Aerodynamics of Reentry Capsule

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Transonic Dynamic Instability of disk-shaped Capsule

By

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Abstract:
In order to investigate the dynamic stability of MUSES-C capsule, both dynamic-wind tunnel tests and free flight test are carried out. In the wind tunnel tests using free-rotation method, it is measured not only an amplitude of an oscillation caused by dynamic instability in a transonic regime, but also a pressure distribution over the frontal and base surfaces, which reveals that the oscillation is promoted primarily by the force acting on the base surface. Based on the results obtained in the dynamic wind-tunnel test, the aerodynamic moments are described in a simple form on each Mach number. Applying this expression of aerodynamic moments into equation of motion, the prediction of the motion of the capsule become possible. In order to validate this prediction method, the free-flight test using a balloon is carried out. In it the maximum Mach number reaches 1.1, and the oscillation of the capsule during descent from altitude of 36km is measured. The result obtained in the free-flight test shows the almost same oscillation as the prediction gives. It validates the proposed method in a reasonable accuracy in terms of predicting maximum amplitude of the oscillation.

1. INTRODUCTION

In recent years, so-called sample-return mission, getting sample soil or regorith from other planet back onto earth, is strongly promoted by many researchers in the area of engineering, as well as in the astrophysics. In the Institute of Space and Astronatucal Science (ISAS), MUSES-C project is going toward the launch in 2003, in which the sample soil from some Asteroid will be carried back to earth (ISAS (1995)). When returning to earth with samples, reentry capsule is employed. Most of reentry capsules are bluff bodies, primary due to higher drag coefficient. Such a body with low ballistic coefficient, however, is known to suffer from violent oscillation, especially in transonic range. The violent oscillation may cause failure of a parachute deployment, which results in a total failure of a recovery of the sample.

This tendency on the dynamic behavior was recognized in the early stage of the development of Viking capsule, which entered atmosphere of Mars. In seek of appropriate capsule shape

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for the entry to a thin atmosphere of the planet, many experiments using ballistic rage were carried out (Sammonds (1971), Krumins (1967), Uselton et al. (1972)). During that process, the tendency of divergence was recognized in observations of the motion of probes flying in ballistic range, even if the shapes have static stability. In these cases, it could be termed that the capsule shape has dynamic instability. From the relevant research, it is known that this dynamic instability is observed especially in transonic regime.

In general, it is quite difficult to obtain the aerodynamic dynamic characteristics by a ground test primary due to its subtle force or moment as compared to a static one. In a history of dynamic testing, roughly three testing techniques exist; one is free-oscillation, another is forced-oscillation, and the other is free-flight technique. However, it has not still been established the prediction method of the motion of the capsule in real flight from the results obtained in ground tests. For this reason, the free-flight test with real size is indispensable for the development of the capsules. From the engineering standpoint of view, the establishment of the prediction technique of the dynamic behavior of the capsule is desired.

The primal purpose of this study is the establishment of the prediction method based on a wind tunnel test. In addition to that, through the experiments, to obtain the fundamental information onto the cause of dynamic instability, which is still unknown, is also another important purpose of this study.

2. DYNAMIC WIND-TUNNEL TEST

In order to observe the motion of capsule induced by dynamic instability, dynamic wind tunnel tests are carried out in the transonic wind tunnel of ISAS. In addition, unsteady pressure measurement ia also included in these test, to obtain fundamental information on dynamic instability.

2.1 Test Apparatus

In the dynamic wind-tunnel test, free-rotation method (Niwa et al. (1996)) is adopted as a dynamic test technique, which is one of the variations of the classical free oscillation method. The difference between this and classical method is in that in this method the model could rotate freely by aerodynamic moments because no constraining device such as spring is attached. This method was used also in the dynamic test of OREX (Yoshinaga et al. (1996)). In Fig. 1, the test apparatus is schematized. The model could rotate around its axis of rotation from −30 to 30 degrees in a pitch plane, which is sustained aft by strut support through a pair of ball bearings in doer to reduce friction as minimum as possible. The position of center of gravity of the movable parts is adjusted to coincide to that of axis of rotation in order not to produce any moment around it due to C.G. offset. The stopper device is installed inside of the sting support to keep the zero angle-of-attack condition until the free stream is established. Once the flow is established, the stopper is released electronically and the model starts to rotate simply by aerodynamic moment. The motion of the model is detected by the potentiometer attached at the axis of rotation. The output signal from potentiometer and the stopper-release status signal are amplified and converted to digital signals in the A/D converter, simultaneously.

