roughness elements include height  $k$ , diameter  $d$ , spacing  $l$ , and  $k$  is a key factor to affect the boundary layer flow. According to the theory of boundary layer, height  $k$  should be greater than the critical height but less than boundary layer thickness. First of all, we need to calculate the height range of roughness elements. Height  $k$  is determined by Mach number  $Ma$ , Reynolds number  $Re$  and the installation position of roughness  $x$ . In this study, taking the NACA0012 airfoil and mid-wing combination as experimental models, the installation position is identified as 6% chord length from the leading

edge of the models. Theoretical calculation method is as follows:

Checking the literature NACA TN4363<sup>16</sup>, we know Reynolds number based on the critical height of roughness  $R_{k_c}$   $Re = 600$ . Reynolds number based on the position of roughness  $R_x$  can be obtained by formula (1).

$$R_x = \frac{\rho_\infty u_\infty x}{\mu_\infty} = \frac{u_\infty x}{\nu_\infty} \quad (1)$$

According to  $\frac{R_{k_c}}{\sqrt{R_x}}$  and  $Ma$ , we can find out the dimensionless height of roughness element  $\eta_k$  by the literature NACA TN4363 and the height of roughness elements can be obtained by formula (2).

$$k = \frac{2x\eta_k}{\sqrt{R_x}} \quad (2)$$

### 3 The formula and manufacturing processes of roughness elements

Ingredients of roughness elements are constituted by putty and hardener, and the mixture ratio is 50:1. This formula has the characteristics of fast curing, easy molding and strong adhesion. The high precision manufacturing of roughness elements is realized through the mould method. The way to make it is to put the ingredients into the taper hole on the mould which is pasted on the surface of the model. After the putty becomes stiff, the plastic mould is removed off and a series of roughness elements are formed on the surface of the test model. The mould is made by three-layers drilling technology. The three layers are composed of protective layer, mould layer and spacing layer. The protective layer is used to avoid the burrs on the edge of the hole and the cutting depth is controlled by the spacing layer. The finished mould is shown in Figures.3. The height, diameter and spacing of roughness elements can be controlled precisely by mould. According to the results of theoretical calculation, the thickness of the mould layer is designed as 0.1mm which is the height of roughness elements. The discrete roughness elements installed on the surface of model are shown in Figure 1.

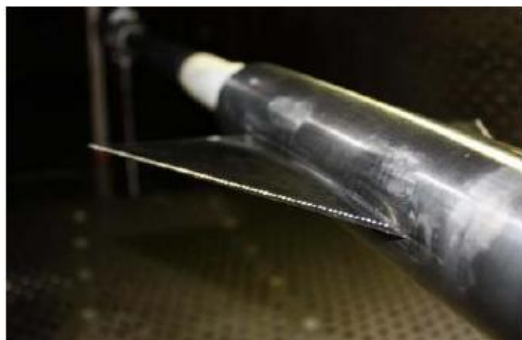


Figure 1. Discrete roughness elements installed on model

## 4 Experimental Results

The present study was carried out in NF-6 pressured continuous transonic wind tunnel at the Northwestern Polytechnical University, Xi'an, China. This tunnel has two test sections: one is 2D section with the size of 0.4m(width)×0.8m(height)×3m(length) and the other is 3D section with the size of 0.8m(width)×0.6m(height)×3m(length). The stagnation pressure and stagnation temperature of the tunnel air can be controlled from 1.0 to 5.5 bar and between 283 K and 323 K. The Mach number range is  $Ma = 0.3 \sim 1.2$ . The sublimation technique was used to visualize the location of laminar to turbulent boundary-layer transition on the model surface. Photographs were taken in real time from a camera through an optical window mounted on the ceiling wall of the test section. The height, diameter and spacing of roughness elements are 0.1mm, 1.2mm and 2.5mm respectively.

