CHALLENGES IN SOLID BOOSTER SEPARATION DYNAMICS ANALYSIS FOR A WINGED BODY

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Abstract

The jettisoning of burnt solid rocket booster stage (HS9) from winged body configuration under hypersonic regime has been analyzed. The separation event takes place in the deceleration period of the vehicle i.e., aerodynamic drag is more dominating than the thrust generated by tail off phase of the solid booster. The separation environment in terms of dynamic pressure and Mach No are synthesized with all possibilities of HS9 stage performance and finalized the separation system requirement. The separation system realized should be able to take away separated HS9 stage sufficiently away from TDV stage as well as to avoid collision with TDV component such as rudder, hydraulic lines at the end of separation plane. A six-degree of freedom rigid body separation dynamics analysis has been carried out using the vehicle data and aerodynamic properties at the instant of separation. The aerodynamic coefficient data for HS9 stage is derived from wind tunnel test in Time March approach. The procedure for time march studies are described in detail in this paper. Also there are critical protrusions like hydraulic lines located around separation plane which are to be examined in detail during the pull out phase. It is to be ensured that separated HS9 stage does not collide with the protrusions at TDV aft end and vertical fin. This paper attempts to bring out the design and analysis efforts made during the separation of HS9 stage from winged body. Subsequently from the flight data analysis it is evidenced that the separation performance is normal and collision free.

Keywords: *HS9 Stage, TDV Stage, Dynamics, Collision, Separation, Time March Approach, Protrusions*

Nomenclature

C_X = Axial force coefficient
C_Y = Side force coefficient
C_Z = Normal force coefficient
C_{MX} = Rolling moment coefficient
C_{MY} = Pitching moment coefficient
C_{MZ} = Yawing moment coefficient
[F] = Resultant of all the external forces in the respective B-frame
I = Moment of inertia (constant)
m = Mass (constant)
[M] = Resultant of all external moments about mass centre in the respective B-frame
[r] = Position vector in LI-frame $[x\ y\ z]^T$
[V] = Velocity vector in body frame $[u\ v\ w]^T$
[ω] = Angular velocity vector (body rate) $[p\ q\ r]^T$
0 = Subscripts corresponds to separation time t = 0.0 s

Introduction

Separation dynamics design and analysis is an integral part of space vehicle design and analysis. The Technology Demonstrator Vehicle (TDV) is a winged body configuration with double delta wing based on reflex airfoil and a solid booster (HS9 stage) is used as a lower stage for boosting TDV to Mach 6 condition. After the burn out of HS9 stage, it is separated from ongoing stage and aerodynamic characteristics are an important factor affecting the trajectory of separated bodies. At HS9 separation condition, the TDV stage mass is less than HS9 stage mass whereas the aerodynamic drag on TDV is more than HS9, this is mainly due to winged body configuration of TDV. Hence there is a need for a jettisoning system to take the separated HS9 away from TDV. Once HS9 is sufficiently away from TDV, the HS9 leading edge experiences free stream flow which generates large aerodynamic drag. This high aerodynamic drag on HS9 will take it further away from TDV. Hence aerodynamic characterization is an important design input for realistic estimation of separation analysis. The aerodynamic data for HS9 is generated from 0.254 m hypersonic wind tunnel tests at Mach 5 for different grid points based on Time March approach. The aerodynamic data for TDV is also generated from wind tunnel through grid test. After booster burn out, it is also proposed to coast the combined vehicle to a benign separation environment as well as to reduce the tail off thrust implication due to solid booster. The separation and jettisoning of spent booster are carried out at this instant. The main challenges in the separation of booster are, under this complex hypersonic aerodynamic environment in presence of winged body, separated stage should not collide with the Hydraulic lines protruding inside and vertical tail of TDV which is protruding outside the separating booster and separated body should not catch up with ongoing stage by any chance. Considering all the above aspects the analysis is aimed for the following:

- prediction of appropriate separation environment in terms of dynamic pressure and angle of attack,
- identify the number of retro rockets, their thrust level, burn duration and location to ensure sufficient gap built up just after separation and
- identify location for placing hydraulic lines to provide collision free separation.

Separation System and Requirements

Separation dynamics design must ensure a collision free separation between the separating bodies since this is one of the critical phases in flight where there is a acute possibility of mission failure due to a collision between separating bodies. In the case of HS9, a split collect release mechanism is used to physically separate the booster stage from TDV stage and jettisoning is achieved using retro rockets. Subsequent to this, the HS9 stage starts moving away from the TDV. Since this separation occurs at lower altitudes, aerodynamics also plays a key role in deciding the trajectory of separated HS9 stage. The mission requirement for this separation is that the separated HS9 should not collide either with the vertical tail or with the protrusions located at the aft end of TDV during its pull out phase.

Analysis Methodology

The separation process has been analyzed using the in-house developed stage separation dynamics software, which performs six degrees of freedom trajectory simulation for multiple rigid bodies. The basic formulation of SEPPACK is given below for completeness. Two basic types of frames of reference are used in the analysis. The first is Local Inertial frame (LI-frame) frozen at time of separation command but moves with vehicle velocity at separation command. Origin of this frame is body mass center. The orientation of this frame is as follows:

- X axis - From mass center towards nose tip
- Y axis - Pitch axis (from P- towards P+)
- Z axis - So as to form a right handed system. Naturally it is the yaw axis.

