VI CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
VI NATIONAL CONGRESS OF MECHANICAL ENGINEERING
18 a 21 de agosto de 2010 – Campina Grande – Paraíba - Brasil
August 18 – 21, 2010 – Campina Grande – Paraíba – Brazil

WIND TUNNEL TESTS OF THE SONDA III AEROSPACE VEHICLE

Maria Luísa Collucci da Costa Reis[1], mluisareis@iae.cta.br
João Batista Pessoa Falcão Filho[1], jb.falcao@ig.com.br
Olympio Achilles de Faria Mello[2]. oamello@gmail.com

[1] Instituto de Aeronáutica e Espaço, Praça Mal. Eduardo Gomes, 50, CEP 12226-904, São José dos Campos, SP
[2] Atech, Rua do Rocio, 313, CEP 04552-000, São Paulo, SP

Abstract: *Scale models of aerospace vehicles are tested in wind tunnels in order to predict the performance of their full-scale counterparts during actual flight. A test campaign of the sounding rocket vehicle Sonda III is being carried out at the Brazilian Pilot Transonic Facility of the Institute of Aeronautics and Space. The Sonda III is a two stage research rocket designed to carry a payload capable of supplying technical data of experiments conducted under microgravity conditions. A model of the second stage of the vehicle was tested for several angles of attack, at Mach numbers in the transonic range. The purpose of the first part of the campaign is to estimate the aerodynamic loads that act on the test article. This paper describes the model and airflow configurations of the experiment and presents the results of these tests. The aerodynamic loads consist of three forces referred to as drag, side, and lift, and three moments denominated as rolling, pitching, and yawing. The loads are measured by a six-component aerodynamic internal balance whose sensor elements are strain gages arranged in Wheatstone bridges. The strain gage readings and the aerodynamic loads are related to a so-called calibration matrix composed of parameters evaluated during the balance calibration. Besides the aerodynamic loads, the measured parameters during the tests are total pressure, static pressure and total temperature. The data reduction consists of obtaining the variation of aerodynamic coefficients with angle of attack for the range of Mach number covered in the tests. Curves of load coefficients versus angle of attack are shown. Variation of the drag, lift and pitching coefficients with the Mach number and the behavior of lift force and pitching moment coefficient gradient with the Mach number for angle of attack equal to zero are compared with specialized bibliography. Error analysis revealed that the forces and moments measured by the balance are the dominant components of the uncertainty in the estimated aerodynamic load coefficients, the contribution of the measurement of flow field parameter, being negligible. Sources of errors of the experiment are pointed out and the proposed methodology used to minimize them is described.*

***Keywords*:** sounding rocket, wind tunnel tests, metrological reliability

1. INTRODUCTION

The vehicle SONDA III is a sounding rocket developed by the Brazilian Institute of Aeronautics and Space (IAE). This is a double stage vehicle with 0.30 m diameter second stage, capable of carrying a payload of approximately 100 kg up to an altitude of 600 km (Fig. 1). It is one of the sounding rocket family named Sonda, which started with Sonda I, first launched in 1965. Sonda III was launched twenty seven times between 1976 and 2002.

Two stage vehicle
Total length: 8 m
Maximum diameter: 0.557 m
Total mass: 1548 kg
Payload mass: 100 kg
Apogee: 600 km

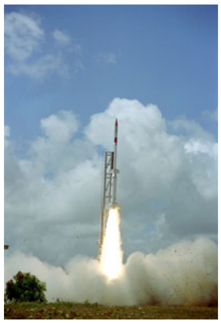

Figure 1. Sonda III sounding rocket.

The aim of this study is to obtain the data reduction and analyze the results of the tests of scaled models of the rocket, carried out at the Pilot Transonic Wind Tunnel Facility (PTWT) in IAE. (Fig. 2).

Figure 2. The Pilot Transonic Wind Tunnel Facililty (PTWT).

In a wind tunnel, the air flows over the test article, simulating actual flight conditions. Data originating from tests are used to predict flight performance of the full scale counterpart.

The procedures and methodologies employed will be used as a guide in future tests for other aerospace vehicles developed by Brazilian aerospace programs.

Measured quantities include total pressure, static pressure and total temperature of the flow, as well as the strain gage readings supplied by an internal balance.

2. THE WIND TUNNEL TESTS

This paper presents the estimated aerodynamic coefficients resulting from the tests of the second stage of Sonda III, for angles of attack, α , varying from -10º to +10º and for Mach numbers, M, varying from 0.30 to 1.00. The model was fixed in a sting support with the fins in a crossed position (–⌖–) in relation to the wind tunnel test section (Fig. 3a). The model used in this study is around 0.35 m length and has fins aligned at 0^o relating to the longitudinal axis of the fuselage (Fig. 3b).

a) b)

Figure 3. a) Second stage model at the test section. b) From left to right, models with fins at 0^o, 2.5^o and 5^o.

The internal balance, the instrument which measures the aerodynamic loads acting on the test article (Fig. 4) is located inside the fuselage. A balance measures the loads by using strain-gages, arranged in a Wheatstone bridge, in which the strain produced by the loads is measured (AIAA, 2003). A balance calibration is performed prior to the tests to evaluate the numerical relationship between the voltage and loads applied (Reis et al., 2008).