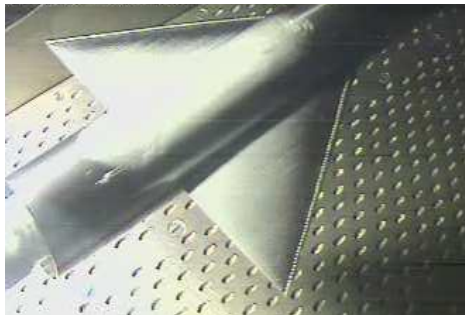
### 4.1 Transition characteristics

Figure 2 shows the naphthalene-film sublimation experiment result of the NACA0012 airfoil model at  $Ma = 0.80$ ,  $\alpha = 0^\circ$ ,  $Re = 3.0 \times 10^6$ . As the air flows, the elevated shear and temperature associated with high turbulence of the boundary layer at the location of transition cause the naphthalene to increase its rate of sublimation in the turbulent region with respect to that of the laminar region. Consequently, the naphthalene is removed in the turbulent area before the naphthalene in the laminar area is appreciably affected. Under the fixed transition, the white coating after the roughness strip immediately disappears leaving a dark band which spreads downstream towards the airfoil trailing edge, while under the free transition, a dark area across the airfoil span appears near the airfoil trailing edge. It is seen that the roughness elements have played a better role in promoting the boundary layer transition.

Figure 3 shows the naphthalene-film sublimation experiment result of the AGARD-B mode at  $Ma = 0.75$ ,  $\alpha = 0^\circ$ ,  $Re = 2.0 \times 10^6$ . Under the fixed transition, the white coating after the roughness strip immediately disappears, while under the free transition, a dark area across the wing span appears near the airfoil trailing edge with acute-angled dark band. It verifies that the roughness elements have a same transition excitation effect for 3D model.



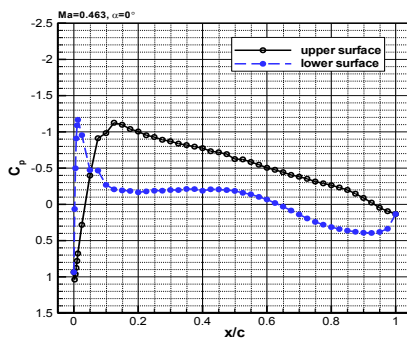
Figure 2. The naphthalene-film sublimation experiment result of NACA0012 airfoil mode,  $Ma = 0.80$ ,  $\alpha = 0^\circ$ ,  $Re = 3.0 \times 10^6$



**Figure 3.** The naphthalene-film sublimation experiment result of AGARD-B model,  $Ma = 0.75$ ,  $\alpha = 0^\circ$ ,  $Re = 2.0 \times 10^6$

### 4.2 Reliability verification in the high dynamic pressure condition

In order to verify the reliability of roughness elements under the high dynamic flow condition, verified experiment was performed through the using of total pressure regulating technology. The experiment model is a supercritical airfoil and the total pressure  $p_0$  is 2bar. Figures 4 and presents the surface pressure distribution the supercritical airfoil under high total pressures. It can be seen from the figures that the experimental curves are smooth and pressure distribution is reasonable under high total pressure flow condition. This illustrates that the property of roughness elements are stable and reliable and this transition technology can satisfy the requirement of pressured wind tunnel experiment.

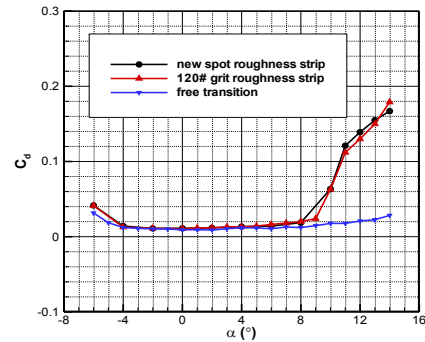


**Figure 4.** Pressure distributions of supercritical airfoil under high total pressures,  $p_0=2\text{bar}$

### 4.3 Additional resistance characteristics

Additional resistance is the key indicators of roughness strip. Figure 5 gives the resistance coefficients curves of 2D airfoil models under different transition patterns. The “new spot roughness strip” curve is the experimental result of discrete roughness elements and the “120# grit roughness strip” curve is the experimental result of 3mm wide 120# emery strip. The result shows a good agreement between the discrete elements and emery roughness strip and the additional resistance produced by the two transition patterns have the same magnitude. As shown in Figure 5, in the angle of attack from  $-4^\circ$  to  $9^\circ$ , the resistance of free and fixed transition are basically identical, suggesting that in the range of small angle of attack, additional resistance produced by roughness strip can be ignored. But at an angle of attack greater than  $10^\circ$ , resistance of fixed transition