The second type of frame is the body co-ordinate system (B-frame) attached with the body having origin at body mass center. This frame is parallel to local inertial frame at time of separation command. The transformation from body frame to local inertial frame and vice versa can be achieved through a transformation matrix in which a prefixed sequence of rotation of Euler angles Φ, θ and ψ is used.

The equations of motion in body frame are,

$$m\,[\,dV/dt + \omega\, x\, V\,] = F \tag{1}$$

$$Id\omega/dt + \omega\, x\, I\omega = M \tag{2}$$

The above rigid body equations of motions are solved to obtain V and ω.

The body rate ω is transformed as Eulerian rate in the predefined local inertial frame. The sequence of rotation of Euler angles Φ, θ, and ψ decides the transformation matrix transforming the body rates to Eulerian rates.

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = [\,TRMAT\ 1\,] \begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{3}$$

Next, the body velocities u, v and w are transformed to the local inertial frame using the transformation matrix for a vector in body frame to the inertial frame.

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix} = [\,TRMAT\,] \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{4}$$

Equations 1 to 4 represent a set of 12 first order equations for each of the separating body and are integrated by the modified Euler method with suitably chosen integration step-size and the following inertial initial conditions (12 conditions).

$$V_o = \omega_o X r_o \,;\, \omega = \omega_o \,;\, \theta = \theta_o \,;\, r = r_o \tag{5}$$

With above the position and attitude of the body in the local inertial frame and velocity and body rate in body frame are obtained. The local inertial velocity and attitude rates are also available by transformation (3) and (4) as above.

Collision modeling in the software is done by assuming the separating bodies to be circular and the lateral shift between two centers i.e. for the two bodies of the circles are studied in local inertial frame. Initially the difference between two radii corresponds to the gap available between two bodies and as the simulation progress, the resultant lateral shift is calculated using the shift along pitch and yaw axes. The relative motion between separating stages are analyzed to ensure a collision free separation. Different parameters such as pull out distance, time of pull out, relative distance between the critical points during pull out and angular rates of the separating bodies are monitored for the analysis. The separation system design process depends on different physical parameters and since in reality these parameters can have a nominal value along with dispersions, sensitivity studies as well as worst case studies have been performed for a detailed analysis of the separation process.

Jettisoning System Description

The jettisoning of HS9 stage is achieved through retro thrusters. There are two retro rocket thrusters located P- and P+ side of HS9 stage. These retro rockets are located on a base shroud of the HS9 stage. The retro rocket thrust profile, action duration, locations has been finalized based on the separation dynamics studies. A typical retro rocket thrust history is shown in Fig.1.

Separation Geometry

The separation plane is located at 6500 mm down from the TDV nose. There are various protrusions located at aft end of TDV. The protrusion location details are shown in Fig.2. HS9 inter-stage geometrical details are shown in Fig.3. As seen from this figure, the HS9 fore end brackets (6 numbers) are projecting inward from the separation plane. During the separation, it is to be ensured that the separating HS9 does not interfere with the protrusions as well as vertical fin at TDV aft end. On examining the separation geometry, it is observed that to ensure a collision free separation, sufficient radial clearance should be ensured between the protrusions and interstage and also between the protrusions and HS9 fore end brackets. For a typical protrusion, the maximum pull out length is 70 mm and the minimum lateral clearance is 46 mm.

Aerodynamic Environment at Separation

The separation event occurs in atmospheric phase of flight. The aerodynamic environment at TDV/HS9 separation was provided from the actual control simulation results. The data was provided for nominal, lower bound and upper bound trajectories based on HS9 stage performance. The details are given in Table-1. The nominal case corresponds to the nominal performance of propulsion system and drag at that instant. The -3 Sigma case corresponds to low thrust i.e., under performance of propulsion system, so the separation of stages take place in lower altitude such that dynamic pressure and alpha will be more resulting in higher drag. The +3 Sigma case corresponds to high thrust i.e., over performance of solid booster, so the separation of stages take place in higher altitude such that dynamic pressure and alpha will be lesser resulting in

Table-1 : Separation Environment

Trajectory Parameters	Minimum (-3 Sigma)	Nominal Case	Maximum (+3 Sigma)
Altitude (Km)	44.3	47.1	49.5
Mach No.	4.2	4.6	5.0
Dynamics Pressure (kPa)	2.2	1.8	1.6
Alpha (Deg)	3.4	1.97	1.2
Beta (Deg)	0.08	0.003	0.12

lower drag. The trajectory parameters are shown in following Table-1. Wind tunnel tests were carried out for minimum and maximum α cases. The sign convention used is shown in Fig.4.

TDV Aerodynamics Derived Using Grid Approach

An empirical aerodynamic model is derived from experimentally obtained data using an approach named grid approach. Here the data is generated at well defined points of independent aerodynamic states. We aimed at the two extreme trajectories within which the actual path of the TDV will lie. The aerodynamic coefficients of TDV as function of angle of attack (deg) and for Beta 0° and 5° after separation are shown in Fig.5. For Beta -5° side force coefficient and yawing moment coefficient is taken in opposite sign.

From the Fig.5, it is seen that pitching moment coefficient is negative for both α=1.2° and 3.4° due to its unsymmetrical wing geometry configuration, which can decrease the angle of attack by its rotational moment. This means that TDV has a nose down rotation during our interval of interest. The normal force is negative for lower angle of attack ($\leq$+1.5°) and becomes positive beyond α > +1.5°. Hence, for TDV bottom movement, translational effect and rotational effect are additive for angle of attack beyond +1.5°. For lower angle of attack, these two effects are in opposite direction. In case of beta plane, yawing moment coefficient is positive for TDV stage indicates that TDV bottom rotates away from HS9 stage. The side force coefficient C_Y is always negative, hence similar to alpha plane, here also the translation effect and rotation effect are in additive for positive beta plane.