2.2 Limit-Cycle Oscillation

Typical time history of angle of attack is demonstrated in Fig. 2, under the condition of Mach 1.3. The abscissa corresponds to the elapsed time counted from stopper release. It is

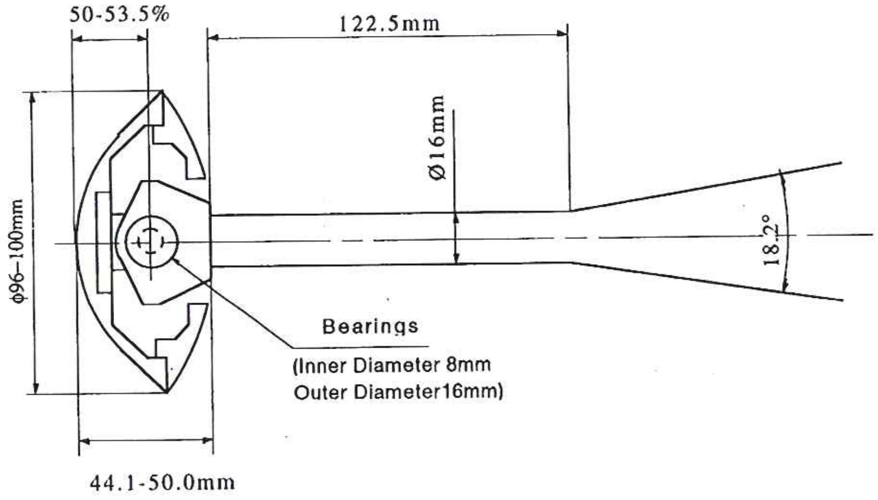

Fig. 1: Test apparatus.

shown that the slight disturbance, which arisen from stopper release, grows monotonously due to dynamic instability, and that the oscillation results in a so-called limit cycle with almost constant amplitude. This type of oscillation with limit cycle are observed under the condition of Mach number from 1.0 to 2.2, typically. The amplitude of limit cycle varies depending on Mach number, and its maximum, up to 30 degrees, is observed at Mach number of unity. In higher Mach number than 2.2, the disturbance does not grow, and it means dynamically stable.

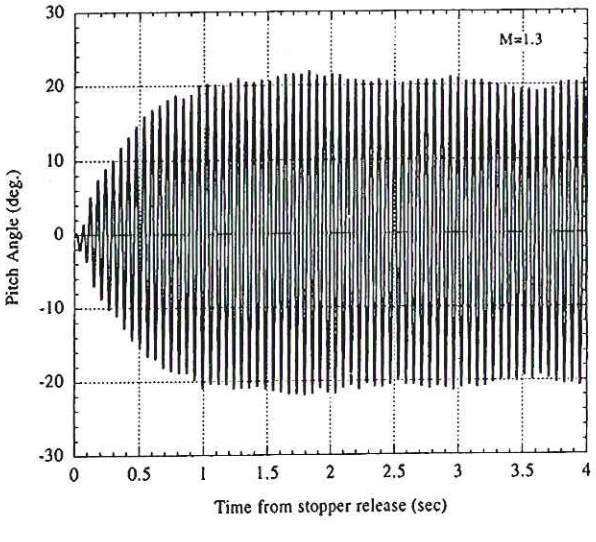

Fig. 2: Typical time history of oscillation (M=1.3).

2.3 Unsteady Pressure Measurement

In an attempt to clarify a role of aerodynamic moments during the limit-cycle oscillation, unsteady pressure measurement are conducted with the same apparatus described in 2.1. Four subminiarure pressure sensors (Entran EPI-41) are installed in the model, with two of them for frontal pressure distribution, and the rest for base pressure distribution. A pair of sensors on each surface are distributed symmetrically in a pitch plane. Before the measurement it is confirmed that the effect of elasticity of signal lines of pressure sensors on the motion could be ignored.