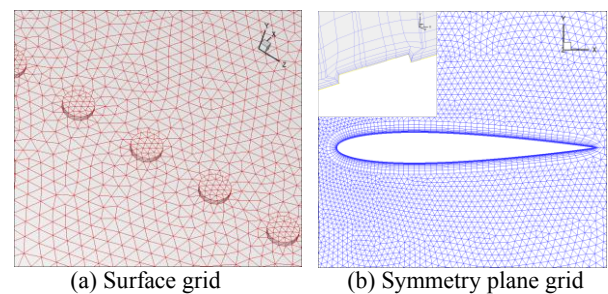
patterns increases significantly and, consequently, the additional resistance need to be subtracted from the total resistance.



**Figure 5.** Resistance coefficients curves of supercritical airfoil models under different transition patterns

## 5 Scale effect of roughness elements

Roughness elements’ height  $k$  diameter  $d$ , and the spacing  $l$  (the distance between the neighboring elements), is the key parameters affecting the transition characteristics. Taking 3D NACA0012 straight wing, with a chord length of 200mm and aspect ratio of 0.5, as the calculating model, the influence of configuration parameters of roughness elements on the transition characteristics was investigated through the numerical simulation method. By using the  $\gamma-\bar{Re}_\theta$  transition model, according to surface friction drag distribution, the transition position has been predicted successfully. Computational grids are composed of prism boundary layer grid and tetrahedral spatial grid, and the height of first boundary layer grid is 10-5m, as shown in Figure 6. Calculation parameters are as follows:  $Ma = 0.6$ ,  $\alpha = 2^\circ$ ,  $Re = 2.74 \times 10^6$ .



**Figure 6.** Computational grids of discrete roughness elements fixed transition model

### 5.1 Influence of height $k$ on the transition characteristics

The roughness elements height  $k$  is chosen to be 0.08mm、0.1mm、0.12mm、0.16mm、0.2mm, and diameter  $d$  of 1mm and spacing  $l$  of 2.5mm remain constant. Roughness elements are mounted on the upper surface of the wing from the leading edge of 6% chord and there is no roughness element on the lower surface. Figure 7 shows the calculation results of  $k = 0.1\text{mm}$ . It can be seen that the position of the skin friction drag increasing suddenly on the upper surface

is more close to the leading edge, which indicates that the transition position is moved forward under the action of roughness elements. Calculation results of other four cases also show a similar tendency. Figure 8 presents the transition position variation with roughness elements height. With the increase of height, transition position is moved to the leading edge of the wing. Near the  $k = 0.1$  mm, transition position is very sensitive to the height. But when  $k$  is greater than 0.15 mm, the transition position are not easy to be changed by adjusting the roughness elements height.