HS9 Aerodynamics Derived Using Time March Approach

The space marching approach for the present study has major limitation of high spatial resolution data requirement as the vehicle has unsymmetrical flow in pitch and yaw planes and also non-linear behavior in the coefficients due to complex flow field prevailing downstream of winged TDV configuration. The above features calls for enormous grid points from the wind tunnel experiments and hence more realistic Time March approach is conceived for the present study. The aerodynamic force and moment coefficients of HS9 stage after separation are derived from wind tunnel tests in two phases such as

- Phase 1: With trajectory condition shown in Table-1 and assumed HS9 fin deflection at null condition.
- Phase 2: Over and above Phase 1, extra dispersion in separation environment is considered and for separated HS9 fin deflection and HS9 tail off thrust at separation (300 N) has also been accounted.

The Phase 2 aerodynamic coefficients of HS9 stage after separation are shown Fig.6. Just after separation, the HS9 stage is under the shadow of TDV wake flow and aerodynamic forces are contributed from the fins and aft region of HS9 booster only. However, as the separation progresses, the aftbody is exposed to the freestream flow and influence of forebody gradually diminishes. Hence the separating HS9 body is highly influenced by the presence of TDV and its proximity due to complex aerodynamic flow field around it. So it is quite appropriate to derive HS9 stage aerodynamic coefficients as a function of relative position between the two bodies. The data is derived as a function of relative axial distance (Δx) between the bodies using Time March approach. In Time March studies, the dynamics of separating HS9 is simulated numerically by making use of the direct aerodynamic forces and moments obtained from wind tunnel experiments, not from analytical or computational methods. During this process, measurements are first made at the initial settings and these are then used to predict the configuration in the next time step. Model, is then, reset in that configuration in wind tunnel and measurements are made again. This is continued till reaching our time duration of interest or tunnel limit whichever is earlier. This procedure for Time March studies is well established and used for expendable launch vehicle strap-on separation studies [1].

It is seen that pitching moment coefficient from Fig.6 is always negative indicating HS9 has a nose down moment. Since the aft end of HS9 has fins and also forebody is under the shadow of TDV, normal force is acting near aft end of HS9 (behind the C.G. of HS9 body). The normal force coefficient C_Z is always positive as the angle of attack is positive. Normal force is the integrated differential pressure load between windward and leeward sides. The net displacement of HS9 is lesser as movement due to translation and rotation are in opposite direction in pitch plane (HS9 top movement). Similarly, yawing moment is positive for HS9 stage, which indicates that it rotates away from protrusion and the side force coefficient C_Y is always negative. Here also the displacement due to translation and rotation are in opposite direction for HS9 side. So the net gap between two bodies is lesser than its actual motion.

Dispersion band for aerodynamic coefficients is arrived at based on repeatability error and other possible sources of error for flight scaling.

Mass and Inertia Related Properties

The mass and inertia related properties of the separated bodies used for the analysis is shown in the following Table-2. The c.g locations are measured from nose of the vehicle.

Analysis Results

A 6-DOF trajectory simulation has been performed for the TDV and HS9 stage using the relevant inputs described above. The usual method adopted in any separation dynamics analysis is as follows. First a nominal case is simulated keeping all the input parameters at their nominal values and the relative movement between the bodies is monitored to examine the possibility of collision between them. In the next step, each of the input parameters is perturbed one at a time within their dispersion limit and the sensitivity of their dispersion on the dynamics is quantified. In the final step, the input parameters are perturbed one over the other in worst case sense maximizing the relative radial movement between them and the possibility of collision between the separating bodies is examined.

An approach similar to the above is followed here also. First a nominal case is simulated and further worst case is built over this nominal case. In case of Phase 1 aerodynamics data it has been observed that separated HS9 stage will collide with ongoing TDV stage. The results of the analysis are shown in Table-3.

From Table-3, the major input dispersions affecting the dynamics significantly are (i) Aerodynamics dispersion (ii) Combined body rate at the instant of separation followed by the retro rocket force dispersion. It is also seen that from the above table that the relative radial movement at the end of pull out is 13 mm in the nominal case and 51 mm in the worst case against the available initial radial clearance of 46 m between TDV and HS9 stage. This shows that separated HS9 stage will collide on with ongoing TDV stage. Based on Phase 1 studies the following are the conclusions drawn.

Table-2 : Mass and Inertia Properties

Parameter	HS9	TDV
Mass (kg)	2600	1800
$c.g_z$ (mm)	15000	5000
$c.g_y$ (mm)	-10	0.0
$c.g_x$ (mm)	500	400
I_{xx} ($kg.m^2$)	1000	700
I_{yy} ($kg.m^2$)	30000	5000
I_{zz} ($kg.m^2$)	28000	5000

Table-3 : Worst Case Synthesis - Phase 1 Study

Sl. No.	Case Definition	Radial Movement at the End of Pull Out (mm)
1	Nominal case	13
2	Case 1 + Mass dispersion	20
3	Case 2 + Moment of Inertia dispersion	21
4	Case 3 + c.g dispersion	26.5
5	Case 4 + TDV stage aero dispersion	35
6	Case 5 + HS9 stage aero dispersion	40.5
7	Case 6 + Retro thruster force dispersion	45.5
8	Case 7 + Initial body rate of -2°/s - Worst Case	51

- In the nominal case, the separation is found to be collision free.
- But in the worst case, the radial clearances available at both the top and bottom protrusions are not sufficient to ensure a collision free separation. Hence the radial clearances provided at protrusion locations should be increased.
- Dispersions in aerodynamic coefficients are the most sensitive parameters deciding the direction of relative lateral movement in the worst case and reduction in these dispersions will help in improving the margins.

