Aerodynamic loads acting on the M5/ONERA/IAE aeronautical standard model

M L C C Reis¹ ², M S Souza¹ ², M C C Araújo², R R Santos¹
¹Instituto de Aeronáutica e Espaço, Pr. Mal. Eduardo Gomes, 50, CEP 12228904, Brasil
²Instituto Tecnológico da Aeronáutica, Pr. Mal. Eduardo Gomes, 50, CEP 12228900, Brasil

E-mail: marialuisamlccr@fab.mil.br

Abstract. A test campaign to estimate the aerodynamic loads acting on the aeronautical standard model M5/ONERA/IAE is under progress. The model is being tested at the TA-2 subsonic wind tunnel using an external balance. The values of force and moment coefficients and associated uncertainties are evaluated by measuring aerodynamic loads read by the balance sensors and the parameters of the wind tunnel airflow. The campaign is part of an Interlaboratory comparison of results involving other wind tunnel facilities around the world. This paper presents load coefficient curves versus sideslip angle. At TA-2, the uncertainty associated with the pitching coefficient presents the highest value. The dominant contribution comes from the hysteresis.

1. Introduction
During real flight, the airflow exerts pressure and shear stress on the surface of an aeronautical vehicle. Wind tunnel facilities simulate real conditions encountered by the vehicle by driving a flow to a fluid which can either be air or another gas such as helium or nitrogen.

Wind tunnels are classified according to the speed range of the flow: they are subsonic, near sonic, transonic, supersonic and hypersonic. They are built in different sizes and configurations according to the test needs. The circuit can be open or closed, the test section can accommodate a full size, a scale model or part of a model [1].

As in any laboratory, the wind tunnel experimentalists must conduct activities to guarantee the metrological reliability of the test results. These activities include calibration of the measurement chain as well as the calibration of the airflow. The former is related to standard equipment and sensors and for the latter an aeronautical standard model can be used.

This paper is concerned with the second type, i.e., the calibration of the airflow of the subsonic wind tunnel number 2, TA-2. For this purpose, the aeronautical model M5, designed by ONERA, the French Aerospace Laboratory, was used as the standard model. The M5 is a wing/body/tail model and belongs to the M-series family. In the original version, it receives a sting strut as the interface to an internal aerodynamic balance. The TA-2 team modified the design in order to allow different
configurations for the use of external balances. Besides the original sting, the M5/ONERA/IAE model can also be fixed to the test section in single, double or three-strut interfaces (Figure 1).

The wind tunnel TA-2 is a subsonic, atmospheric, closed circuit wind tunnel. It was built in the 1960’s and has contributed to the development of aerodynamic projects for the Brazilian aeronautical sector and the civil engineering industry. The facility is located at the Institute of Aeronautics and Space, Brazil.

The maximum airflow speed for an empty test section is around 140 m/s, \( \text{i.e.} \), the maximum Mach number is approximately 0.40. The test section is 2.1 m high, 3.0 m wide and 3.2 m long. The airflow is driven by an 8.4 m diameter 7-blade-fan connected to a motor drive. The engine power is 1.2 Megawatts with 400 revolutions per minute. The strut configurations provide an angle of attack \( \alpha \) up to \( \pm 30^\circ \) and a turntable permits a yaw angle \( \beta \) of \( \pm 45^\circ \).

An intensive campaign is being carried out at the TA-2 to evaluate the aerodynamic loads acting on the M5/ONERA/IAE in the subsonic regime. The estimated parameters are force and moment coefficients, \( C_F \) and \( C_m \), respectively. The input quantity related to the airflow is the free stream dynamic pressure, \( q \). A six-component external balance composed of six strain-gauges is employed to measure the 3 forces and the 3 moments acting on the model under test (Figure 2). At TA-2, the drag, side and lift forces are denominated \( F_1, F_2 \) and \( F_3 \), while the rolling, pitching and yawing moments are denominated \( F_4, F_5 \) and \( F_6 \), respectively. A reference length, \( l \), and a reference area, \( A \), taken from the geometry of the model are also necessary to evaluate the 3 force coefficients \( C_F \) and the 3 moment coefficients \( C_m \).