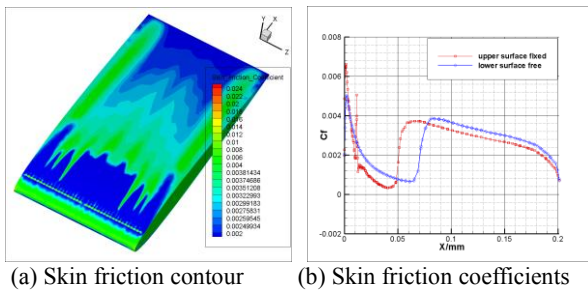


Figure 7. Calculation results of  $k = 0.1$  mm,  $d=1$  mm,  $l=2.5$  mm

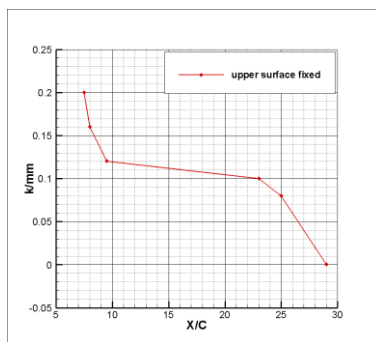


Figure 8. Transition position vs roughness elements height

### 5.2 Influence of diameter $d$ on the transition characteristics

The roughness elements diameter  $d$  is chosen to be 1mm, 1.2mm, 1.5mm, 2mm, and height  $k$  of 0.1mm and spacing  $l$  of 2.5mm remain constant. Roughness elements are mounted on the upper surface of the wing from the leading edge of 6% chord and there is no roughness element on the lower surface. Figure 9 shows the calculation results of  $d = 1.5$ mm. It can be seen that the position of the skin friction drag increasing suddenly on the upper surface is more close to the leading edge, which indicates that the transition position is moved forward under the action of roughness elements. Calculation results of other three cases also show a similar tendency. Figure 10 presents the transition position variation with roughness elements diameter. With the increase of diameter, transition position is moved to the leading edge of the wing. Furthermore, a linear correlation has been found between the transition position and roughness elements diameter.

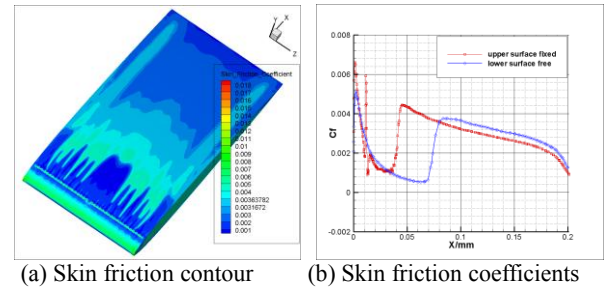


Figure 9. Calculation results of  $k = 0.1$  mm,  $d=1.5$  mm,  $l=2.5$  mm

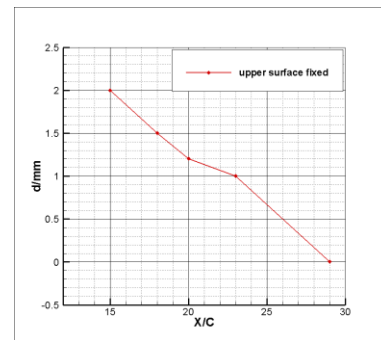


Figure 10. Transition position vs roughness elements diameter

### 5.3 Influence of spacing $l$ on the transition characteristics

The roughness elements spacing  $l$  is chosen to be 2mm, 2.5mm, 3.5mm, 5mm, and height  $k$  of 0.1mm and diameter  $d$  of 1mm remain constant. Roughness elements are mounted on the upper surface of the wing from the leading edge of 6% chord and there is no roughness element on the lower surface. Figure 11 shows the calculation results of  $l=3.5$ mm. It can be seen that the position of the skin friction drag increasing suddenly on the upper surface is more close to the leading edge, which indicates that the transition position is moved forward under the action of roughness elements. However, when the spacing increases to 5mm, the transition position has moved in opposite directions. Figure 12 presents the transition position variation with roughness elements spacing. With the increase of spacing, transition position is moved to the trailing edge of the wing. When  $l$  is greater than 5 mm, roughness elements will not be able to induce the transition. So the roughness elements spacing should be carefully selected.

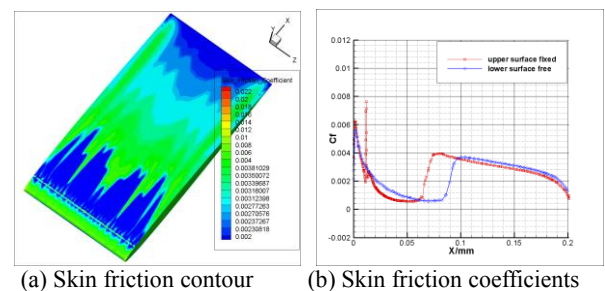
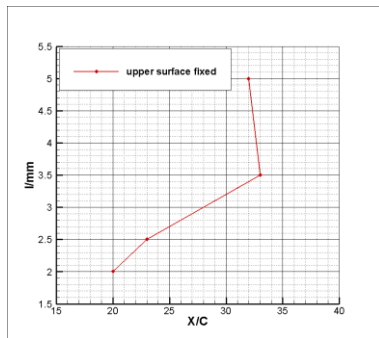


Figure 11. Calculation results of  $k = 0.1$  mm,  $d=1.5$  mm,  $l=3.5$  mm



**Figure 12.** Transition position vs roughness elements spacing

## 5. Conclusion

In this paper we have reported the study of the boundary layer transition technology based on the three-dimensional discrete roughness elements. The fast curing, easy molding and strong adhesion formula and manufacturing processes of roughness elements have been developed. The configuration parameters of roughness elements were calculated and the height range was determined. The main conclusion can be drawn as follows:

- 1) The roughness elements can play a better role in the boundary layer transition for 2D and 3D wind tunnel experiment model and will not damage the inherent aerodynamic characteristics of models.
- 2) The property of roughness elements is stable and reliable in the high dynamic pressure condition and this transition technology can satisfy the requirement of pressured wind tunnel experiment.
- 3) In the range of small angle of attack, the additional resistance of roughness elements is very small and can be ignored.
- 4) With the increase of height  $k$  and diameter  $d$  of roughness elements, transition position is moved to the leading edge of the wing, but spacing  $l$  presents a contrary tendency. When  $l$  is greater than 5 mm, roughness elements will not be able to induce transition.

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## References

1. Y. Huang, F. Qian, K Yu, and et.al. Experimental Investigation on Boundary-layer Artificial Transition Based on Transonic Trip Disk. *Journal of Experiments in Fluid Mechanics (In Chinese)*, Vol. **20**, No. 3, pp. 59~62. (2006).

2. Y. Li, D. Li, Y. Yang, and et.al. Study on the Swept Wing Crossflow Stationary Wave and Its Harmonics. *Journal of Experiments in Fluid Mechanics (In Chinese)*, Vol. **24**, No. 3, pp. 25~28.(2006),
3. Y. Li, D. Yan. An Experimental Investigation on the Effect of Single Two-Dimensional Roughness Elements on Boundary-Layer Transition. *Journal of Peking University (In Chinese)*, Vol.**41**, No.1, pp.71~75(2005)
4. J. C. Juillen, D. Arnal. Experimental and Theoretical Study of Transition Phenomena on an Infinite Swept Wing[R].Rapp.Final No.51/5018, **5** , CERT/ONERA, Toulouse(1990)
5. R. H. Radeztsky Jr, M. S. Reibert, W. S. Saric. Development of Stationary Crossflow Vortices on a Swept Wing [R]. AIAA 2373(1994)
6. B. Muller, H. Bippes. Experimental Study of Instability Modes in a Three-dimensional Boundary Layer. In: Proc AGARD Symp On Fluid Dynamics of Three-Dimensional Turbulent Shear Flows and Transition[R]. Cesme, Turkey,AGARD C-P 438(1988).
7. H. Deyhle, H. Bippes. Disturbance Growth in an Unstable Three-dimensional Boundary-layer and Its Dependence on Environmental Conditions[J]. *Journal of Fluid Mechanics* , 316: 73-113(1996)
8. M. S. Reibert. Nonlinear Stability Saturation, and Transition in Crossflow-dominated Boundary layer[D]. USA: Arizona State University(1996)
9. S. S. Collis, S. K. Lele. Receptivity to Surface Roughness Near a Swept Leading Edge. *Journal of Fluid Mechanics*,, 380: 141-168( 1999)
10. S. Robert, Downs III, B. Edward, White, A.Nicholas. Denissen. Transient Growth and Transition Induced by Random Distributed Roughness[J].*AIAA Journal*, 46(2):451~462(2008)
11. D.Nathaniel ,Varano, L. Roger, Simpson. Structure of Turbulent Boundary Layers and Surface Pressure Fluctuations with Sparse Roughness[R].AIAA 700, (2010)
12. Olaf Marxen, Gianluca Iaccarino. Numerical simulation of the effect of a roughness element on high-speed boundary-layer instability[R]. AIAA 4400( 2008)
13. Chau Lyan Chang, Meelan M. Choudhari. Hypersonic Viscous Flow over Large Roughness Elements[R]. AIAA 0173 (2009).
14. B. Plogmann, W. Wuurz, E. Kruamer. Interaction of a Laminar Boundary Layer with a Cylindrical Roughness Element near an Airfoil Leading Edge[R]. AIA-3077( 2012)
15. A. Braslow, E.Knox, Simplified Method for Determination of Critical Height of Distributed Roughness Particles for Boundary-Layer Transition at Mach Numbers from 0 to 5. NACA TN 4363, 82~83(1958)