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Aerodynamic stability analysis for hypersonic experiments

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Abstract

Several hypersonic experiments have been executed in the last years using sounding rockets. Some examples are BOLT, HiFIRE, and SHEFEX experiments in which research topics like laminar-turbulent transition, scramjet propulsion, and thermal protections are explored. Some of these experiments have singular aerodynamic characteristics since the rockets, together with their payloads, do not have the typical axial symmetry of a sounding rocket. Such configuration poses some problems since sounding rockets generally are aerodynamically stabilized. Therefore, a detailed aerodynamic analysis of the vehicle is required to ensure that the rocket flight is stable. In this paper, aerodynamic coefficients are calculated for different configurations of a hypersonic vehicle composed of a non-axisymmetric payload (the hypersonic experiment itself) plus a sounding rocket. The coefficients are analyzed regarding aerodynamic and flight dynamic aspects. Finally, the more appropriate configuration in terms of aerodynamic stability is presented.

Keywords: *Hypersonic, sound rocket, aerodynamics, stability*

Nomenclature

L_{ref} – Reference length
S_{ref} - Reference area
X_{cp} – Position of the center of pressure
x_{cm} – Position of the center of mass
S_m – Static margin in the pitch plane
S'_m – Static margin in the yaw plane
C_N – Coefficient of normal force
N – Normal force
q_{din} – Dynamic pressure
C_m – Coefficient of pitch moment
m – Pitch moment
C_y – Coefficient of lateral force
C_{N0} - Coefficient of normal force at null variations
C_{Y0} - Coefficient of lateral force at null variations
C_{m0} - Coefficient of pitch moment at null variations
C_{n0} - Coefficient of yaw moment at null variations
$C_{N\alpha}$ - Derivative of the coeff. of normal force relative to angle of attack
$C_{m\alpha}$ - Derivative of the coeff. of pitch moment relative to angle of attack
$C_{Y\beta}$ - Derivative of the coeff. of lateral force relative to angle of sideslip
$C_{n\beta}$ - Derivative of the coeff. of yaw moment relative to angle of sideslip
$\vec{V}$ - air flow velocity
α - Angle of attack
β - Angle of sideslip
$\bar{q}$ - Pitch rate
$\bar{r}$ - Yaw rate

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1. Introduction

In the last years several hypersonic experiments have been conducted using sounding rockets. The Boundary Layer Transition (BOLT) flight experiment is a example of such experiments that had as objective obtain experimental information about boundary layer transition on hypersonic regime [1]. The HiFiRE 5 is another example of experiment using a sounding rocket that envisioned to explore the laminar turbulent transition [2]. Other experiments have also been conducted, such as HiFIRE 2, which had the objective of testing a scramjet engine [3], or the SHEFEX I, intended to analyze the behavior of a new concept of thermal protection in flight [4]. A common characteristic in all these examples is that during in some part of the flight the rocket had a non-axisymmetric payload exposed.

This exposed non-axisymmetric payload generates a problem, since the rocket is no more axisymmetric. Sounding rockets generally do not have a control system and use passive aerodynamic stabilization to ensure their dynamic stability along the atmospheric flight. The asymmetries in these experiments modify the vehicle's aerodynamics and can make a rocket no more stable. Therefore, in order to ensure rocket stability, a detailed aerodynamic analysis of the vehicle is necessary. This paper analyzes the aerodynamic stability of different configurations of a proposal of hypersonic vehicle composed of a non-axisymmetric payload (the hypersonic experiment itself) plus a sounding rocket.

A sounding rocket must be chosen in order to realize the analysis of stability. The Brazilian sounding rocket VSB-30 has been used on several occasions [5] to support such hypersonic experiments and it is a candidate for future experiments. VSB-30 consists of the first stage with booster S31, the boost adapter, the second stage with the motor S30, and finally, the payload, where the hypersonic experiment is positioned. The burning time of the S31 is 16 s and for the S30 is 30 s [6]. Therefore, the VSB-30 is the rocket chosen to be used in the analysis.

