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EFFECTS OF REYNOLDS NUMBERS ON STATIC CHARACTERISTICS OF AERODYNAMICS OF A SLENDER CONE

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Abstract

An experimental study has been performed to investigate the effects of Reynolds number variation on aerodynamic characteristics of slender cones, expecially on the stability of the cones.The experiments were conducted at Mach number 5, 6, 7 in two hypersonic wind tunels of Beijing Institute of Aerodynamics (BIA). The models with smooth surface are two sharp cones with 10 degree and 11 degree half-angle respectively. The Reynolds numbers vary over the region of 1.5×10^6 to 8.0×10^6 based on the length of models and varied region of the angles of attack is from 0 degree to 10 degree.An artificial transition with a roughness strip for comparison has been also conducted at Mach number 5 and Reynolds number 3.4×10^6 . The results indicate that the variation of Reynolds number and the position of boundary layer transition influnce the aerodynamic characteristics of a slender cone distinctly. The main conclusion is that the location of centre of pressure at zero degree angle of attack, compared with theoretical prediction, moves forward regularly when the boundary layer transition occurs on afterbody of cones at a certain region of Reynolds numbers, i.e, static stability decreases. The location of center of pressure varies with angles of attack as well. However, it is no longer a function of an angle of attack when the angle is larger than a critical value, and reaches to the value of Newtonian theory. The results also indicate that the effect is negligible when full laminar flow occurs on the surface of a cone or turbulent flow does on most of a cone surface. Newtonian theory should be used carefully because viscosity of flow is not considered, and then, the effect of variation of Reynolds number on aerodynamic characteristics is concealed in the theory.

I. Introduction

Investigation on boondary layer transition is important for designing of a vehicle. The variation of status and transition location of boundary layer influnces not only heat transfer on a body surface, skin friction, sensitivity of boundary layer separation etc., but also the stability of vehicles distinctly. It is known that there are many parameters influncing boundary layer transition, such as Reynolds numbers, Mach numbers, angles of attack, surface roughness, nose bluntness, turbulent level of flow, environmental noise and so on. Among them, Reynolds number is a principle parameter for controling boundary layer characteristics. Therefore, it is necessary and important to investigate the effect of Renolds numbers associated with boundary layer transition. At present, it seems that experimental investigation is still an important method to get reliable results on viscous effects in the field of aerodynamics because there are many difficulties for theoretical calculation to investigate the viscous effects. This paper will specially discuss the effects of boundary layer transition on static aerodynamic characteristics of vehicles while the references [1] , [2] have investigated the effects on the characteristics.

II. Experimental programme

A sharp cone model is often taken as a basic measuring standard in aerodynamic experiments in order to examine the reliability of experimental data for a hypersonic wind tunnel. It is found that there is discrepancy between experimental data and theoretical prediction obtained using Newtonian theory sometimes. The discrepancies are believed to be attributed to the effect of Reynolds number which is not considered in Newtonian theory. To investigate the effect systematically, a series of tests of measuring aerodynamic force for sharp cones with 10 and 11 degree half-angle was performed at various Reynolds numbers by varying stagnation pressures.

The experiments were conducted in hypersonic tunnel No.2 and No.3 of Beijing Institute of Aerodynamics (BIA). Both of them are open jet, intermittent blowdown facilities. The test section is 200x200mm for Tunnel No.2 and 170x170mm for Tunnel No3.

The models were fabricated of stainless steel with smooth surface. A 10 degree half-angle cone with base diameter of 50mm was tested at Mach number 5 and 7 in the Tunnel No3. The Reynolds number based on the model length varied over the region of 2.0 to 6.2×10^6 at Mach number 5 and 1.5 to 3.9×10^6 at Mach number 7. The angles of attack were varied from 0 degree to 6 degree. A 11 degree half-angle cone with a base diameter of 55mm was tested at Mach number 5 and 6 in the Tunnel No.2 The Reynolds number based on the model length varied over the region of 2.8 to $8.0x10^6$. The angles of attack were varied from 0 degree to 10 degree.