Based on recommendation from phase 1 separation studies, the protrusions are relocated in such a way that total pull out length is reduced to nearly half and available gap by geometry is also increased by 40 mm. So with this revised geometry phase 2 studies are made. Phase 2 separation dynamics analysis carried with HS9 fin deflected condition. From the study, it is observed that separated HS9 stage does not collide with ongoing TDV stage and even under the worst case the radial clearance of 49 mm is ensured. In addition to the above, studies are carried out with the aero data using CFD approach for the jet on condition.

A Schlieren flow visualization of different phases of pull out is shown in Fig.7. Schlieren pictures show that there is no HS9 leading edge shock till 525 ms due to TDV shadowing effect. As HS9 moves axially downwards and also lateral movement, expose the leading edge to the flow, which causes shock at its leading edge. It is also evident that this shock is getting stronger with separation time. This will lead to increase in axial force and reduction in the moments as the leading edge contribution on aerodynamic coefficients is gradually increasing. The velocity and rate histories of both the bodies are shown in Fig.8 and Fig.9. The results are provided for nominal as well as worst case.

As seen from Fig.8 and Fig.9, the negative longitudinal velocity of HS9 stage is much higher compared to that of TDV stage. Hence there is no possibility of HS9 moving towards the TDV.

Flight Experience

The reusable launch vehicle technology was successfully demonstrated and HS9 stage separation was also a part of that experiment. Using the above analysis approach with the preflight input data, a collision free separation of HS9 stage was predicted.

No direct measurement to monitor the clearance between HS9 stage and TDV was possible in the flight. Hence, to examine whether the separation was collision free or not, some of the indirect measurements were seen. Two of such measurements are structural sensor data (2MAFSB04 - Axial mode accelerometer, 2MAFSB05 - Bending mode accelerometer) and body rate. These two are shown in Fig.10 and Fig.11.

It is seen from Fig.10 that the separation event is captured as a sudden change in signature in the accelerometer data. Subsequent to that the signature is damping out. Any collision during the pull out phase would have reflected another change in the accelerometer signal pattern. Similarly the level change obtained in the body rate figure 11 during HS9 separation is comparable with the prediction. Also from the vehicle acceleration data tail off thrust at HS9 separation is estimated and found to be less than the preflight prediction. Based on these observations, it can be confirmed that separation was collision free in the flight thus validating our prediction.

Conclusions

The objective of this paper is to highlight the challenges involved in the separation dynamics analysis of solid booster stage from a winged body. Particularly, the paper emphasizes on the studies carried out to finalize the separation system requirement as well as the separation environment. Analysis is carried out using wind tunnel aerodynamics data in Time March Approach. Based on the study, to ensure safe separation, it is recommended to relocate the various protrusions and also recommended to tighten the dispersion levels of various sensitive parameters. With the finalized configuration, collision free separation with adequate margin is ensured between the separated stages. The prediction methodology is further validated by the successful separation of HS9 stage in the actual mission.

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Reference

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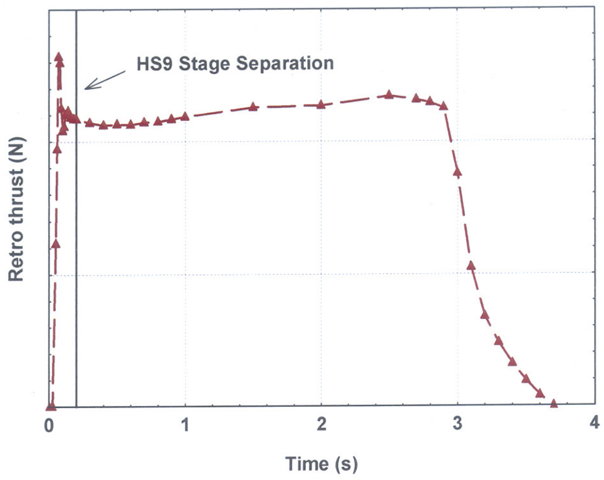