The mission of this hypersonic experiment consists of launching the vehicle in a trajectory that permits it to achieve certain conditions of Mach and altitude. The analysis presented here focuses on the early stages of the flight when the rocket can suffer stability problems resulting from its non-conventional geometry. Two configurations of the rocket are analyzed. These configurations differ in the type of fins used in the rocket's first stage. The first type consists of smaller trapezoidal fins, and the second corresponds to greater swept fins. These geometries are used in CFD simulations to generate aerodynamic coefficients that cover all the flight of the first stage.

Fluent and other programs present in the ANSYS bundle are used to obtain the necessary aerodynamic coefficients using CFD. Fluent has already been used to calculate aerodynamic coefficients for missile like geometries resulting in good agreement with the experimental data [7]. Rocket stability is analyzed in terms of static margin concept calculated from the results of the CFD simulations. Finally, a comparison between the static margin from different configurations is made to determinate which one is appropriate to fly.

2. Aerodynamically stabilized rockets

The aerodynamic forces and moments that act on a rocket can be modeled through aerodynamic coefficients. These coefficients may be associated with dimensionless factors. For example, if N is the aerodynamic normal force and m is the aerodynamic pitch moment, the respective dimensionless coefficients are defined by:

$$C_N = \frac{N}{q_{din} S_{ref}} \tag{1}$$

$$C_m = \frac{m}{q_{din} S_{ref} L_{ref}} \tag{2}$$

where q_{din} is the dynamic pressure at the infinity, S_{ref} is the reference area and L_{ref} is the reference length. A diagram with the system of reference for the aerodynamic coefficients of interest is presented in Fig. 1.

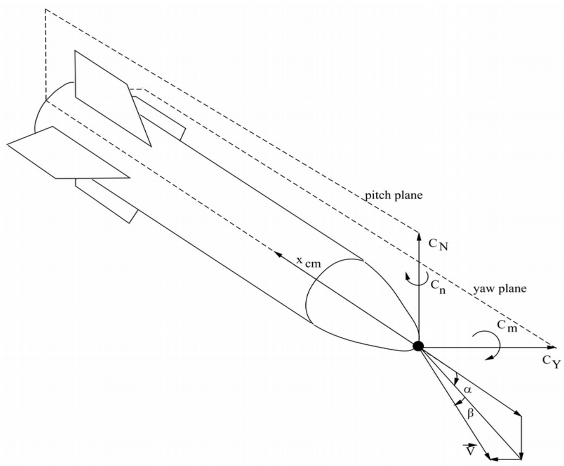

Fig 1. System of aerodynamic coefficients.

In Fig. 1 the coefficients are: the coefficient of normal force C_N , coefficient of lateral force C_Y , coefficient of pitch moment C_m and coefficient of yaw moment C_n . The angles of attack α and sideslip β , the air flow velocity $\vec{V}$ and the position of the center of mass x_{cm} are also presented.

Generally, rockets are designed to flight with small perturbations in atmospheric trajectories close to the gravity turn. It means that the variations of the aerodynamic coefficients relatively to parameters like angle of attack, angle of sideslip or dimensionless rotational rates are small. This allows modeling the coefficients as a linear Taylor expansion relatively to these variables [8].

$$C_N = C_{N0} + C_{N\alpha}\alpha + C_{N\bar{q}}\bar{q} \tag{3}$$

$$C_m = C_{m0} + C_{m\alpha}\alpha + C_{m\bar{q}}\bar{q} \tag{4}$$

where $\bar{q}$ is the pitch rate, C_{N0} and C_{m0} are the coefficient of normal force and pitch moment at null variation of parameters, $C_{N\alpha}$ and $C_{N\bar{q}}$ are the stability derivatives of force normal relative to the angle of attack and pitch rate and $C_{m\alpha}$ and $C_{m\bar{q}}$ are the stability derivatives of pitch moment relative to the angle of attack and pitch rate. This set of coefficients are related to the rocket longitudinal dynamic and their variation relative to the sideslip angle is in general negligible. For a symmetric rocket relatively to the yaw plane, like the ones used in hypersonic experiments in study, the values of C_{N0} and C_{m0} are null.