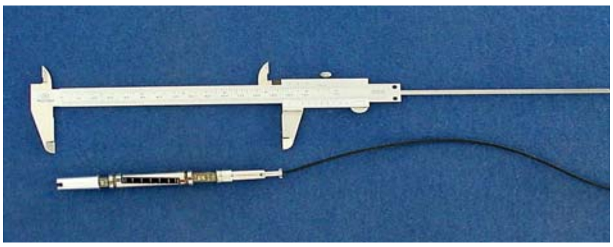

Figure 4. Internal multicomponent balance.

3. DATA REDUCTION

Data reduction includes the estimation of:

− balance calibration polynomial parameters;
− force coefficients: drag (C_D), side force (C_{SF}), lift (C_L);
− moment coefficients: rolling (C_r), pitching (C_m), yawing (C_y);
− lift force and lift moment gradient coefficients; and
− uncertainties in the load coefficients.

Source of errors are investigated, quantified and minimized whenever possible. Uncertainties in the parameters are evaluated according to international standardization (ISO/BIPM, 1995).

3.1. Force and Moment Coefficients

The force coefficients, C_F, and the moment coefficients, C_m, are evaluated through the expressions (1) and (2) respectively (Anderson, 1985):

$$C_F = \frac{F}{qA} \tag{1}$$

$$C_m = \frac{m}{qAl} \tag{2}$$

F: aerodynamic force (drag, side or lift);
m: aerodynamic moment, (rolling, pitching or yawing);
q: dynamic pressure;
A: reference area which corresponds to the cross sectional area of the fuselage, equal to 6.2×10^{-4} m^2; and
l: reference length which corresponds to the diameter of the fuselage, equal to 2.8×10^{-2} m.

3.2. Law of Propagation of Uncertainty

According to ISO/BIPM, 1995, the value of the uncertainty in measurement is the positive root square of Eq. (3):

$$u_c^2 = \sum_{i=1}^{N}\left(\frac{\partial y}{\partial x_i}\right)^2 u^2(x_i) \tag{3}$$

where y is the output quantity and $x_{i's}$ are the input quantity. Equation (3) is called the law of propagation of uncertainty.

Applying Eq. (3) to Eqs. (1) and (2) results in the values of the uncertainty in the aerodynamic load coefficients. For example, for the drag force coefficient, C_D, the estimated uncertainty is:

$$u_{C_D}^2 = \left(\frac{\partial C_D}{\partial D}\right)^2 u_D^2 + \left(\frac{\partial C_D}{\partial q}\right)^2 u_q^2 + \left(\frac{\partial C_D}{\partial A}\right)^2 u_A^2 \tag{4}$$

which leads to:

$$u_{C_D}^2 = \left(\frac{1}{qA}\right)^2 u_D^2 + \left(\frac{-D}{q^2A}\right)^2 u_q^2 + \left(\frac{-D}{qA^2}\right)^2 u_A^2 \tag{5}$$

The same procedure is applied to side force, C_{SF}, lift force, C_L, pitching moment, C_m, rolling moment, C_r, and yawing moment, C_y.

3.3. Internal Balance Calibration

The balance is calibrated by applying known loads to the balance and recording the output of the bridges. Using the least squares method results in the estimation of parameters a and b of the polynomial which relates the strain gage readings R to the aerodynamic loads (Reis et al., 2008):

$$F_i = \sum_{j=1}^{6} a_{i,j}R_j + \sum_{j=1}^{6}\sum_{k=j}^{6} b_{i,j,k}R_jR_k \tag{6}$$

As an example, for the drag force D, Eq. (6) becomes:

$$D = a_{1,1}R_1 + a_{1,2}R_2 + a_{1,3}R_3 + ... + a_{1,6}R_6 + b_{1,1,1}R_1R_1 + b_{1,1,2}R_1R_2 + ... + b_{1,6,6}R_6R_6 \quad (7)$$

3.4. Lift Force and Pitching Moment Coefficient Gradient

The gradient of lift and pitching coefficients at $\alpha = 0^o$, named $C_{L\alpha}$ and $C_{m\alpha}$ respectively, are evaluated by taking the derivative of the third degree polynomials fitted to the curves $C_L \times \alpha$ and $C_m \times \alpha$, and solving it for $\alpha = 0^o$. This quantity is also known as the stability derivative and is an important parameter for the development of the aircraft control system. The choice of the polynomial degree was based on the chi-square quantity, χ^2 (Press et al., 1992).

4. RESULTS AND DISCUSSION

The following sections will present the aerodynamic coefficient values of the drag force, C_D, lift force, C_L, and pitching moment, C_m, versus angles of attack, α, of the Sonda III second stage model, for different velocities of wind tunnel flow. Estimation of the lift and pitching gradients for $\alpha = 0^o$ will be shown as well.

4.1. Drag Force Coefficient

Variation the drag force coefficient, C_D, versus the orientation of the body in the flow, α, is presented in Figure 5 for Mach number, M, equal to 0.30. Near $\alpha = 0^o$, the behavior of this aerodynamic load component is as predicted (Schlichting, 1979). The drag coefficient is approximately proportional to the square of the angle of attack, α. Uncertainty curves, u_{CD}, are also shown, for a 95 % level of confidence (ISO/BIPM, 1995). Values of u_{CD} are estimated using Eq. (5). Analysis of uncertainty revealed that the first term u_D in Eq. (5), corresponding to the measurement of the input quantity D, is the dominant component of uncertainty in C_D. Two sources of error contribute to the value of u_D: the balance calibration and the dispersion of the wind tunnel flow, quantified through the standard deviation of the signal.

