Aerodynamic Charasteristics of Tumbling-Rectangular-Flat Plate Under Free Flight

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1. Introduction

When a body falls in fluid, the body often experiences autorotations, namely, various kind of rotating motions, such as tumbling, flat spin and corning. Tumbling is a rotating motion with an axis perpendicular to a falling direction. Tumbling is a very important phenomenon in aeronautical and space engineering, ballistics and meteorology. For example, when an satellite re-entries into the atomosphere, its body collapses into many fragments which are disperse in the wide range of field. Some fragments fall in tumbling motion. Then tumbling is useful to predict fragment's motion.

In 1953,Smith researched tumbling experimentally about an airplane nose[1]. Bustamante and Stone conducted to understand that many of flat plates and cylindrical bodies finally come to tumbling, high-altitude free-flight experiments[2]. They confirmed subsonic and supersonic wind-tunnel experiments using bearing supported models, and supersonic flight experiments using models launched by a gun. Smith[3] measured lift and drag coefficients, rotating rate etc. of tumbling flat plates in a windtunnel experiments at Reynolds numbers $Re=1.3\times10^3\sim2.8\times10^5$. He concluded that inertia moment ratio of plate Γ or aspectratio AR does not affect tumbling, on condition that the Γ is larger than 1 and that AR is larger than 3. Also he concluded that non-dimentional rotating rate Ω^* increases with increasing Re. Moreover he considered that later stall takes part in significant role on tumbling. Iversen[4] analized by previous researchers, and denied the relation between Ω^* and Re by Smith. According to him, the relation of Ω^* is due to the friction of bearings, not due to the variation of Re. Ishida[5] calculated tumbling flat plates, and Oshima et al.[6] calculated tumbling elliptic cylinders, to get vorticity distributions, streamlines and lift and drag coefficients. Yoshinaga et al.[7-9] investigated the relationships of energy transfer between a tumbling body and flow, by means of phase-plane diagram. The bodies are flat plates and rocket-shaped bodies.

As the aforesaid, there have been only a few reserches about tumbling, due to the difficulty of free-flight experiments. For example, we can not get a fundamental values of tumbling character, such as terminal rotating rate. So in this study, we do free-flight test of tumbling flat plate, in order to measure Ω^*, lift coefficient and drag coefficient.

Nomenclature

AR	: Aspect ratio=l/w
C_D	: Drag coefficient= $D/(0.5\,\rho_{air}U_\infty^2 lw)$
C_L	: Lift coefficient=$L/(0.5\,\rho_{air}U_\infty^2 lw)$
C_T	: Torque coefficient=$T/(0.5\,\rho_{air}U_\infty^2 lw^2)$
d	: Plate depth m
D	: Drag N
g	: Gravity acceleration m/s^2
I	: Plate inertia moment kg·m^2
Γ	: Iinertia moment ratio = $32I/(\pi\rho_{air}w^4 l)$
l	: Plate span m
L	: Lift N
m	: Plate mass kg
n	: Plate rotating rates s^{-1}
Re	: Reynolds numbers = $\rho_{air}U_\infty w/\mu_{air}$
T	: Torque N·m
U_∞	: Mean current velocity m/s
w	: Plate width m
X	: Holizontal distance m
Y	: Vertical distance m
α	: Attack angle deg
α''	: Attack angular acceleration deg/s^2
λ	: Depth-to-width ratio=d/w
μ_{air}	: Air viscosity N·s/m^2
ρ_{air}	: Air density kg/m^3
Ω^*	: Non-dimentional rotating rate=$\pi nw/U_\infty$

2.Experimental method

2-1.Governing parameters

As governing parameters, we consider Re, Γ, λ and AR. So, physical quantities to describe tumbling character, like Ω^*, C_D, C_L and L/D, are functions of Re, Γ, λ and AR.

2-2.Experimental equipments

The schematic of free-flight-experiment system is shown in Fig.1. Flat plates fall from a launcher in 7 m high to the ground floor. This system is indoor avoid of disturbances. Dimentions of the flat plate are l=0.3 $\times 10^{-1}$~1.5×10^{-1}m, w=1.5×10^{-2}m, h=4.5×10^{-3}m, AR=2 ~20 λ=0.3. The plates are made of foam polystyrene or wood. We can control the inertia I by kinds of materials of the plate. The launcher gives the plate an initial rotation. After release, the plate begin to fall tumbling. We take stereographic pictures by two high-speed cameras with 2000 frames/sec, and get the angle and the position of the plate, doing about one rotation, after computer proceeding.