The pitch moment coefficient requires a point of reference to be calculated. In general, this point is the vehicle nose. The static stability of the vehicle can be evaluated considering the moment relatively to the vehicle center of gravity. The expression with the transformation of the center of reference is:

$$C_m^{cm}=C_m-\frac{x_{cm}}{L_{ref}}C_N=\left(C_{m\alpha}-\frac{x_{cm}}{L_{ref}}C_{N\alpha}\right)\alpha+\left(C_{m\bar{q}}-\frac{x_{cm}}{L_{ref}}C_{N\bar{q}}\right)\bar{q} \quad (5)$$

where x_{cm} is the longitudinal position of the rocket center of mass. The longitudinal stability corresponds to a rocket rotational motion in the pitch plane and the longitudinal static stability criteria consists in ensure that the term

$$\left(C_{m\alpha}-\frac{x_{cm}}{L_{ref}}C_{N\alpha}\right)>0 \quad (6)$$

what means that when the angle of attack increases a positive pitch moment will be generated, acting to reduce the angle of attack, and ensuring the rocket stability. This term can be rewritten with the introduction of the center of pressure x_{cp} and the static margin:

$$S_m=\left(C_{m\alpha}-\frac{x_{cm}}{L_{ref}}C_{N\alpha}\right)\frac{1}{C_{N\alpha}}=\frac{\left(x_{cp}-x_{cm}\right)}{L_{ref}} \quad (7)$$

where

$$x_{cp}=\frac{C_{m\alpha}}{C_{N\alpha}}L_{ref} \quad (8)$$

S_m is the value of reference for longitudinal stability [9]. In fact, for the VSB-30, a minimum value of 1.5 is required. The value of reference corresponds to the maximal value of diameter of the rocket central body.

In the case of an axisymmetric vehicle, the symmetry ensures that the longitudinal stability will result in lateral stability. However, the same is not true for a vehicle with bilateral symmetry, which is the case for the type of hypersonic experiment under analysis. In this case, an analysis of lateral static stability is also necessary. In fact, the analysis is quite similar. The coefficients of lateral force and yaw moment expand as:

$$C_Y=C_{Y\beta}\beta+C_{Y\bar{r}}\bar{r} \quad (9)$$

and

$$C_n=C_{n\beta}\beta+C_{n\bar{r}}\bar{r} \quad (10)$$

where $\bar{r}$ is the yaw rate. Converting the yaw moment coefficient to the center of mass, the resulting expression is:

$$C_n^{cm} = C_n - \frac{x_{cm}}{L_{ref}} C_Y = \left(C_{n\beta} - \frac{x_{cm}}{L_{ref}} C_{Y\beta} \right) \beta + \left(C_{n\bar{r}} - \frac{x_{cm}}{L_{ref}} C_{Y\bar{r}} \right) \bar{r} \tag{11}$$

Defining the center of pressure x'_{cp} relatively the yaw plane as:

$$x'_{cp} = \frac{C_{n\beta}}{C_{Y\beta}} L_{ref} \tag{12}$$

the expression of stability margin in the yaw plane is obtained as:

$$S'_m = \frac{\left(x'_{cp} - x_{cm} \right)}{L_{ref}} \tag{13}$$

Finally, the complete static stability of the non-axysimmetric vehicle can be obtained ensuring that the values of stability margin for the pitch and yaw planes be greater than the minimal required value.

3. Aerodynamic model

The aerodynamic model was developed using computational tools provided by ANSYS. The geometries analyzed are similar with the main difference in the fins of the first stage. The first configuration has four trapezoidal fins in the first stage, called trapezoidal fin set. The second configuration has four swept fins in the first stage, what will be termed swept fin set. The swept fin set is the same used in the second stage. These two geometries are presented in Fig. 2 and 3.

