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TRIM STATE CALCULATION AND ANALYSIS OF HYPERSONIC VEHICLE

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ABSTRACT

Research on Hypersonic air vehicles has been one of the most interesting and talked about field of aeronautics in the recent years. These hypersonic aircraft's operate under extremely hard conditions and a very turbulent environment. The vehicle's flight envelope detection at early stages of research is very critical to model the control algorithm for the vehicle. Determining the trim conditions of an aircraft are highly crucial to know the operating points of the aircraft. The trim conditions of the aircraft for a specific maneuver set the points around which the aircraft is operated, thus a flight envelope is estimated. In this study the trim conditions are determined for a hypersonic aircraft using 6DoF vehicle dynamics and standard calculated aerodynamic database. In this study a hypersonic vehicle developed by NASA which is a conceptual air breathing hypersonic winged cone model is chosen. The vehicles aerodynamic data is analyzed. A 6DoF equation set was developed to describe the vehicle dynamics. These simultaneous nonlinear equations were solved using the Newton's Method which involves a Jacobian calculation. A MATLAB code is written to perform the numerical simulations and to solve the nonlinear system of equations. The trim states were found for various conditions of the vehicle at steady wings level flight traveling at constant altitude and Mach number. The body velocities of the vehicle in the x, y, and z directions are found, the deflection required by the control surfaces to maintain cruise is found.

KEYWORDS: Trim State, Mach no, Angle of attack, Hypersonic, Newton's Method.

I. INTRODUCTION

To determine an aircraft's steady state flight parameters, which is also called trim states is very important in numerous engineering studies. The trim states are given as the input for the design and analysis of any aircraft model. The trim analysis done to find the trim points are usually called as trim conditions which help in developing the analysis and design of that vehicle model. The trim states found using the aerodynamic and the propulsion models of the vehicle model is used to provide the data needed as initial conditions and to determining the flight operation envelope and to determine the performance characteristics. Control algorithms for the vehicle model are designed at points which are given by the trim conditions. These trim states give the starting point for the comparison of different vehicle models. These trim states can also be used to do the comparison study on implementation of the same vehicle model in different configurations.

The speed of the hypersonic vehicle is very high (more than five times of sound speed), therefore, it takes very less time to reach the target/destination. However, these performance advantages are dependent upon advances in current state-of-the-art technologies in many critical areas, one of which happens to be the control system design. The control and stabilization of AHV are very challenging because its aerodynamic characteristics are different from the conventional (subsonic or supersonic) air vehicles.