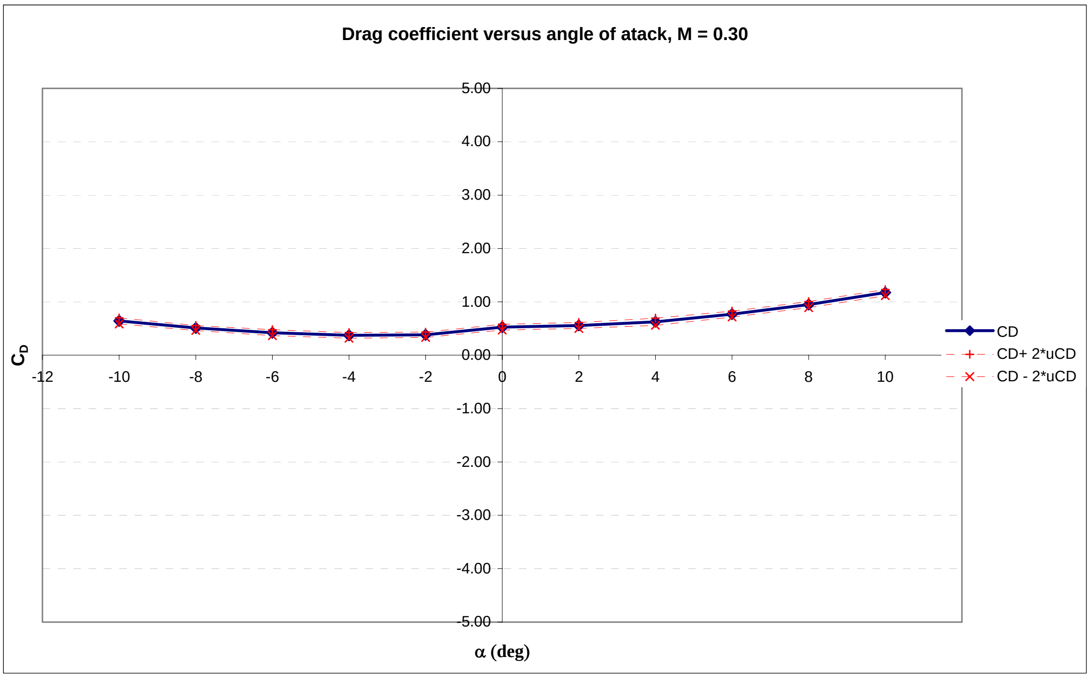

Figure 5. Drag coefficient and uncertainty versus angle of attack, for Mach number equal to 0.30.

Figure 6 presents curves of $C_D \times \alpha$ for the range of Mach numbers covered in the tests. For M = 1.00, the drag force value for $\alpha = -10^o$ exceeds the balance load capacity and is not part of the experimental data. Uncertainty limits were suppressed for clarity.

It is noted that the curves are not symmetrical in relation to $\alpha = 0^o$, indicating that the methodology employed in the tests must be changed. The procedure adopted nowadays is to start the tests at positive angles, from 0^o up to 10^o. Afterwards, the attitude α of the model is directly moved to the angle equal to -2^o, therefore the positioning system of the test section sweeps the largest mechanical path. Besides, the strain gages of the balance may have already been subjected to their limit loads. The proposal for future tests is to measure the zero error values (defined in JCGM 200,

2008) of the internal balance when the attitude of the model changes from positive to negative values. Nowadays, the zero error value is measured only at the beginning of each run, when $\alpha = 0^o$. Another option to be analyzed is to carry out the tests varying α from -10°, passing through 0° and finally reaching + 10°. To vary the time of acquisition of experimental data can also be considered, with the object of investigating the temperature effect on the sensors of the balance. Furthermore, internal balance calibration at several ranges of temperature is suggested as well.