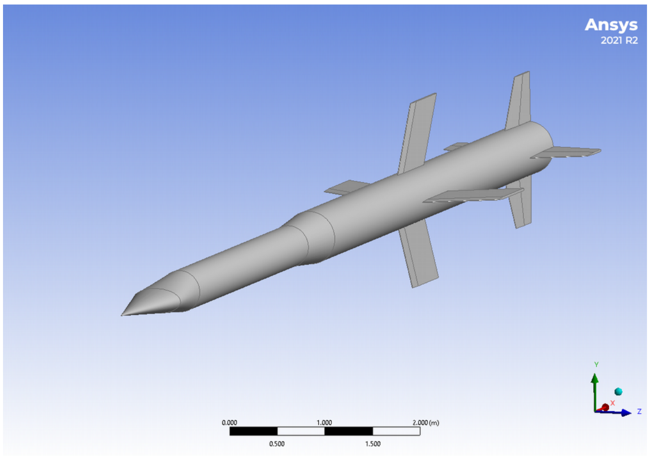

Fig 2. Geometry with the trapezoidal fin set in the first stage.

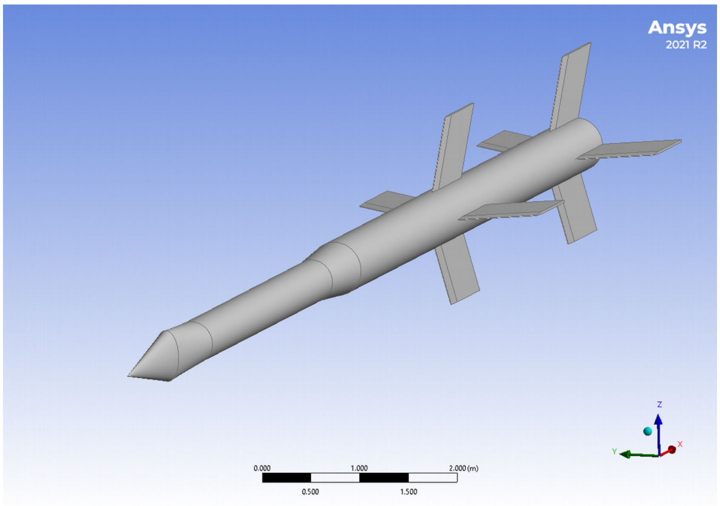

Fig 3. Geometry with the swept fin set in the first stage.

The non-structured meshes used in the study are composed of a mix of prismatic and tetrahedral elements. The vehicle presents two symmetry plans that are the pitch and the yaw plans of analysis. Therefore, the meshes used can be generated with half of the complete domain, resulting in the economy of computational effort. A prismatic layer of elements covers the surface of the rockets to result in a best solution for the boundary layer. The domain is spherical since the majority of the simulations occur in the subsonic regime. A series of regular and refined meshes with a number of elements varying from 19.0 million to 38.0 million elements were used. The regular meshes were used in many simulations and the refined ones were used in the mesh convergence analysis. Some details of the meshes can be observed in the Fig. 4 and 5.

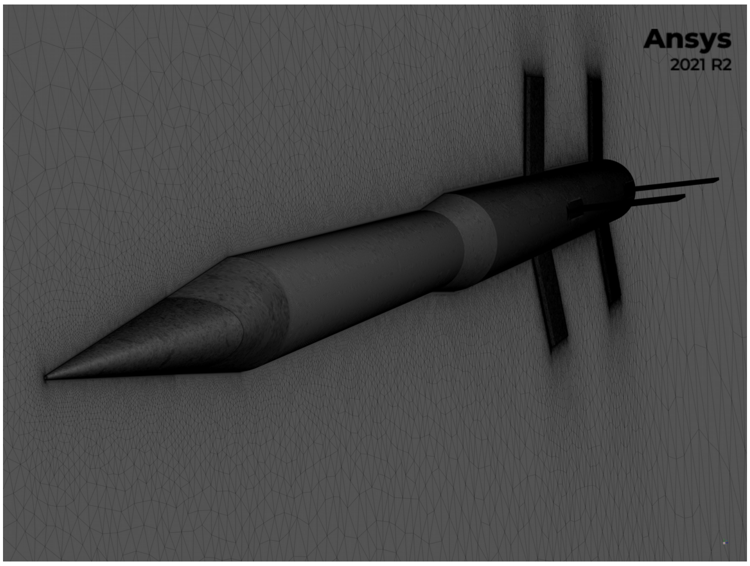

Fig 4. Detail of the mesh in the region of the experiment.