Fig.1 Retro Rocket Thrust Time History

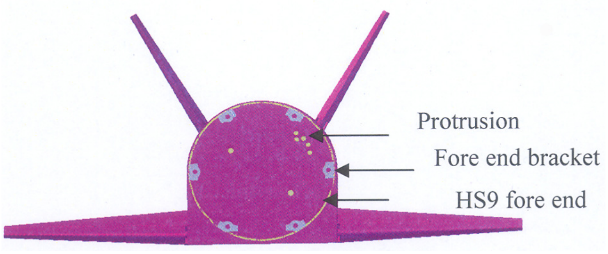


Fig.2 TDV Protrusion Details

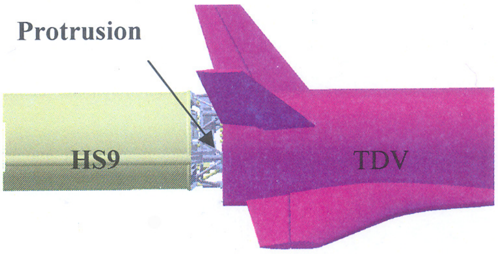


Fig.3 HS9 Interstage with TDV Geometry

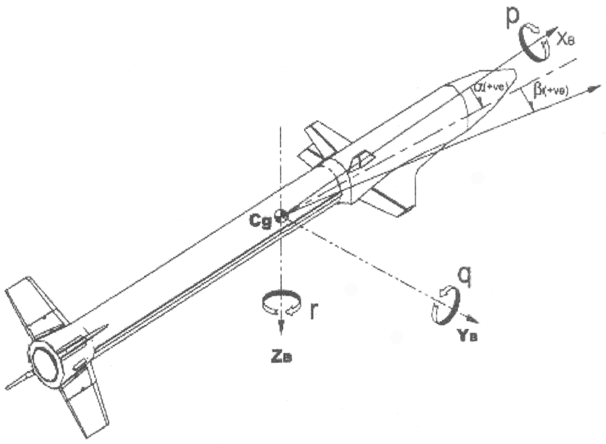


Fig.4 Sign Convention

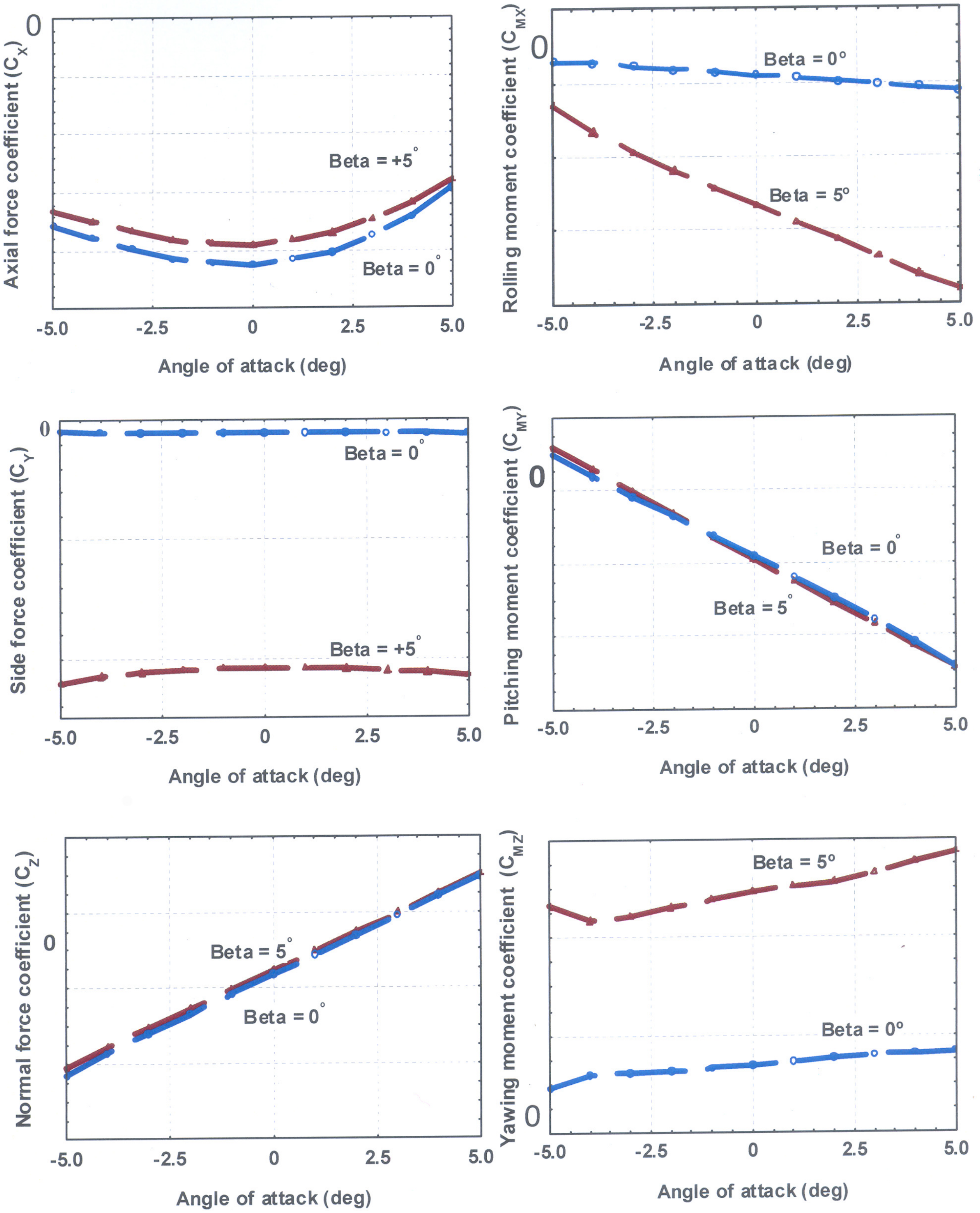


Fig.5 Aerodynamic Coefficient of TDV