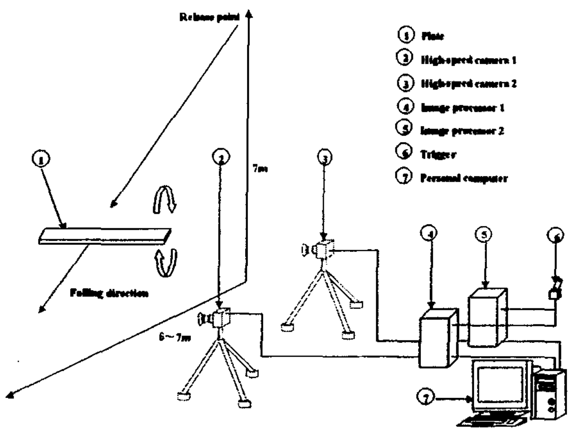

Fig.1 Experimental arrangement.

3.Results and discussion

3-1Falling motion of a tumbling flat plate (a sample)

Fig.2 illustrates a sequence of fallling motion of the tumbling plate during about one rotation, Re=3.47×10^3, λ=0.3, Γ=4.87×10^1, AR=10. The flat plate reaches the terminal condition. The plate falls from a right upper corner to a left lower corner, with clock-wise tumbling. It is recognized that the center of the plate is in waving motion, which synchronises with the plate rotation.

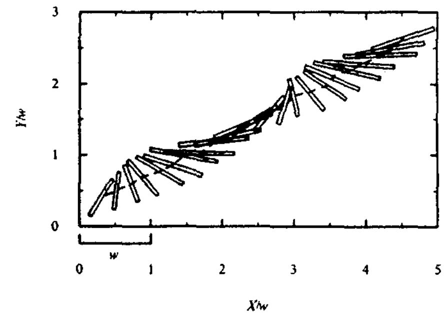

Fig. 2 Locus of a falling rectangular plate, at λ=0.3, Γ=3.29×10^0, Re=2.1×10^3, and AR=10.A broken line denotes the center of mass in air.Time interval is 0.002s.

3-2.Effect of Reynolds number Re

The Reynolds number Re is one of 4 governing parameters. Re is not controllable, but the other 3 are controllable in free-flight experiments. So, we examin the Reynolds-number effect at first. As a result, Re effect on tumbling is not so large, in the tested range of Re=1.9×10^3~4.2×10^3.

3-3.Effect of aspect ratio AR

Tumbling is fundamentally a two-dimentional phenomenon. But, actual tumbling is not perfectly two-dimentional, because the existence of plaate ends. Smith[3] described that there is no affecton tumbling, on condition that Γ is larger than 1 and that AR is larger than 3, at Re=1.3×10^3~2.8×10^5. On the other hand, according to Iversen[4], the effect on Ω^* still exists till AR=4, although Ω^* were proportional to AR at $\Gamma\gg1$. In their sudies, λ is mach smaller than 1, and in Iversen's study, $AR\leqq4$. So, we investigate the AR effect on Ω^* at AR=2~20, λ=0.3, Γ=7.73×10^0, 2.24×10^1, Re=1.9×10^3~4.2×10^3. The result is plotted in Fig.3. It is turned out that Ω^* is independent of AR, provided that AR is larger than about 10.And also it is clear that Ω^* is strongly dependent on Γ.The effect of AR to L/D are shown in Fig.4. L/D increases, as AR increases from 2 to 10.

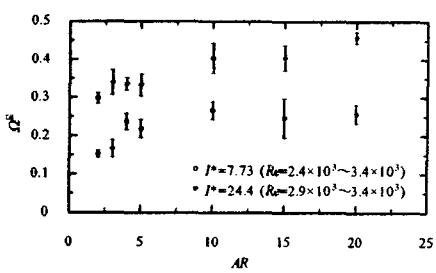

Fig. 3 Ω^* versus AR,at λ=0.3.

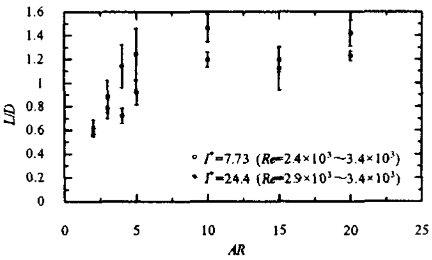

Fig.4 L/D versus AR, at λ=0.3.

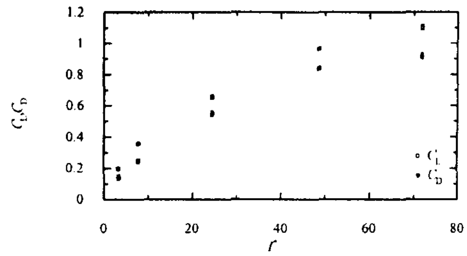

Fig. 7 C_L,C_D versus Γ, at λ=0.3, AR=10 and Re=1.9 × 10^3 ~ 4.2 × 10^3.