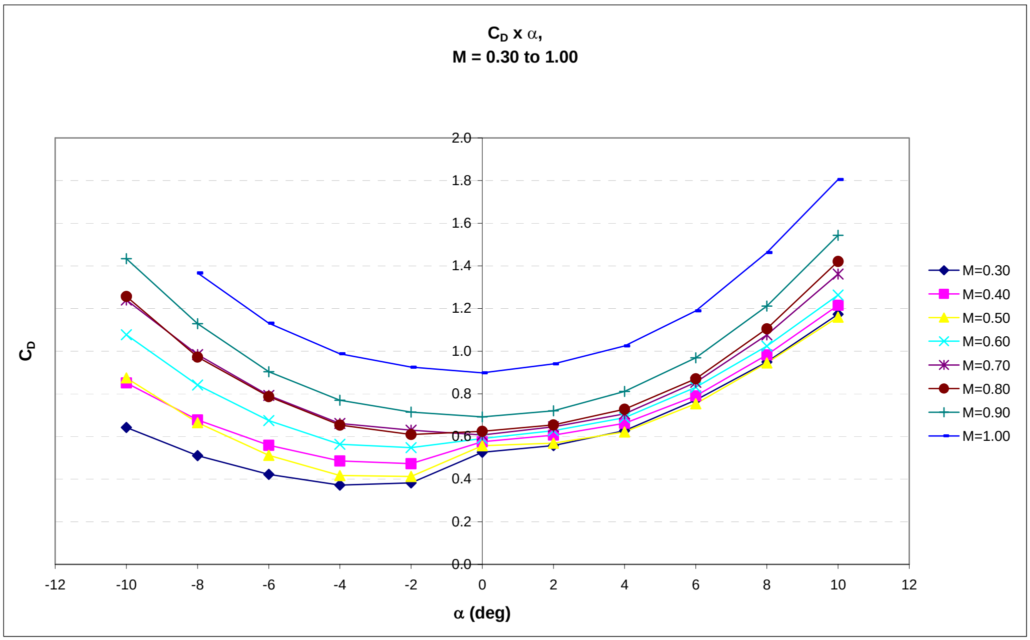

Figure 6. Curves $C_D \times \alpha$ for Mach number varying from 0.30 to 1.00.

4.2. Lift Force Coefficient

Variations of lift force coefficient, C_L, with angle of attack α are presented in Fig. 7. Lift coefficient increases when the vehicle angle of attack increases. Third order degree polynomials were fitted to the data points using the least squares methodology (Press et al., 1992).

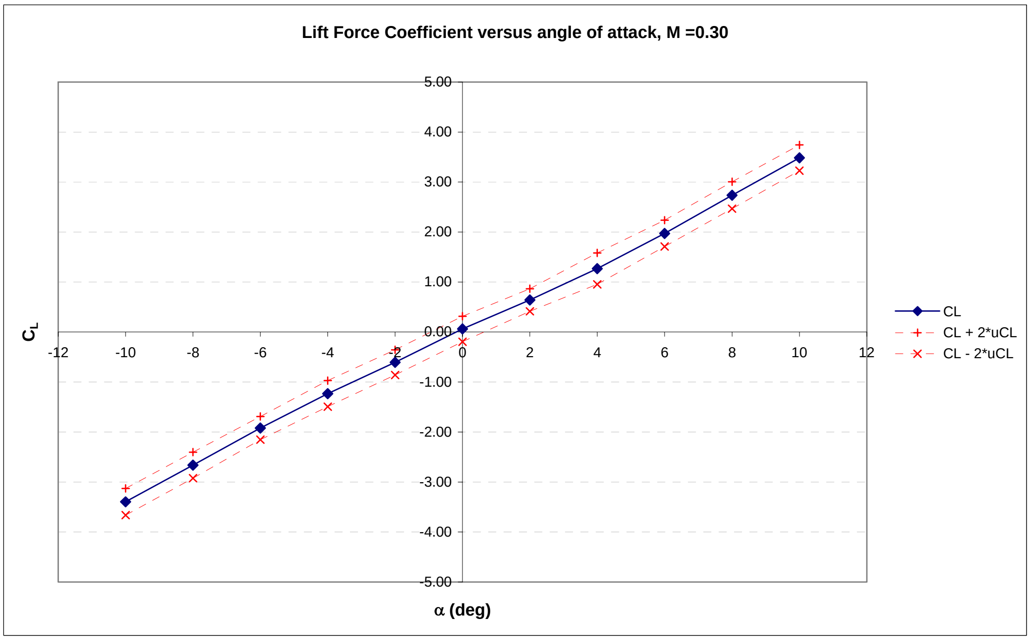

Figure 7. Lift coefficient versus angle of attack. Mach number equal to 0.30. Uncertainty limits also shown.

Figure 8 presents curves of $C_L \times \alpha$ for the Mach number range 0.30 up to 1.00. In the range near $\alpha = 0^o$, the lift coefficient changes linearly with angle of attack. At larger angles, C_L grows more than linearly (Schlichting, 1979). The equations of the fitted curves are presented in Table 1.