For comparison, an artificial transition with a roughness strip on the model has been also conducted for the 10 degree half-angle cone at Mach number 5 and Reynolds number $3.4x10^6$ to examine the effects of the position of boundary layer transition. The roughness strip on the cone surface is a circlet with the wideth of 5mm and located at 13mm from the nose-tip. The roughness elements were constructed by small plastic balls with diameters of 0.3 to 0.4mm. The experimental results exhibit that the aerodynamic chracteristics of cones are rather sensitive to the position of boundary layer transition.

The experimental conditions are shown in Table 1.

Table 1 The Experimental Conditions

Models	M	$Rex10^{-6}$	α
10 degree cone	5	2.0--6.2	0°—6°
	7	1.5--3.9	
11 degree cone	5	3.0--8.0	0°—10°
	6	2.8--7.7	

The experimental conditions were kept the same at a certain Mach number for each run except varying stational pressures. Therefore, it is likely that the variation of the aerodynamic coefficients is only influnced by the variation of Reynolds number.

III. Results and Discussions

The trend of variation of the derivation of normal force coefficient and longitudinal moment coeffigient at zero degree angle of attack C_n^α C_m^α and the coefficient of centre of pressure Xcp at zero degree angle of attack with variation of Reynolds numbers is illustrated in Fig. 1 to Fig. 4. The trend of variation of these coefficients with angles of attack and Mach numbers is also illustrated in these figures and compared with the theoretical value obtained using Newtonian theory.

According to Newtonian theory, for a sharp cone,

$$Cn=COS^2\theta * SIN2\alpha , \quad Xcp=2/3(1+tg^2\theta)$$

Where θ is a half-angle of a cone and α is an angle of attack.

As known, the theoretical values do not vary with the variation of Reynolds number because viscosity is not considered in Newtonian theory. The experimental results, however, indicate that the coefficient C_n^α and Xcp at zero degree angle of attack vary distinctly in a certain region of Reynolds numbers when boundary layer transition occurs on the afterkbody of a cone. For example, for a 10 degree cone, compared with the theoretical value, the coefficient of C_n^α decreases and the location of centre of pressure moves forward up to the order of 2 per cent of the model length at M=5, Re= $(2.0-4.0)\ x10^6$ (Fig.3a). The experimental results for 11 degree cone show the similar trend. As shown in Fig.3b, the location of centre of pressure of the cone moves forward up to 1.8 per cent of the model length.

Now, the experimental results about the viscous effect of Reynolds numbers on static characteristics of aerodynamics of a slender cone are summarised as follows. A 10 degree cone is taken as an example.

1. Variation of the aerodynamic coefficients with Reynolds numbers

As illustrated in Fig. 1 to Fig.3, the coefficients of Cn, Cm and Xcp vary regularly with varied Reynolds numbers. For example, the coefficient C_n^α, C_m^α decrease and the location of the centre of pressure moves forward at M=5, $Re \leqslant 4x10^6$ .Compared with the theoretical prediction, the maximum movement of the location of centre of pressure is up to the order of 2 per cent of the model length at Reynolds number $2.7x10^6$. The location moves slightly backward while Reynolds number is a little larger than $4x10^6$ and then, it gradually agrees with the value of inviscid theory with increasing Reynolds number.

The aerodynamic characteristics are attributed to unsymmetrical transition on the model surface. There is an induced normal force on the cone, the direction of which is opposite to the main normal force when unsymmetrical transition occurs between windward and leeward on the cone surface. According to the experimental result of oil-visualization for a 10 degree cone at the Tunnel No. 2, the onset of the transition on the cone surface is located at 60 per cent of model length (from the tip of the cone) at Mach number 5 and Reynolds number $4x10^6$ [3]. That is the boundary layer transition occurs on the afterbody of the cone. An induced normal force produced by unsymmetrical transition gives the model an destabilizing additional longitudinal moment. And, the effect of unsymmetricity is large because the area of the afterbody surface of a cone is large. Therefore, the variation of values of C_n^α, C_m^α, Xcp is distinct as illustrated in Fig.1, 2, 3a, where M = 5, $Re \leqslant 4x10^6$ and M=7, $Re > 2.1x10^6$. While the