Fig. 3 shows the pressure coefficient difference at the two points on frontal surface as a function of angle of attack, during a cycle in a limit-cycle oscillation. The ordinate is pressure coefficient difference, $\Delta Cp = Cp_1 - Cp_2$, where Cp_1 denotes pressure coefficient at port 1 in upper side, and Cp_2 at port 2 in lower side, as indicated in the figure, respectively. The pressure difference ΔCp_f could be interpreted as representative of aerodynamic moment acting over frontal surface, because the arm length toward axis of rotation is equal both in ports 1 and 2. Since the positive value of ΔCp_f means the nose-up moment, in Fig. 3 the overall negative slope of pressure difference corresponds to the statically stable moment. In the figure it is shown that the shifts arisen due to angular velocity, from the averaged curve shown at the center of the curves, acts as a dynamically stable moment. For example, when the angular velocity is positive, the shift is negative, that is, nose-down direction. Nose-down moment indicates it acts to reduce positive angular velocity.

Similarly, in Fig. 4 the pressure coefficient difference at two points on base surface are presented during a cycle in a limit-cycle oscillation. The ordinate shows pressure coefficient difference $\Delta Cp_b = |Cp_3| - |Cp_4|$, where Cp_3 denotes pressure coefficient at port 3 in upper side, and Cp_4 at port 4 in lower side, as indicated in the figure, respectively. As in Fig. 3, the positive ΔCp_b corresponds to nose-up moment in Fig. 4. As in the case of Fig. 3, the overall negative slope of pressure difference corresponds to the statically stable moment. However, it should be noted that the shifts arisen due to angular velocity change their tendency at around -14 and 14 deg. of angle of attack. For example, in the region of $-14\,\mathrm{deg.} < \alpha < 14\,\mathrm{deg.}$ the shift due to positive angular velocity is positive, that is, dynamically unstable moment, whereas in $\alpha > 14\,\mathrm{deg.}$ or $\alpha < -14\,\mathrm{deg.}$ the shift due to positive angular velocity is negative, that is, dynamically stable moment. It is also noted that 14 deg. of angle of attack is close to the half value of limit-cycle amplitude.

3. DESCRIPTION OF AERODYNAMIC MOMENT IN EQUATION OF MOTION

Since the wind-tunnel-test model is one-degree-of-freedom, the equation of motion will be written,

$$I\ddot{\alpha} = qSd \cdot C_m(\alpha, \dot{\alpha}) \tag{1}$$

where, I: moment of inertia, q: dynamic pressure, S: reference area, C_m: pitching moment coefficient around axis of rotation. Based on the qualitative results obtained above, it is found that pitching moment coefficient could be expanded in a following form;

$$\ddot{\alpha} - \frac{qSd^2}{IV} \cdot \epsilon \left\{ 1 - \frac{\alpha^2}{\delta^2} \right\} \cdot \dot{\alpha} + \frac{qSd}{I} \cdot \left(a + b\alpha^2 \right) \cdot \alpha \tag{2}$$

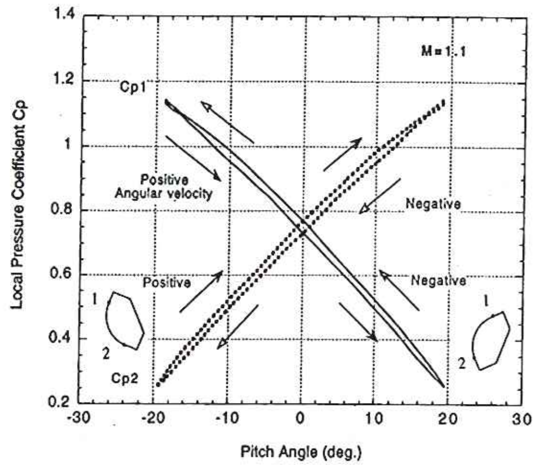

Fig. 3: Pressure-coefficient difference at front surface during limit-cycle oscillation (M=1.1).