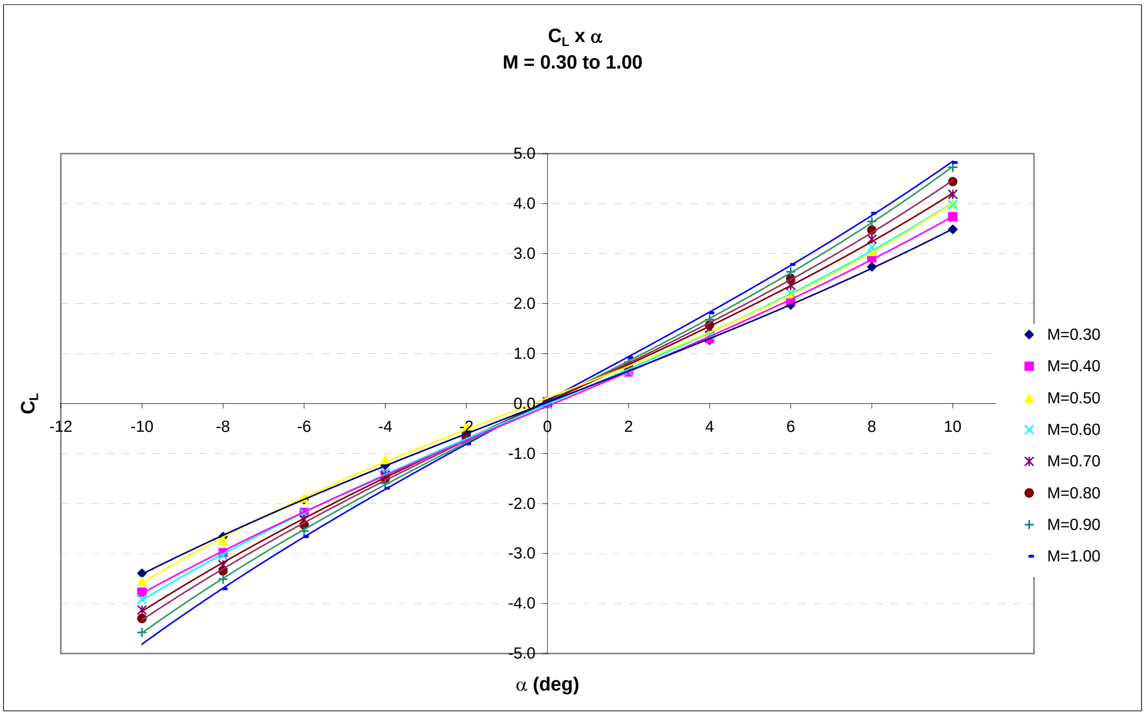

Figure 8. Curves $C_L \times \alpha$ for Mach numbers varying from 0.30 to 1.00.

Table 1. Polynomial fitting for data $C_L \times \alpha$.

M	Fitted curve
0.30	$y = 0.0003x^3 + 0.0002x^2 + 0.3129x + 0.0242$
0.40	$y = 0.0004x^3 + 0.0003x^2 + 0.3416x + 0.0518$
0.50	$y = 0.0007x^3 + 0.001x^2 + 0.3137x + 0.1122$
0.60	$y = 0.0005x^3 + 0.0005x^2 + 0.3461x + 0.0107$
0.70	$y = 0.0005x^3 + 6\times10^{-6}x^2 + 0.3708x + 0.0336$
0.80	$y = 0.0005x^3 + 0.0003x^2 + 0.3857x + 0.0345$
0.90	$y = 0.0006x^3 + 0.0004x^2 + 0.4059x + 0.0335$
1.00	$y = 0.0005x^3 + 0.0005x^2 + 0.4356x + 0.0656$

4.3. Pitching Moment Coefficient

Values of the pitching moment coefficient, C_m, versus angle of attack, α, are shown in Fig. 9. The pitching moment decreases for rising values of α.

One observes that the 95 % level of confidence uncertainty limits $C_m \pm 2\times u_{Cm}$ are approximately identical to the curve of the measurand, C_m, indicating that the uncertainty associated to the pitching aerodynamic load has a low value. This behavior can be also noted for the drag force coefficient (Fig. 5). Comparison reveals that the lift force has the highest level of uncertainty (Fig. 7). For M = 0.30 and $\alpha = 0^o$, the estimated standard uncertainty u_{Cm} is equal to 0.01, against 0.03 for u_{CD} and 0.13 for u_{CL}. Figures 5, 7 and 9 have the same y-axis scale for improved visualization and comparison of the uncertainty limits.

The family curves $C_m \times \alpha$ for several Mach numbers and corresponding polynomial fitting are presented in Fig. 10 and Table 2.

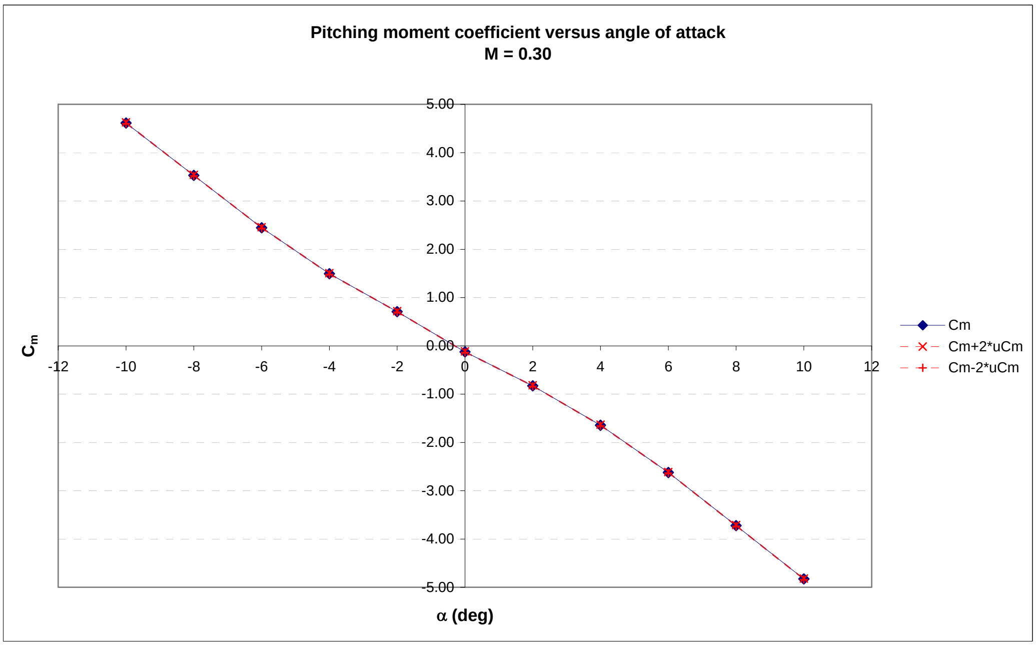

Figure 9. Pitching moment coefficient versus angle of attack. Mach number equal to 0.30. Uncertainty curves almost coincident to that of the measurand C_m.