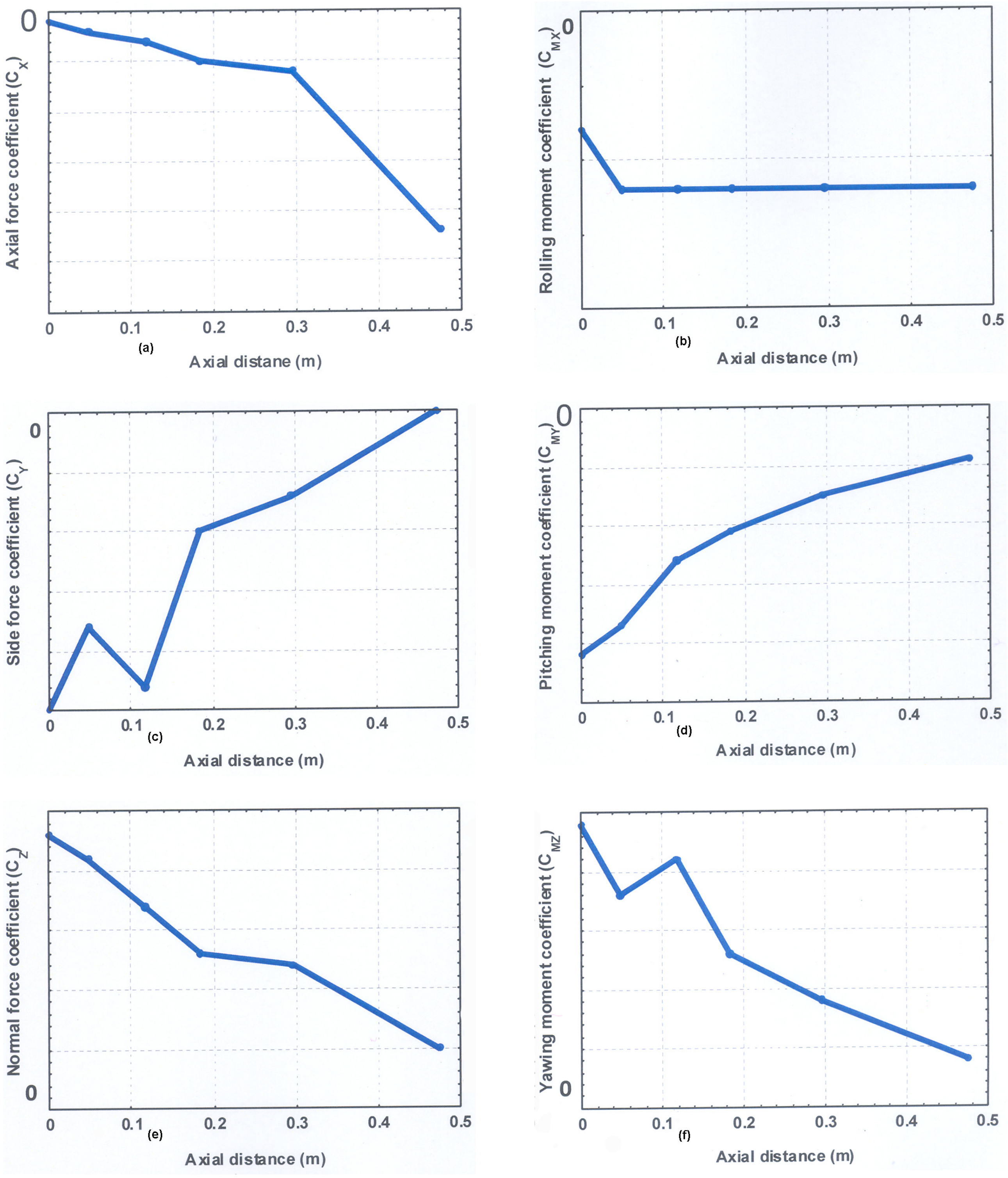
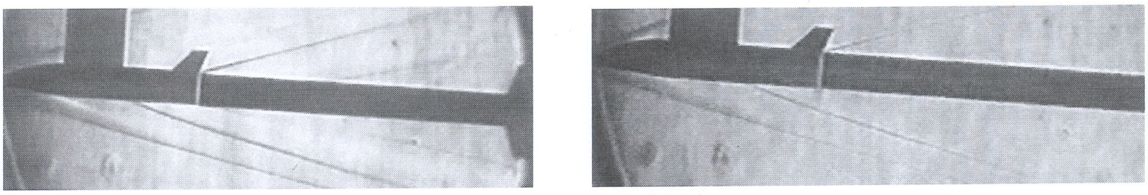
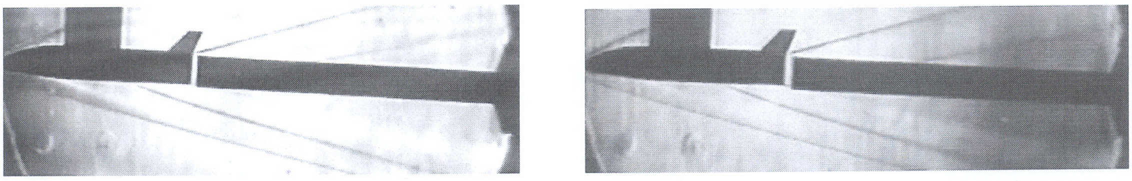


Fig.6 Aerodynamic Coefficient of HS9 Stage (a) Axial Force Coefficient (b) Rolling Moment Coefficient (c) Side Force Coefficient (d) Pitching Moment Coefficient (e) Normal Force Coefficient (f) Yawing Moment Coefficient