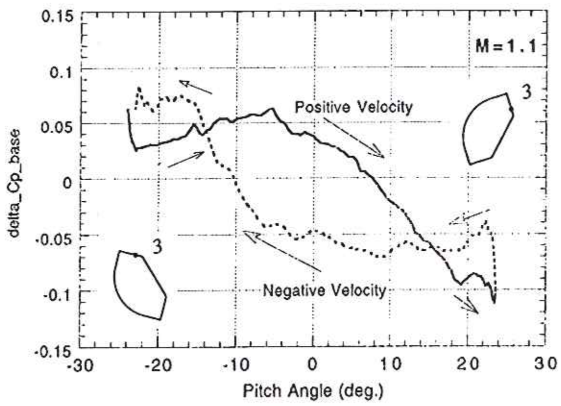

Fig. 4: Pressure-coefficient difference at base surface during limit-cycle oscillation (M=1.1).

where, V: free-stream velocity, d: model diameter,ϵ, δ, a, b:constants. In Eq. (2), assuming $\epsilon > 0$, when $|\alpha| < \delta$, it acts as negative damping, therefore, the oscillation grows, even if a is negative ($a \gg b$). When $|\alpha| > \delta$, it acts as positive damping, therefore, the oscillation declines. The oscillation expressed in Eq. (2) will result in a limit-cycle oscillation. It should be noted that the amplitude in a limit-cycle oscillation is equal to 2δ, independent on other constants, such as I, q, V, d, ϵ, a, b. In Eq. (2) the damping-in-pitch coefficient and pitching moment coefficient correspond to the second term, and third term, respectively.

In the wind tunnel test, d and I are known, and q, V are known from conventional measurement. From the experimental time history of angle of attack as shown in Fig. 2, the combination of constants such as ϵ,δ,a,b could be determined on each Mach number, using least square method. Fig. 5 shows the comparison of time history of angle of attack between the experimental curve and the fitted curve based on Eq. (2), at the case of M=1.3. It shows good agreement between them.

In Fig. 6, the angular acceleration during a limit-cycle oscillation is presented as a function of angle of attack. It is derived from curve-fit results expressed in Eq. (2). The ordinate, angular acceleration, could be readily converted to the pitching moment by multiplying moment of inertia. It is shown that the induced moment due to angular velocity changes its tendency at $\alpha = \pm 12\,\text{deg}$. As seen in Fig. 4, in $-12\,\text{deg} < \alpha < 12\,\text{deg}$ it acts as dynamically unstable moment, whereas in $\alpha < -12\,\text{deg}$ or $\alpha > 12\,\text{deg}$ it acts as dynamically stable moment. As described earlier, δ is identical to 12 deg., a half value of limit-cycle amplitude (24 deg.).

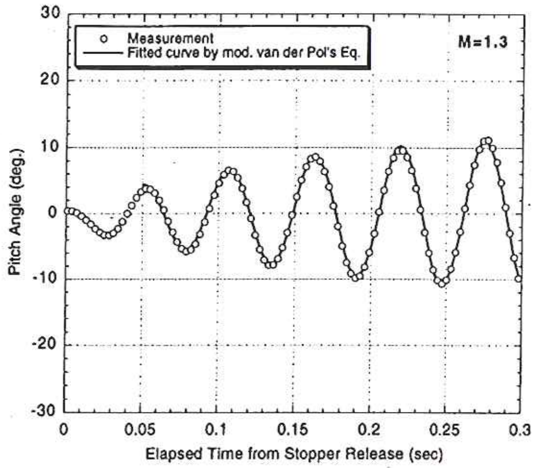

Fig. 5: Comparison of experimental data and fitted curve (M=1.3).