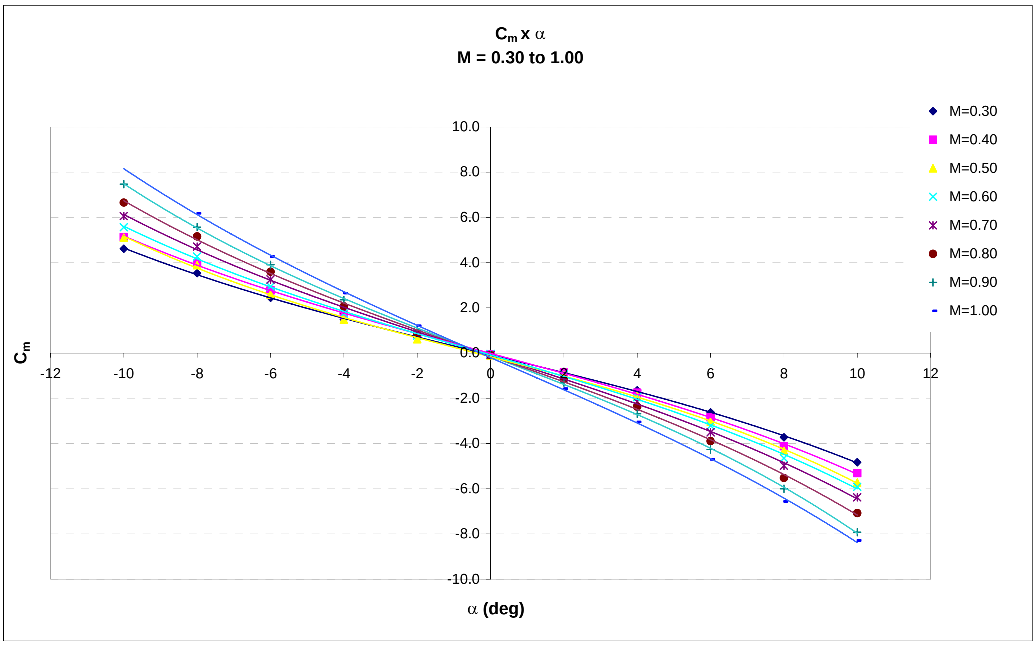

Figure 10. Curves $C_m \times \alpha$ for Mach numbers varying from 0.30 to 1.00.

Table 2. Polynomial fitting for curves $C_m \times \alpha$.

M	Fitted curves
0.30	$y = - 0.0008x^3 - 0.0008x^2 - 0.3913x - 0.0779$
0.40	$y = -0.0009x^3 - 0.0007x^2 - 0.4349x - 0.0149$
0.50	$y = - 0.0013x^3 - 0.0013x^2 - 0.4198x - 0.1642$
0.60	$y = - 0.0011x^3 - 0.0012x^2 - 0.4683x - 0.0840$
0.70	$y = - 0.0011x^3 - 0.0006x^2 - 0.5172x - 0.1033$
0.80	$y = - 0.0013x^3 - 0.0009x^2 - 0.5670x - 0.1236$
0.90	$y = - 0.0016x^3 - 0.001x^2 - 0.6170x - 0.1365$
1.00	$y = - 0.0012x^3 + 0.0009x^2 - 0.7069x - 0.2029$

4.4. Lift Force Coefficient Gradient

The lift force coefficient gradient, denoted by $C_{L\alpha}$, is estimated by taking the first derivative of the polynomial fitted to $C_L \times \alpha$ data (Table 1), and resolving it for $\alpha = 0^o$ (Military Handbook, 1990). One can see in Fig. 11 and in Table 3 an increase in $C_{L\alpha}$ when the Mach number of the test increases. It can be noticed in Fig. 11 that the value of the gradient correspondent to M = 0.40 does not follow the general tendency of the data points. The cause of this error was not clarified and the test must be repeated.