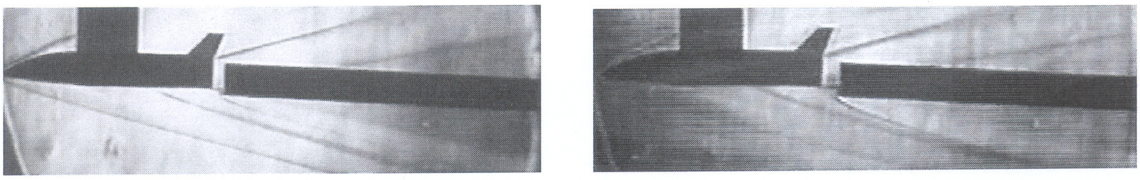
Time =0 ms

Time =350 ms



Time =525 ms

Time =625 ms



Time =775 ms

Time =960 ms

Fig.7 Schlieren Flow Visualization of HS9 Stage Separation

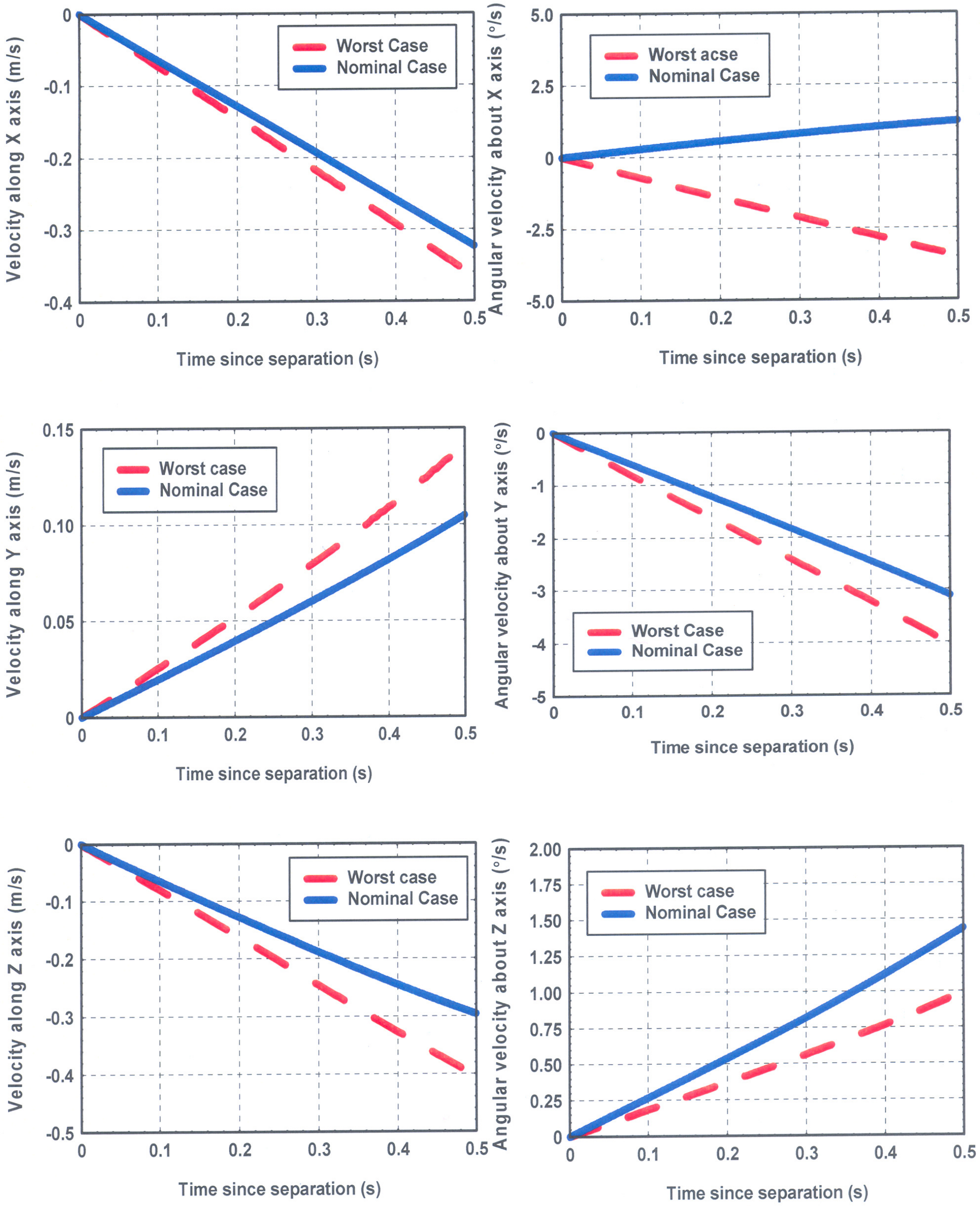