4. FREE-FLIGHT TEST AND PREDICTION METHOD

4.1 Free-Flight Test

In order to verify the discussions described in previous sections, free-flight test with real size capsule is carried out (Hiraki (1997)). In a free-flight test, the degree of freedom is six, as not in the case of wind tunnel test. The capsule has a similar shape but different in size and mass property, such as weight and moment of inertia. It is lifted up to 36km in altitude by a balloon with 30,00m^3 from Sanriku Balloon Center, and then separated from gondola by a command from GSE. During the descent, the flight Mach number exceeds unity, where the dynamic instability is expected to be severest. Inside the capsule two-axis rate sensor is on-board, and angular rates in pitch and yaw are directly measured. In addition, as CCD camera is also installed in rearside of the capsule, the attitude during descent could be known from the traces of balloon and Sun on the images taken by it.

Flight environment, such as Mach number and dynamic pressure is presented in Fig. 7 as a function of time counted from separation. The maximum Mach number established is approximately 1.1, at around 45 seconds from separation. As shown in Fig. 7, flight Mach number and dynamic pressure varies as time increases, whereas they remain constant during

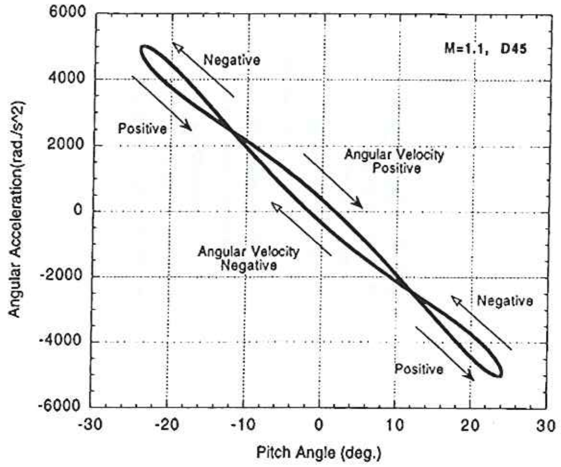

Fig. 6: Angular acceleration during limit-cycle oscillation derived by curve fit (M = 1.1).

the blow in the wind tunnel test.

The time history of total angle of attack derived from CCD images is diagrammed in Fig. 8. In order to reduce the effort of derivation minimum only a limited history during one cycle of oscillation at a certain interval of time is presented, which is denoted by a solid circle in the figure. The solid line is illustrated for help of understandings, which is representing the envelope of the time history. The maximum value is achieved not at maximum Mach number but after the dynamic pressure exceeds its peak.

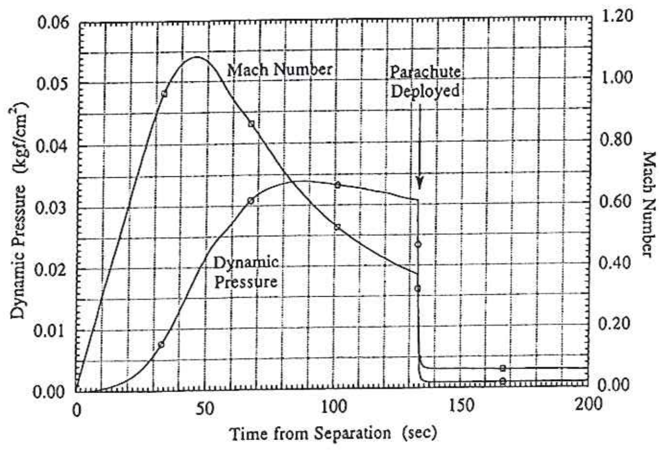

Fig. 7: Mach number and dynamic pressure during descent in free-flight test.

4.2 Prediction Method

From the engineering point of view, quantitative prediction of the motion induced by the dynamic instability is required before the flight, since it might cause fatal failure of parachute

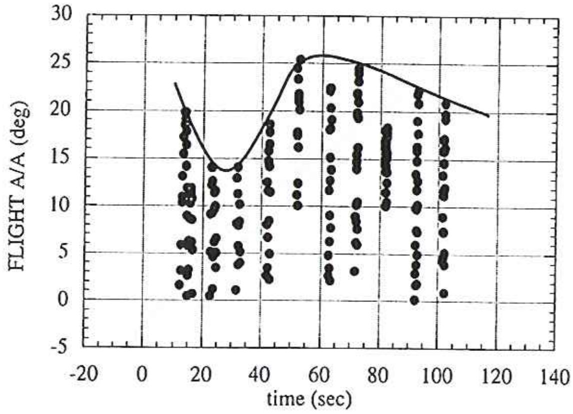

Fig. 8: Total angle of attack derived from CCD image in free-flight test.

deployment. In this section, prediction method is proposed, which is based on dynamic-wind-tunnel-test results.