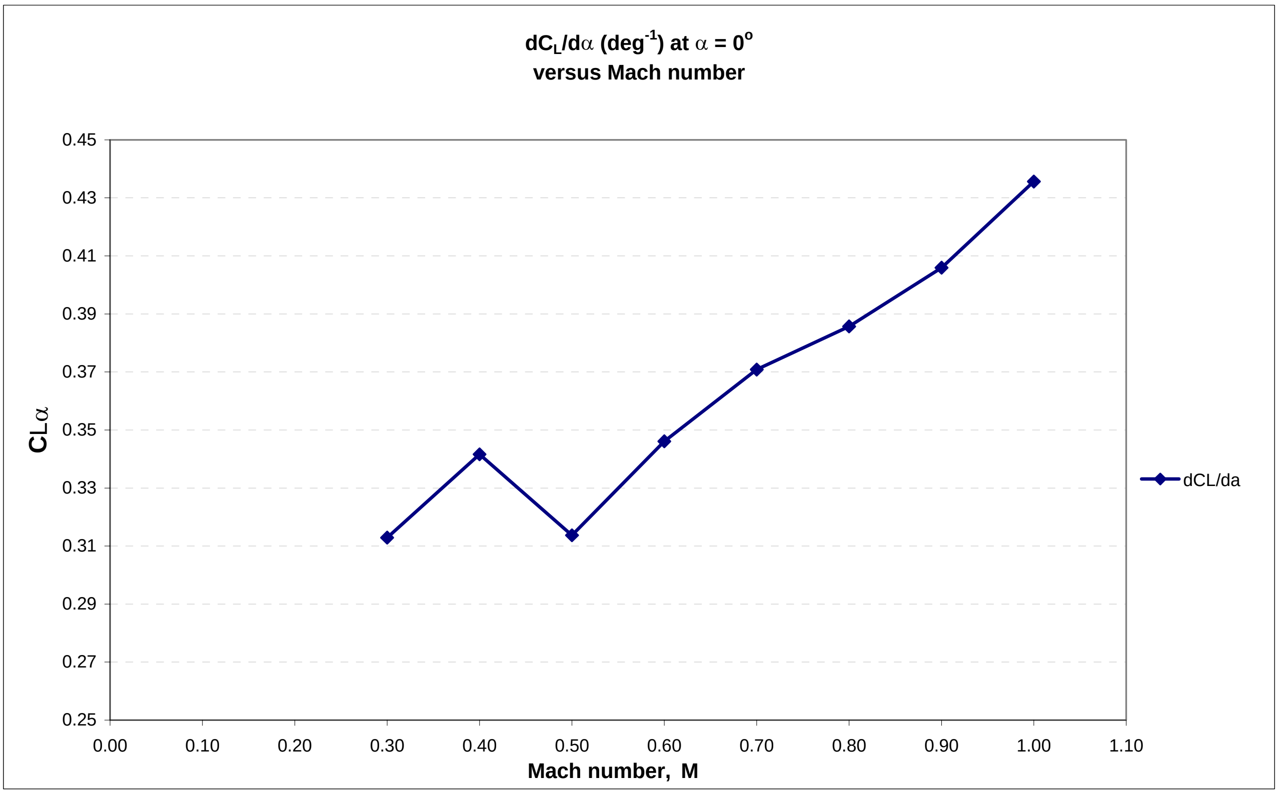

Figure 11. Gradient of the lift force coefficient as a function of Mach number.

Table 3. $C_{L\alpha}$ **gradient at** $\alpha = 0^o$**.**

M	$dC_L/d\alpha$ (deg^{-1})
0.30	0.3129
0.40	0.3416
0.50	0.3137
0.60	0.3461
0.70	0.3708
0.80	0.3857
0.90	0.4059
1.00	0.4356

4.5. Pitching Moment Coefficient Gradient

Analogous to the procedure described in section 4.4, the gradient of the pitching moment coefficient $C_{m\alpha}$ is estimated by taking the derivatives of the third order degree polynomial related in Table 2. The results are shown in Fig. 12 and Table 4. Values of $dC_m/d\alpha$ decrease for high flow velocities.

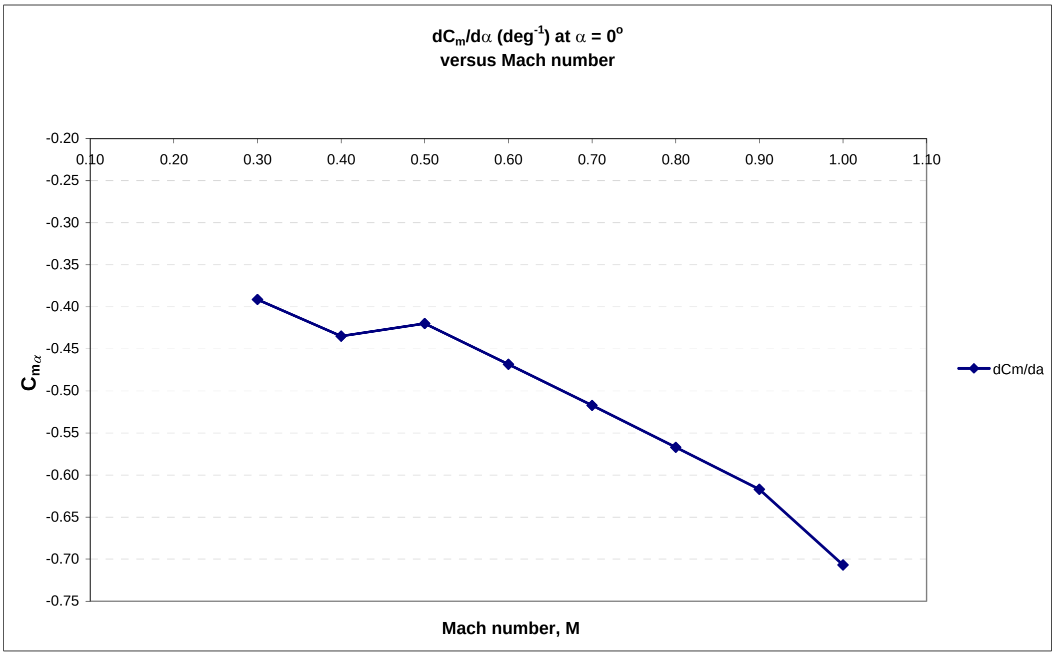

Figure 12. Gradient of the pitching moment coefficient as a function of Mach number.