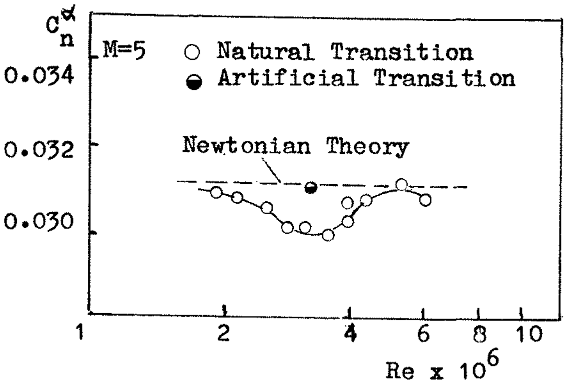


Figure 1. Variation of the Derivation of Normal Force Coefficient with Reynolds Numbers

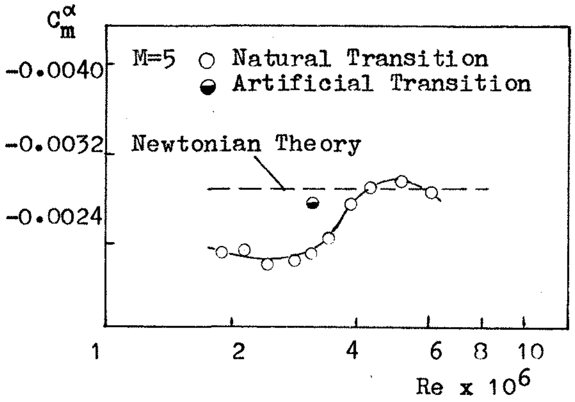
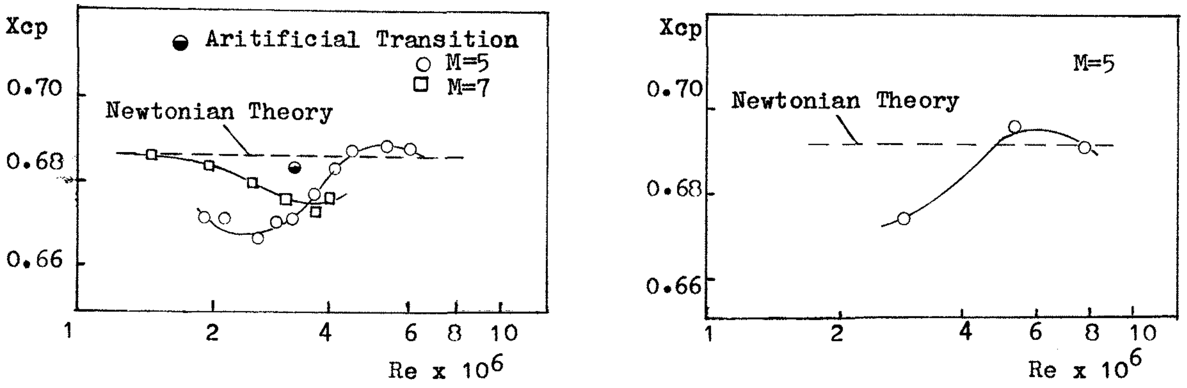