As described in section 3 the combination of constants in Eq. (2), such as ϵ,δ,a,b, are obtained on each Mach number, where dynamic wind tunnel test is carried out. Using this combination of constants on each Mach number, the motion of the capsule in free-flight test could be estimated based on Eq. (2). Since the flight environment, such as dynamic pressure and velocity varies as time, spontaneous values should be used in Eq. (2), instead of constant values in the case of wind tunnel test. Not to mention, the combination of constants should be renewed since flight Mach number varies as time, as well. Fig. 9 shows the predicted total angle of attack of the capsule by the present method. In comparison with Fig. 8 and 9, the agreement is well especially after the peak is achieved.

Though the mass property and flight environment are different in dynamic wind tunnel test and in the free-flight test, the good agreement is obtained especially after the maximum peak is achieved. When the motion in pitch and yaw is described in Eq. (2), the combination of I, q, V, d, and that of constants ϵ, δ, a, b might affect the time for the oscillation in pitch or yaw to reach in a limit cycle, but dose not affect the amplitude of limit-cycle oscillation if δ remains the same, as previously shown in section 5. The fact that the angle of attack is in good agreement between the predicted results and the free-flight data, is indicating that the constant δ obtained in dynamic wind-tunnel test is almost identical to that in free-flight test. The other constant ϵ obtained in dynamic wind-tunnel test might not be identical to that in free-flight test, however, it gives difference only in time for the oscillation in pitch and yaw to reach in a limit cycle, not in a limit-cycle-oscillation amplitude. Similarly, the combination of I, q, V, d, also gives the same difference in it.

From an engineering standpoint of view, it is quite important to predict the maximum amplitude of the oscillation due to dynamic instability. The comparison made above validates that the proposed method based on the dynamic wind-tunnel test results gives prediction in sufficient accuracy for that purpose.

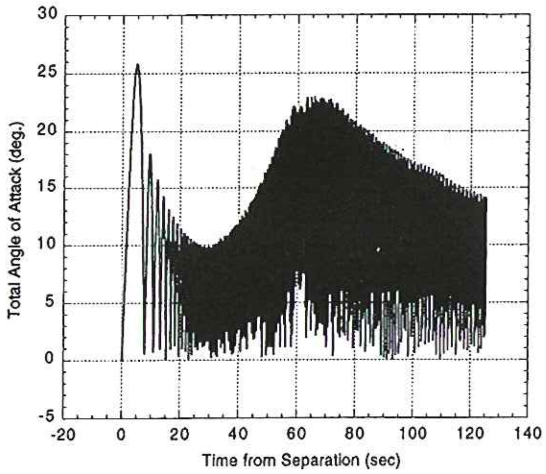

Fig. 9: Predicted total angle of attack history by propsed method.

5. CONCLUSION

In order to investigate the dynamic stability of MUSES-C capsule, both dynamic-wind tunnel tests and free flight test are carried out. In the wind tunnel tests using free-rotation method, it is measured not only an amplitude of an oscillation caused by dynamic instability in a transonic regime, but also a pressure distribution over the frontal and base surfaces, which reveals that the oscillation is promoted primarily by the force acting on the base surface. Based on the results obtained in the dynamic wind-tunnel test, the aerodynamic moments are described in a simple form on each Mach number. Applying this expression of aerodynamic moments into equation of motion, the prediction of the motion of the capsule become possible. In order to validate this prediction method, the free-flight test using a balloon is carried out. In it the maximum Mach number reaches 1.1, and the oscillation of the capsule during descent from altitude of 36km is measured. The result obtained in the free-flight test shows the almost same oscillation as the prediction gives. It validates the proposed method in a reasonable accuracy in terms of predicting maximum amplitude of the oscillation.

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