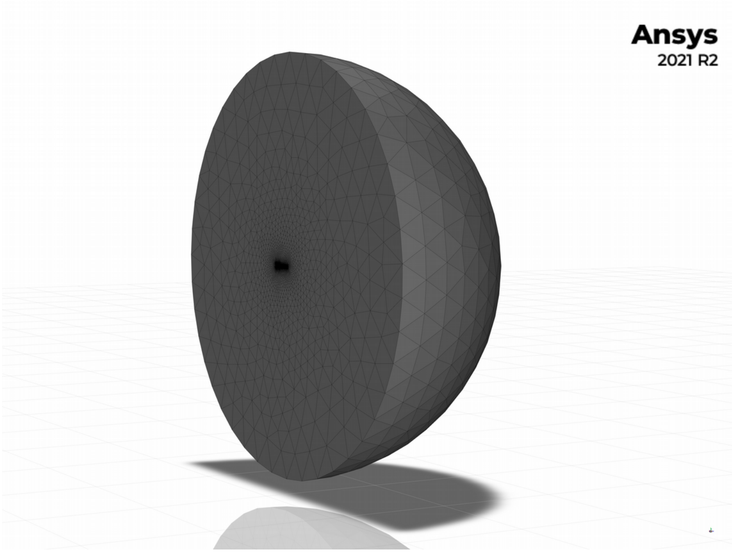

Fig 5. Mesh and the complete view of the domain.

The Fluent RANS solver has several options to conduct simulations. The pressure-based solver was chosen because it ensures good results with faster convergence. The scheme was chosen coupled since it also improves convergence. The flowchart of the solver is presented in Fig. 6. It is possible to verify that the momentum and continuity equations are solved simultaneously. Next, the mass flux in the faces of the elements is solved, and finally the remaining governing equations [10].

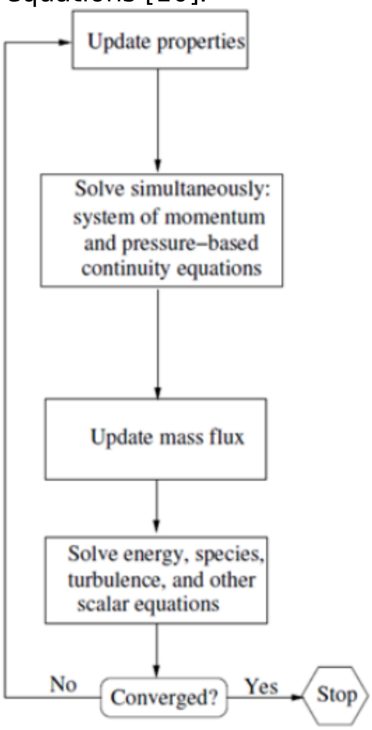

Fig 6. Pressure-based coupled algorithm. Obtained from [10].

The realizable k-epsilon turbulence model is used because it has a less restrictive requirement of y+ relatively to other models. Smaller y+ results in finer meshes and increases the computational cost. This model requires y+ between 30 and 300 to ensure good results.

The boundary conditions imposed on the domain are adiabatic wall for the vehicle, a symmetry plane for pitch or yaw planes, depending on the case, and pressure far field for the external surface of the hemisphere. The conditions on the far field are obtained from a reference trajectory. They are parametrized by the Mach number and are presented in Table 1

Table 1. Environmental conditions used in the simulations

Mach [-]	Pressure [Pa]	Temperature [K]	Altitude [km]
0,1	100541	287,7	0,065
0,3	99788	287,3	0,129
0,5	98365	286,5	0,249
0,9	88758	281,0	1,103
1,1	83177	277,5	1,634
1,3	77478	273,8	2,207
2	67541	266,7	3,294

The simulations uses angle of attack or angle of sideslip equal to 1°. From the simulations considering the pitch plane case the values of C_N and C_m are obtained and from the simulations considering the yaw plane case the values of C_Y and C_n are obtained. The stability derivatives and pressure centre values can be calculated considering the previous equations.