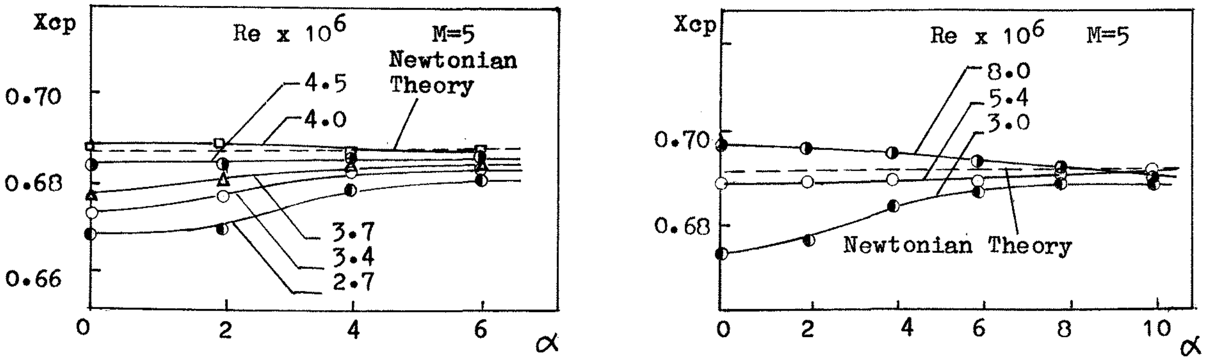
Figure 2. Variation of the Derivation of Longitudinal Moment Coefficient with Reynolds Numbers



a. 10° Cone

b. 11° Cone

Figure 3. Variation of the Center of Pressure with Reynolds Numbers



a. 10° Cone

b. 11° Cone

Figure 4. Variation of the Center of Pressure with Angles of Attack

location of boundary layer transition moves forward to the forebody with increasing Reynolds number, the additional moment increases the stability of the model. However, the varied amount of C_n^α and Xcp is small because the surface area of the forebody is small, and, the effect induced by unsymmetric transition is small as well.

The experimental results also indicate that the effect of boundary layer transition on static stability of a cone is negligible when there is turbulent flow on most surface of the model and the coefficients of C_n^α, Xcp are in good agreement with the theoretical value obtained using Newtonian theory which is illustrated in Fig. 1 where M=5 and Re $>6x10^6$. For this experimental condition, the oil-visualization results [3] indicate that the transition onest of a 10 degree cone locates on about 40 per cent of the model length i.e. on the forebody of the model.

The experimental results with an artificial transition at Mach number 5 and Reynolds number $3.4x10^6$ have proved the effect of position of boundary layer transition on aerodynamic characteristics of slender cones (Fig.1,2,3). As mentioned above, the transition strip is located on the surface of 10 percent of the model length which made turbulent flow occur on most of the model surface. On the other hand, the experimental result of the oil-visualization indicates that the onset of natural transition locates on about 70 per cent of the model length for a 10 degree cone with smooth surface under the same experimental condition. The present results show that there are distinct differences between aerodynamic characteristics of artificial and natural transition. For the former, where turbulent flow occupied most of the cone surface with artificial transition, the values of C_n^α and Xcp agree with the value obtained using Newtonian theory. But for the later, where the position of transition locates on the afterbody surface of the cone, the values of C_n^α and Xcp are 3.3 per cent and 2.2 per cent less than the theoretical value respectively. It means that the stability of cones is influnsed distinctly. It is shown in Table 2.

Table 2 Comparison of Aerodynamic Characteristics Between Natural and Artificial Transition

	10 degree cone	M=5	Re=$3.4x10^6$	$\alpha=0^0$	
	Natural transition (A)	Artificial transition (B)	The value of Newtonian theory (C)	$\frac{(A-C)}{C}$	$\frac{(B-C)}{C}$
C_n^α	0.0321	0.0332	0.0332	-3.3%	0
Xcp	0.672	0.684	0.687	-2.2%	-0.4%

2. Variation of the aerodynamic coefficients with the angles of attack

As illustrated in Fig.4, the effect of Reynolds number variation on the stability of cones at different region of angles of attack is distinct. It is that the experimental value of Xcp near zero degree angle of attack is less than the theoretical value obtained using Newtonian theory over the region of certain Reynolds numbers. For example, the location of centre of pressure moves forward 1 to 1.5 per cent of the model length in the region of angles of attack from zero degree to 4 degree when M=5, Re=$3.4x10^6$ for natural transition of boundary layer.