Table 4. $C_{m\alpha}$ **gradient at** $\alpha = 0^o$**.**

M	$dC_m/d\alpha$ (deg^{-1})
0.30	- 0.3913
0.40	- 0.4349
0.50	- 0.4198
0.60	- 0.4683
0.70	- 0.5172
0.80	- 0.5670
0.90	- 0.6170
1.00	- 0.7069

5. CONCLUSIONS

It was possible from this study to estimate the drag force, lift force and pitching moment coefficients of the second stage of the sounding rocket Sonda III, at the PTWT facility in both subsonic and transonic range. Uncertainty in the coefficients was analyzed. Variation of the gradient for lift force and pitching moment coefficients has also been evaluated.

Besides the evaluation of the aerodynamic parameters of Sonda III, this study supplies indications about the methodology to be employed in future tests of Brazilian aerospace vehicles. The Sonda III campaign is still in progress, and includes tests in several model configurations and operation conditions of the wind tunnel. For the Mach number range considered in this study, the values of the load and gradient coefficients are in accordance with specialized literature.

6. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to CNPq, The Brazilian National Council of Research and Development, for the partial funding of this research, under Grant n.º 102506/2010-8.

7. REFERENCES

AIAA, 2003, R-091-2003 Recommended Practice,“Calibration and Use of Internal Strain-Gage Balances with Application to Wind Tunnel Testing”, American Institute of Aeronautics and Astronautics, VA, USA, 64 p.

Anderson Jr., J. D., 1985, “Introduction to Flight”, McGraw-Hill, 3th edition, 616 p.

ISO/BIPM, 1995, “Guide to the Expression of Uncertainty in Measurements”, 101 p.

JCGM 200, 2008, Joint Committee for Guides in Metrology, “International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM)”, 90 p.

Military Handbook, 1990, MIL-HDBK-762(MI), “Design of Aerodynamically Stabilized Free Rockets”, USA Department of Defense.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., Flannery, B. P., 1992, “Numerical Recipes”, Cambridge University Press, 2nd ed.,759 p.

Reis, M. L. C. C., Castro, R. M., Falcão Filho, J. B. P., Barbosa, I. M., Mello, O. A. F., 2008, “Calibration Uncertainty Estimation for Internal Aerodynamic Balance”, XII IMEKO TC1&TC7 Joint Symposium, Annecy, France.

Schlichting, H., Truckenbrodt, E., Ramm, H. J., 1979, “Aerodynamics of the Airplane”, McGraw-Hill, 541 p.

8. RESPONSABILITY NOTICE

VI CONGRESSO NACIONAL DE ENGENHARIA MECÂNICA
VI NATIONAL CONGRESS OF MECHANICAL ENGINEERING
18 a 21 de agosto de 2010 – Campina Grande – Paraíba - Brasil
August 18 – 21, 2010 – Campina Grande – Paraíba – Brazil

WIND TUNNEL TESTS OF THE SONDA III AEROSPACE VEHICLE

Maria Luísa Collucci da Costa Reis[1], mluisareis@iae.cta.br
João Batista Pessoa Falcão Filho[1], jb.falcao@ig.com.br
Olympio Achilles de Faria Mello[2]. oamello@gmail.com

[1] Instituto de Aeronáutica e Espaço, Praça Mal. Eduardo Gomes, 50, CEP 12226-904, São José dos Campos, SP
[2] Atech, Rua do Rocio, 313, CEP 04552-000, São Paulo, SP

Abstract: *Scale models of aerospace vehicles are tested in wind tunnels in order to predict the performance of their full-scale counterparts during actual flight. A test campaign of the sounding rocket vehicle Sonda III is being carried out at the Brazilian Pilot Transonic Facility of the Institute of Aeronautics and Space. The Sonda III is a two stage research rocket designed to carry a payload capable of supplying technical data of experiments conducted under microgravity conditions. A model of the second stage of the vehicle was tested for several angles of attack, at Mach numbers in the transonic range. The purpose of the first part of the campaign is to estimate the aerodynamic loads that act on the test article. This paper describes the model and airflow configurations of the experiment and presents the results of these tests. The aerodynamic loads consist of three forces referred to as drag, side, and lift, and three moments denominated as rolling, pitching, and yawing. The loads are measured by a six-component aerodynamic internal balance whose sensor elements are strain gages arranged in Wheatstone bridges. The strain gage readings and the aerodynamic loads are related to a so-called calibration matrix composed of parameters evaluated during the balance calibration. Besides the aerodynamic loads, the measured parameters during the tests are total pressure, static pressure and total temperature. The data reduction consists of obtaining the variation of aerodynamic coefficients with angle of attack for the range of Mach number covered in the tests. Curves of load coefficients versus angle of attack are shown. Variation of the drag, lift and pitching coefficients with the Mach number and the behavior of lift force and pitching moment coefficient gradient with the Mach number for angle of attack equal to zero are compared with specialized bibliography. Error analysis revealed that the forces and moments measured by the balance are the dominant components of the uncertainty in the estimated aerodynamic load coefficients, being the contribution of the measurement of flow field parameters negligible. Sources of errors of the experiment are pointed out and the proposed methodology used to minimize them is described.*

Keywords**:** sounding rocket, wind tunnel tests, metrological reliability