Fig.8 TDV Stage State Vectors

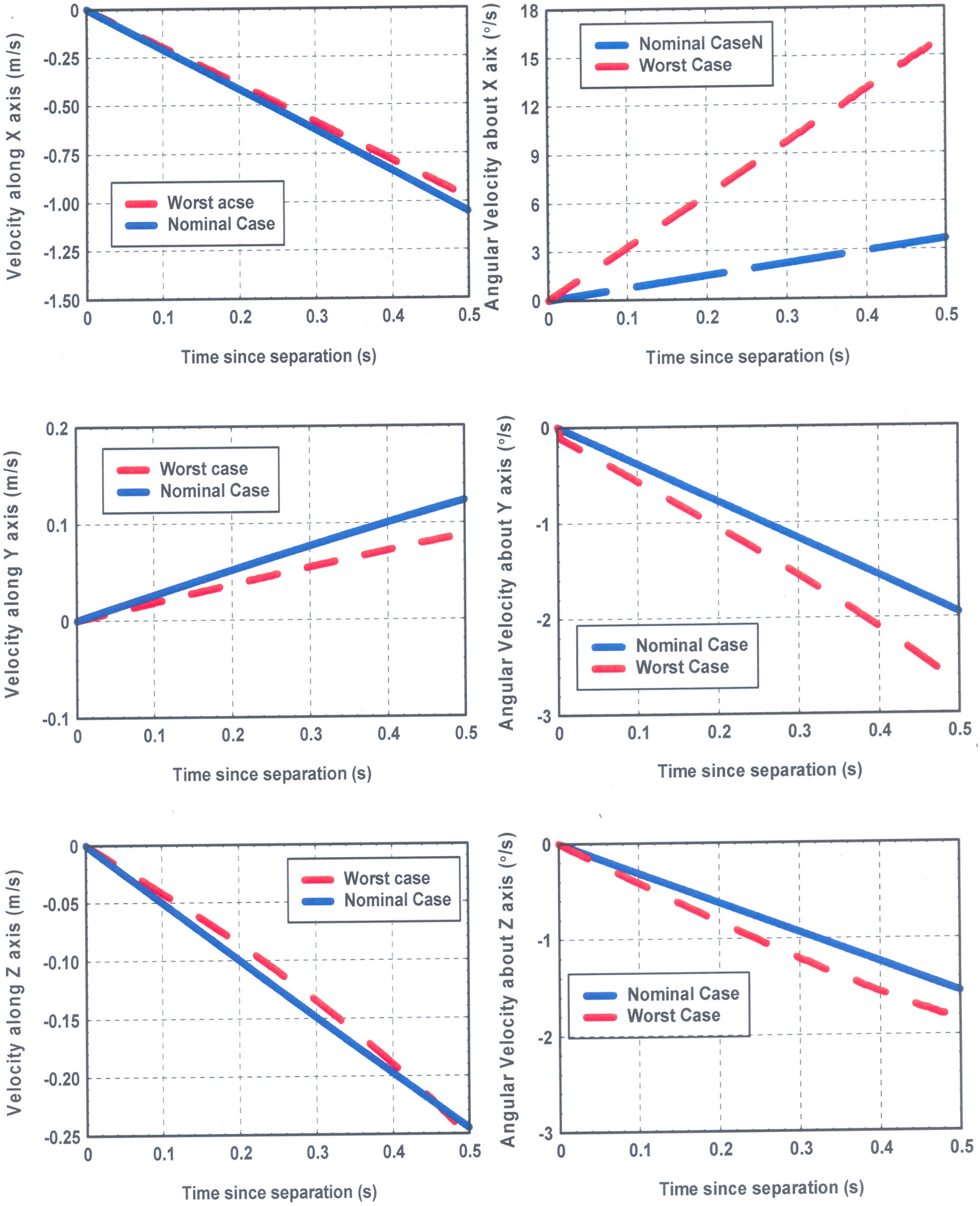


Fig.9 HS9 Stage State Vectors

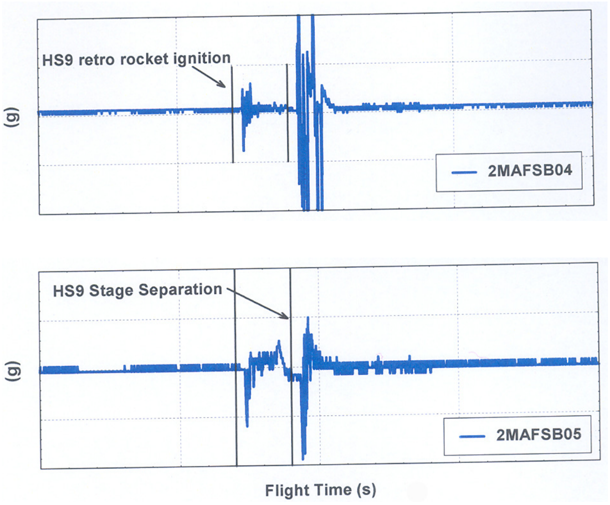


Fig.10 Structural Sensor

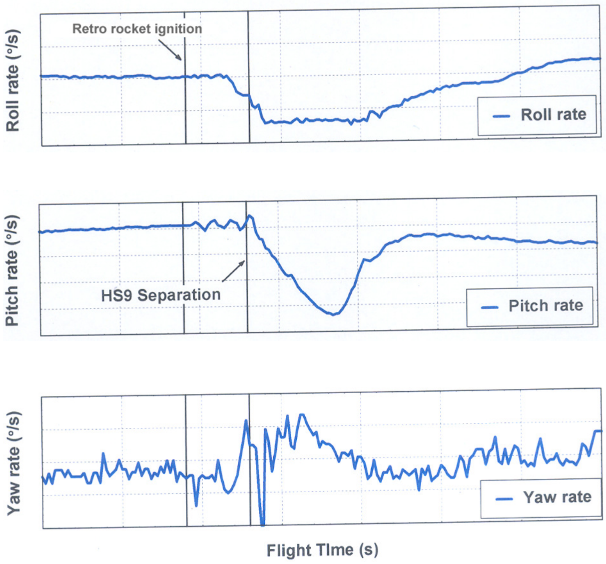


Fig.11 Attitude Rate