4. Results

The simulations were conducted for all configurations and environmental conditions until each reached the aerodynamic coefficients' convergence.

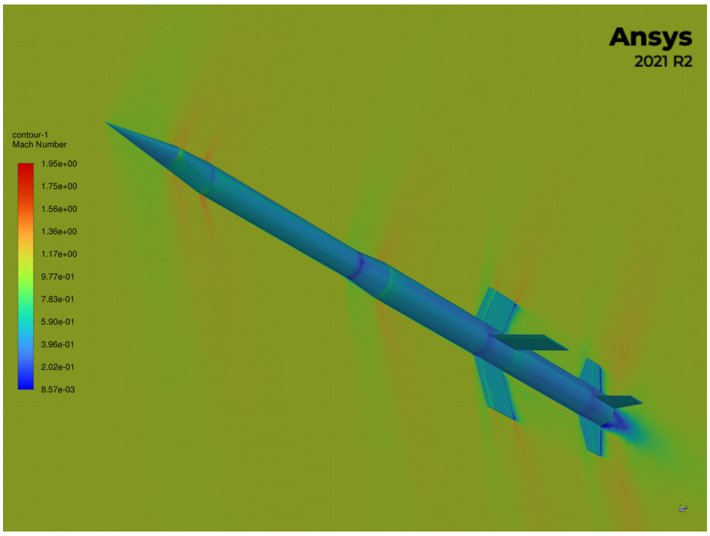

Fig 7. Contours of Mach number for the trapezoidal fins yaw plane case. Mach 1.1.

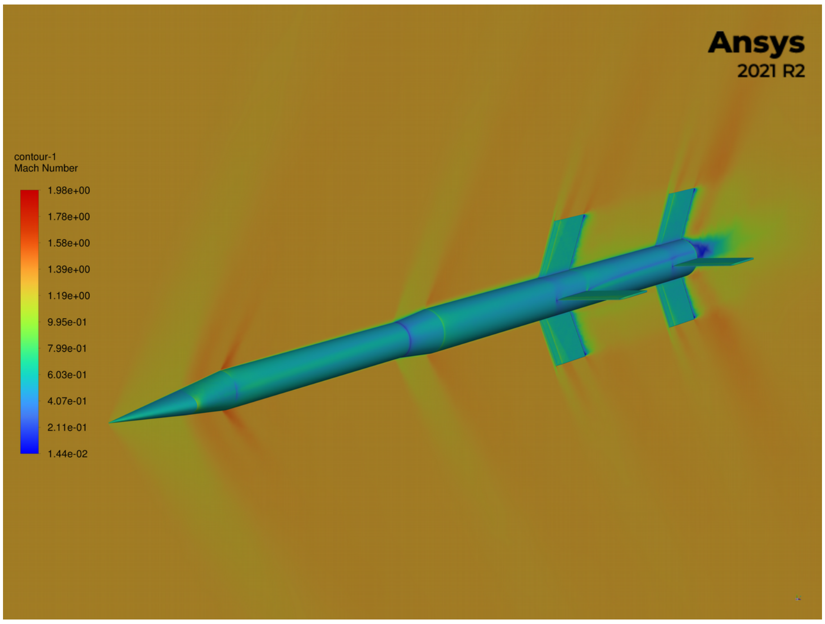

Fig 8. Contours of Mach number for the swept fins yaw plane case. Mach 1.3.

The contour of Mach number for the configuration swept in the pitch plane is presented in Fig. 7 and 8. The system of shock waves formed by the asymmetric geometry of the hypersonic experiment can be observed.