3-4. Effect of inertia-moment ratio Γ

According to Smith's free-flight experiments, it is clear that Ω^* is independent of Γ, if Γ is larger than 1 [3]. Here, in Smith's experiments, Γ is less than 5, and λ=0.007 ~0.013 and AR=3. But according to Iversen, Ω^* is independent at Γ>10 [4]. Here, in Iversen's study, AR=0.5 ~ 6.4 and λ=0.0156.In the present study, we try to investigate the Γ effect on Ω^*, at $\Gamma=10^0$~10^2, AR=10, λ=0.3.

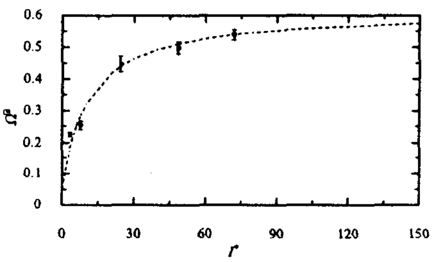

Fig. 5 Ω^* versus Γ, at λ=0.3, AR=10 and Re=1.9 × 10^3 ~ 4.2 × 10^3.

In Fig.5, Ω^* increases with increasing Γ, and asymptotes to 0.6. Ω^* is not constant at $\Gamma<10^2$. Therefore, our result supports Iversen's conclusion. Fig.6 shows the effect on L/D. L/D is constant over the range of Γ tested. But C_L and C_D are not constant in the range of Γ. In Fig.7, we can see the Γ effect similar to Fig.5.

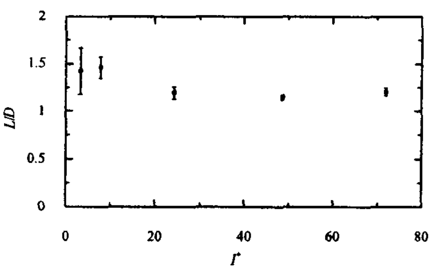

Fig. 6 L/D versus Γ, at λ=0.3, AR=10 and Re=1.9 × 10^3 ~ 4.2 × 10^3.

3-5. Time development along attack angle

Here, we see time development along attack angle α, instead of time history.

3-5-1. Torque T

Torque at each α can get from a relation $T=I\alpha''$. Fig.8 shows the fluctuation of torque coefficient C_T. In one period of tumbling, we can see 4 groups of vigorous C_T fluctuation, remarkable fluctuations of torque are at about α=45, 225 and α=135, 315. Moreover according to Iversen, torque which works on the plate indicates maximum as driving torqe at $\alpha\cong60$, and minimum as braking torque at $\alpha\cong150$, of course time-mean torque is 0. Our result is very different from Iversen's. We think main reason is the difference of λ.

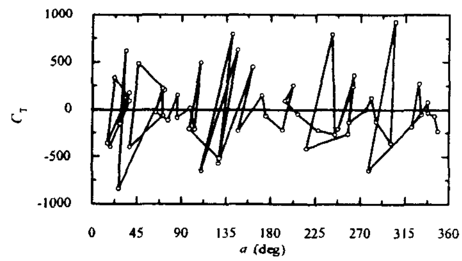

Fig. 8 Torque coefficient C_T versus α, at Γ=4.87 × 10^1, λ=0.3 and AR=10 and Re=3.4 × 10^3.

3-5-2. Lift-to-drag ratio L/D

Fig.9 shows the fluctuation of L/D at λ=0.3, Γ=4.87 × 10^1, AR=10 and Re=3.47 × 10^3. As well as in Fig.8, we can recognize 4 groups in Fig.9. Now, we see that these 4 can be classified into 2 groups. Namely, one group is at about α=45, 225, and the other is at about α=135, 315. In the former, accereIation of rotation with high L/D. In the latter, deccerelation with remarkably high L/D.

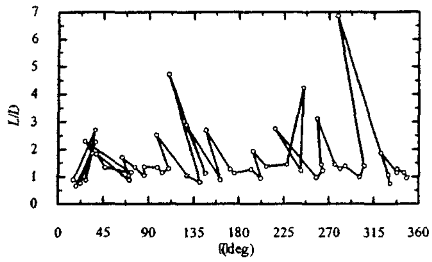

Fig. 9 L/D versus α,at Γ=4.87×10^1,λ=0.3, AR=10 and Re=3.4×10^3.

4.Conclusion

We investigated the aerodynamics characteristics of free-flight tumbling flat plate at Re=1.9×10^3~4.2×10^3, Γ=3.29×10^0~7.19×10^1,AR=2~20, and λ=0.3. Conclusions are as follows.

1) If AR is larger than 10, Ω^* and L/D are independent of AR.
2) If Γ is larger than 10^2, Ω^*, C_L and C_D are independent of Γ.
3) As Γ increases, Ω^* increases monotoniously and asymptote to 0.6.
4) In one period of tumbling, there are 4 groups of vigorous turbulence. These 4 groups can be classified into 2.

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