Ericsson 2 collected experimental data about the characteristics of boundary layer transition for sharp cones and indicated that the variation of position of boundary layer transition is sensitive to an angle of attack. The data show that for a 10 degree cone, the onset on the leeward surface might move forward 50 per cent of the model length when the angles of attack varied from 0 degree to 2 degree at Reynolds number of $8x10^6$. Meanwhile, the onset moved backward on the windface surface, i.e., there is an unsymmetrical transition on the body. Thereforce, the values of C_n^α and Xcp vary distinctly in the region of small angles of attack.

With increasing of an angle of attack, the transition onset on the cone varies continually and the effect of induced moment decreases relatively, so the variation of the value of Xcp decreases as well. The effect is negligible when the angle of attack reaches over a critical value even though the onset of boundary layer transition moves to forebody of the cone where induced moment takes part to increase stability of the cone, because its value is relatively very small compared with main moment of the cone. At that case, the value of Xcp is no longer a function of an angle of attack and gradually agrees with theoretical value for inviscid flow. The trend of variation of centre of pressure with an angle of attack is illustrated in Fig. 4 where Re=3.4x10^{6} and 3.7x10^{6} for a 10 degree cone and Re=3.0x10^{6} for a 11 degree cone. The experimental results also indicate that the critical value of an angle of attack decreases with Reynolds number increasing, as shown in Fig.4a where Re= (2.7-3.7)x10^{6}.

3. Variation of the aerodynamic coefficients with Mach numbers

As mentioned above, the experiments at Mach numbers 5 and 7 with various Reynolds numbers for a 10 degree cone were carried out in the same wind tunnel. As shown in Fig. 3a, the location of centre of pressure does not move forward regularly until Re>2.0x 10^{6} for M=7 where the trend is in good agreement with that for M=5. In other words, the coefficient of the centre of pressure still agrees with the theoretical prediction of Newtonian theory when Re$\leq$2.0x10^{6} at M=7. It is likely that the critical Reynolds number of boundary layer transition for the former is larger than that for the later. This conclusion is agreeable to the trend of variation of transition Reynolds number with Mach number which is given by literatures.

IV Conclusions

1. The effect of variation of Reynolds number associated with asymmetric transition on aerodynamic characteristics of a slender cone is distinct. Induced moment produced by induced normal force takes different part in variation of stability of a cone when the position of boundary layer transition changes with variation of Reynolds numbers. It mainly seems that location of centre of pressure of a cone moves forward and the stability decreases when the boundary layer transition occurs on afterbody of the cone for certain Reynolds numbers. For example, compared with the theoretical prediction of Newtonian theory, the location of centre of pressure may move forward up to the order of 2 per cent of the model length at Mack number 5 and zero degree angle of attack.

2. It is correlated with the sensibility of the boundary layer transition to the variation of angles of attack that the location of centre of pressure varies with the angles of attack. That is, in the region of small angle of attack, the region of boundary layer transition moves forward quickly on leeward with variation of angles of attack, but it moves slightly backward on windward surface. Therfore, the coefficient of the centre of pressure decreases. The trend reduces with increasing angle of attack. The value of Xcp is no longer a fuction of an angle of attack when the angle of attack gets to a critical value. The experimental results also indicate that the value of the critical angle of attack decreases with increasing Reynolds number.

3. The regularity of effect of Reynolds number on aerodynamic characteristics of a slender cone with variation of Mach numbers is correlated with critical Reynolds number of boundary layer transition. In the region of the experimental Mach numbers, the critical Reynolds number of boundary layer transition increases with the increasing Mach number.

4. The effect of variation of Reynolds numbers on aerodynamic characteristics of a slender cone is negligible when there is full laminar flow on cone surface or turbulent flow on most of the surface. Then, the coefficients of forces are in good agreement with the theoretical prediction for inviscid flow.

5. The viscous effect is not considered in Newtonian theory and, of course, the effect of Reynolds numbers on aerodynamic characteristics is neglected. Therefore, Newtonian theory should be used carefully in experiments of static aerodynamic characteristics, especially in the region of low hypersonic speeds.

References

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