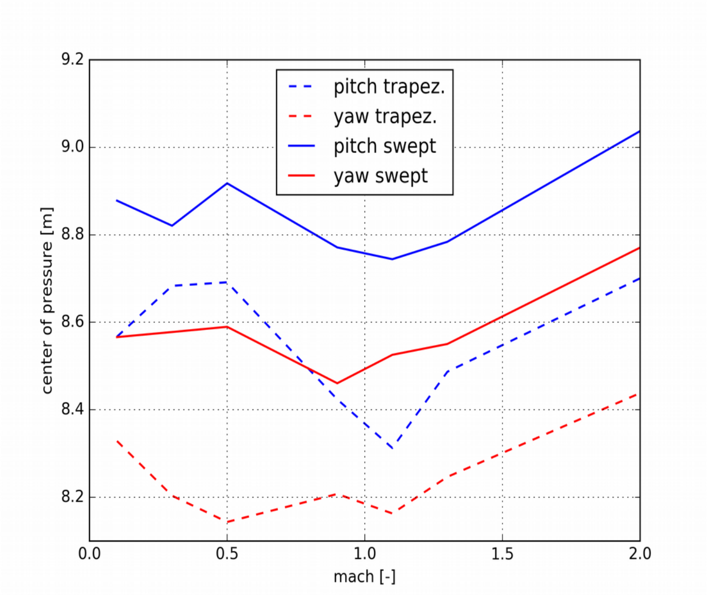

Fig 9. Comparison between values of position of pressure center for the longitudinal e lateral cases and trapezoidal and swept fins sets.

Fig. 9 shows that the x_{cp} increased for the swept fin set relatively to the trapezoidal one. This behaviour was expected since the swept fin set is greater than the trapezoidal one and its iteration with the flow generates greater aerodynamic loads. But it is also remarkable that the values referent to the yaw plane are smaller than the ones of the pitch plane. It indicates that the rocket tends to be less stable in terms of lateral stability than longitudinal stability.

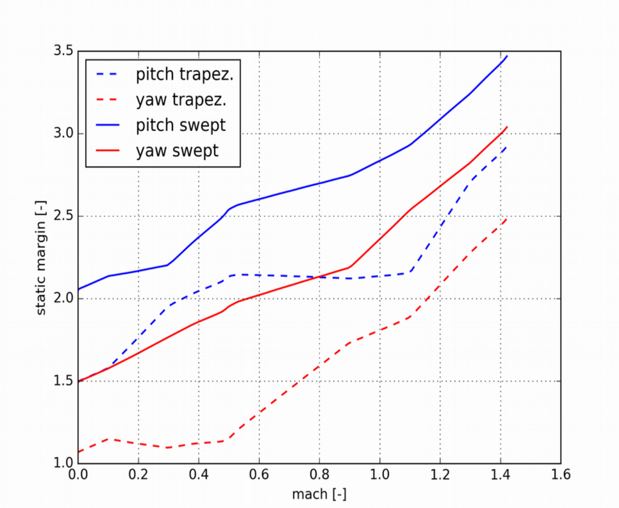

Fig 10. Static margin for both pitch and yaw planes and cases trapezoidal and swept versus Mach number.

Fig. 10 shows the static margin versus Mach number, considering the trapezoidal and swept fin sets and the pitch and yaw planes. It is possible to observe that only the static margin of the trapezoidal case in the yaw plane was smaller than the minimal requirement of static margin of 1.5 up to Mach number 0.7, approximately. These results imply that this case is not acceptable regarding aerodynamic stability, which discards the use of the configuration trapezoidal in the conceptual hypersonic experiment. Finally, the case of swept fins in the first stage is the most appropriate for the experiment.

Conclusions

The study presented the analysis of stability of non-axisymmetric sounding rocket, which is recurrent for hypersonic experiments. A concept of hypersonic experiment was proposed using the VSB-30 as rocket, in two different configurations. A methodology of analysis based on the expansion of a typical approach was carried out. Aerodynamic coefficients were calculated using CFD and finally, the curves of static margin were presented together with the determination of which configuration is the most appropriate for flight.

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