II. METHODOLOGY

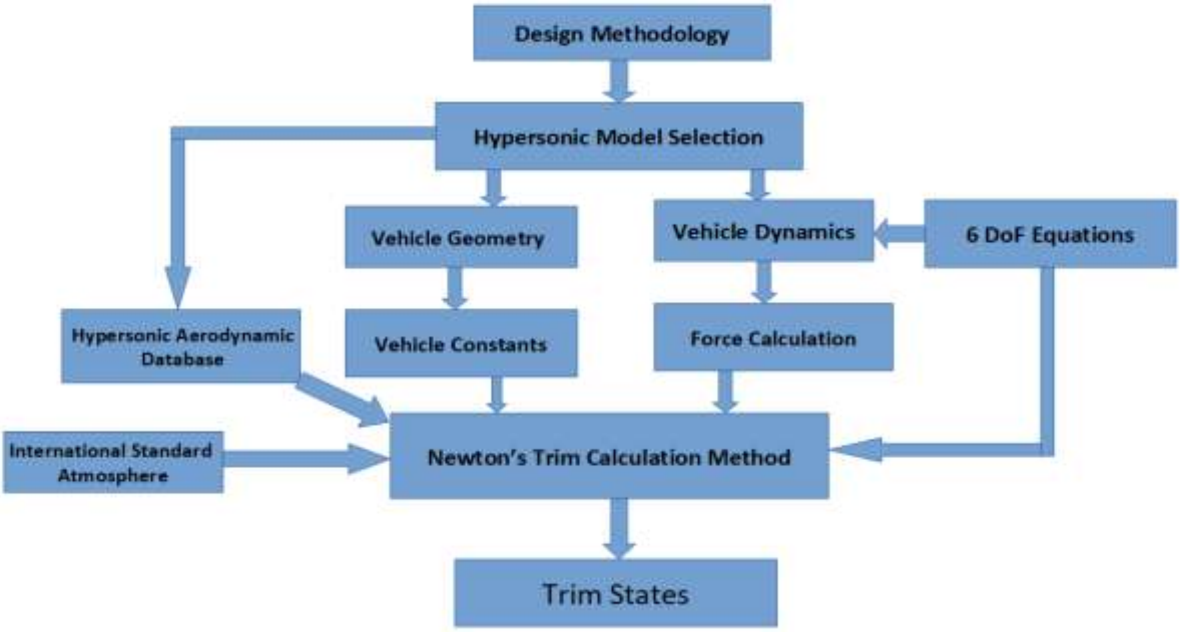

Fig-1: Methodology Flowchart

Firstly a Hypersonic vehicle model is selected. For the present study a winged cone vehicle model is chosen. The vehicle constants like weight of the vehicle, wing span, position of center of gravity and other vehicle constants are obtained from the vehicle geometry. A 6 Degree of Freedom equations of motion is developed for the hypersonic vehicle which constitutes the vehicle dynamics. The aerodynamic data for the control surfaces are obtained from the vehicle model and it is put it into functions of angle of attack and Mach number. All these data which includes the international standard atmosphere model and the 6 degree of freedom equations as are used in the Newton's trim calculation method to find the output trim states. The trim states in this study are found for the aircraft in steady wings level flight at constant altitude and Mach number.

III. MODELING AND ANALYSIS

3.1 Vehicle Model

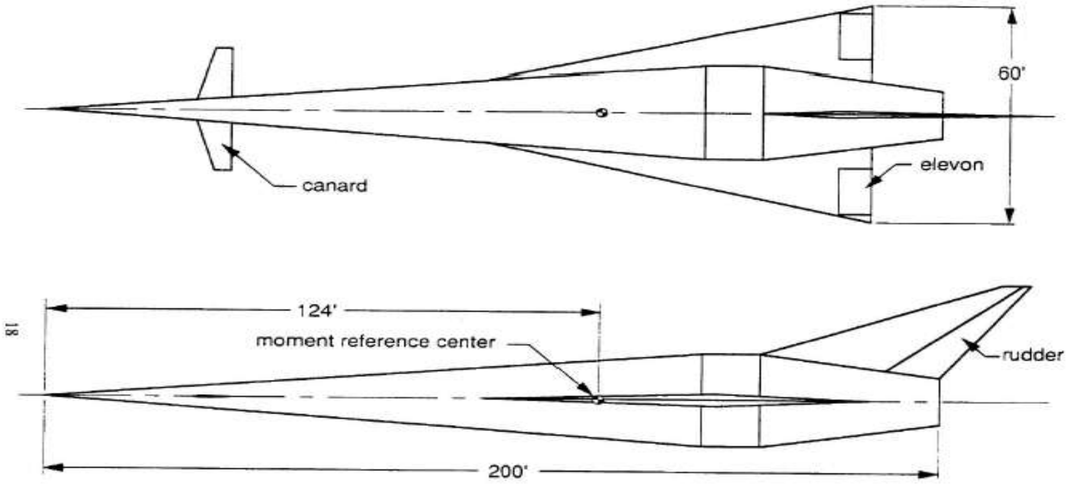

Fig-2: Generic Hypersonic Vehicle

This vehicle model is a winged cone hypersonic model. It has four control surfaces which are the right elevon, left elevon rudder and canards. The canards are control surfaces that increase lift at lower speeds. So at hypersonic speeds the canards are retracted and has no effect on the vehicle's performance. The vehicle has a scramjet engine which is fitted with the vehicles body itself which produces a thrust only in the X direction. The vehicle is assumed to be a rigid body for the simulations.[1]

3.2 Vehicle Dynamics

A 6-DoF (Degree of freedom) equations of motions have been derived from Newton's laws and Euler's theories. Dynamic equations and kinematic equations for translational and rotational equations define the vehicle dynamics. These are a set of differential equations

The translational kinematic **equations for the AHV are given as:**

$$\dot{x} = u\,\boldsymbol{\cos}\,\theta\,\boldsymbol{\cos}\,\psi + (\boldsymbol{\sin}\,\theta\,\boldsymbol{\sin}\,\phi\,\boldsymbol{\cos}\,\Psi - \boldsymbol{\cos}\,\Phi\,\boldsymbol{\sin}\,\Psi)v + (\boldsymbol{\cos}\,\phi\,\boldsymbol{\sin}\,\theta\,\boldsymbol{\cos}\,\psi + \boldsymbol{\sin}\,\phi\,\boldsymbol{\sin}\,\psi)w \qquad 1$$

$$\dot{y} = u\cos\theta\sin\Psi + (\sin\Phi\sin\theta\sin\Psi + \cos\Phi\cos\Psi)v + (\cos\Phi\sin\theta\sin\Psi - \sin\Phi\cos\Psi)w \qquad 2$$

$$\dot{h} = u\sin\theta - v\sin\Phi\cos\theta - w\cos\Phi\cos\theta \qquad 3$$

The **translational dynamic** equations for the AHV are given as:

$$\dot{u} = Rv - Qw - g\sin\theta + \frac{Fax + Ftx}{Mv} \qquad 4$$

$$\dot{v} = wP - vR + g\cos\theta + \frac{Fay}{Mv} \qquad 5$$

$$\dot{w} = uQ - vP + g\cos\theta + \frac{Faz}{Mv} \qquad 6$$

The **rotational dynamic** equations of the AHV are given as:

$$\dot{P} = C_1QR + c_2PQ + c_3L_{am} + c_4N_a \qquad 7$$

$$\dot{Q} = c_5PR - c_6(P^2 - R^2) + c_7M_a \qquad 8$$

$$\dot{R} = c_8PQ - c_2QR + c_4L_{am} + c_9N_a \qquad 9$$

The **rotational kinematic** equations of equations of AHV are given as:

$$\dot{\phi} = P + Q\, sin\, \phi\, tan\, \theta + R\, cos\, \phi\, tan\, \theta \qquad 10$$

$$\dot{\theta} = Q\, cos\, \phi - R\, sin\, \phi \qquad 11$$

$$\dot{\psi} = Q \sin \phi \sec \theta + R \cos \phi \sec \theta \qquad 12$$

Here u, v, w are the body velocities in x, y, z directions respectively. The roll angles, pitch angles and yaw angles are denoted byϕ, θ *and* ψ. The terms P, Q and R are the roll rate, pitch rate and yaw rates around the body x, y and z body fixed axis respectively**.** Moreover h denotes the altitude of the hypersonic vehicle in the inertial frame of reference and x, y is the distance traversed by the AHV in the inertial frame of reference .F_{ax}, F_{ay}, F_{az} are the aerodynamic body forces that acts on the hypersonic vehicle in the x, y and z directions respectively. F_{tx} is the thrust force produced by the scramjet engine along the body x axis. M_v is the mass of the vehicle and g is the acceleration to gravity acting on the AHV in the inertial frame of reference. L_{am}, N_a, M_a are the aerodynamic moments around the center of gravity of the vehicle. The coefficients c_1, c_2, ……, c_3 are calculated from the inertia values of the vehicle as given[4]

$$\left|\begin{matrix} \boldsymbol{c_1} \\ \boldsymbol{c_2} \\ \boldsymbol{c_3} \\ \boldsymbol{c_4} \\ \boldsymbol{c_8} \\ \boldsymbol{c_9} \end{matrix}\right| = \frac{\mathbf{1}}{\boldsymbol{I_{xx}I_{zz} - I_{xx}^2}} \left|\begin{matrix} \boldsymbol{I_{zz}(I_{yy} - I_{zz}) - I_{xz}^2} \\ \boldsymbol{I_{xz}(I_{zz} + I_{zz} - I_{yy})} \\ \boldsymbol{I_{zz}} \\ \boldsymbol{I_{yz}} \\ \boldsymbol{I_{xx}(I_{xx} - I_{yy}) - I_{xz}^2} \\ \boldsymbol{I_{xx}} \end{matrix}\right|$$

$$\boldsymbol{c_5 = (I_{zz} - I_{xx})I_{yy}} \qquad \boldsymbol{c_6 = \frac{I_{xx}}{I_{yy}}} \qquad \boldsymbol{c_7 = \frac{1}{I_{yy}}}$$

IV. RESULTS AND DISCUSSION

Table-1: Trim states at a given Mach number and altitude

Output Trim States	Mach 6, Altitude 24,000m	Mach 7, Altitude 24,000m	Mach 6, Altitude 27,000m
v	2.95×10^{-15}	4.52 ×10□15	2.11 × 10□15
w	91.8673	85.5417	153.26
θ	0.051	0.041	0.085
δ_a	-7.215	-6.060	8.69
δ_e	-7.215	-6.060	8.69

δr	3.58×10^{-15}	3.87×10^{-15}	2.58×10^{-15}
σ_t	0.194	0.191	0.180

Other values that are calculated using the output trim states are pitch angle (α), side slip angle (β), dynamic pressure ($\bar{q}$) and total velocity (Vt) as shown below

$$\alpha = \tan^{-1}\frac{w}{u}$$

$$\beta = \sin^{-1}\frac{v}{Vt}$$

$$\bar{q} = \frac{1}{2} \times (\text{ Air Density}) \times (V_t)^2$$

$$V_t = \sqrt{u^2 + v^2 + w^2}$$

Table 2: Calculated output parameters

Calculated Parameters	Mach 6, Altitude 24,000m	Mach 7, Altitude 24,000m	Mach 6, Altitude 27,000m
α	2.94	2.34	4.87
β	1.65×10^{-18}	2.17×10^{-18}	1.16×10^{-18}
$\bar{q}$	7.40×10^{4}	1.00×10^{5}	4.68×10^{4}
V_t	1789.04	2086.22	1805.31

V. CONCLUSION

A hypersonic winged cone model was selected and its aerodynamic properties were studied in detail. A trimming routine was developed for the winged cone vehicle model. Trim conditions for the vehicle was developed for the vehicle when it is in steady, wings level flight at constant altitude and Mach number. A 6-Dof equations of motions is derived to describe the vehicle dynamics. Aerodynamic forces and moments were calculated using the hypersonic winged cone model database for each control surface. Newton's method is used to solve the system of simultaneous nonlinear differential equations. The deflections of the control surfaces was found out at various trim conditions. It was seen that the numerical outputs for the trim conditions match with the theoretical values.

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