Once it has been tested at the TA-2 wind tunnel, the model will be transferred to other facilities in order to compare test results, in the scope of an Interlaboratory Program. The data repeatability, accuracy and uncertainty will be analyzed and the airflow quality of each wind tunnel will be checked [2].

**Figure 1.** The standard model M5 installed at the TA-2 test section in a two-strut configuration.

**Figure 2.** The TA-2 six-component external balance.

### 2. Methods

For the present study, the M5 model was tested at a nominal airflow speed of 200 km/h. The angle of attack \( \alpha \) was maintained at 0\(^\circ\) and the sideslip angle \( \beta \) varied from -5\(^\circ\) to +5\(^\circ\). The test was comprised of one cycle of increasing \( \beta \) beginning at -5\(^\circ\) and going in 1\(^\circ\) steps to +5\(^\circ\) and then returning in similar fashion to -5\(^\circ\). With this procedure, it is possible to analyze the hysteresis of the wind tunnel instrumentation thereby allowing a type A uncertainty evaluation.

A previous calibration of the external balance supplied the uncertainty values associated with the measured aerodynamic forces and moments [3]; this is a type B uncertainty evaluation. No wind tunnel correction and no tare results were applied to the experimental data, \text{i.e.}, the information presented in this paper is the raw data. The results are related to the origin of the external balance and to the wind reference axes.
The characteristics of the model are:
- Reference area, $A$, is the geometric area of the wing = 0.5260 m$^2$;
- Reference length, $l$, for the pitching moment is the mean aerodynamic cord of the wing = 0.295 m; and
- Reference length, $l$, for the rolling and yawing moments is the span of the wing = 1.964 m.

3. The Mathematical Modelling
The mathematical modelling of the aerodynamic forces and moments is the polynomial expressed by equation (1). The modelling considers second order interactions of the strain-gauge readings, $R$. The output quantity $F_i$ represent drag, side or lift if force is being evaluated. For the evaluation of the aerodynamic moment, $F_i$ represents pitching, rolling or yawing, $\beta$ is the sideslip angle.

$$F_i = a_{i,1}R_1 + a_{i,2}R_2 + a_{i,3}R_3 + a_{i,4}R_4 + a_{i,5}R_5 + a_{i,6}R_6 + a_{i,7}R_1R_1 + a_{i,8}R_1R_2 + a_{i,9}R_1R_3 + a_{i,10}R_1R_4 + a_{i,11}R_1R_5 + a_{i,12}R_1R_6 + a_{i,13}R_1\sin \beta + a_{i,14}R_1\cos \beta + a_{i,15}R_2R_2 + a_{i,16}R_2R_3 + a_{i,17}R_2R_4 + a_{i,18}R_2R_5 + a_{i,19}R_2R_6 + a_{i,20}R_2\sin \beta + a_{i,21}R_2\cos \beta + a_{i,22}R_3R_3 + a_{i,23}R_3R_4 + a_{i,24}R_3R_5 + a_{i,25}R_3R_6 + a_{i,26}R_3\sin \beta + a_{i,27}R_3\cos \beta + a_{i,28}R_4R_4 + a_{i,29}R_4R_5 + a_{i,30}R_4R_6 + a_{i,31}R_4\sin \beta + a_{i,32}R_4\cos \beta + a_{i,33}R_5R_5 + a_{i,34}R_5R_6 + a_{i,35}R_5\sin \beta + a_{i,36}R_5\cos \beta + a_{i,37}R_6R_6 + a_{i,38}R_6\sin \beta + a_{i,39}R_6\cos \beta$$

(1)

The force and moment coefficients, $C_F$ and $C_m$, are respectively expressed by [4]:

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

(2)

and

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

(3)

The dynamic pressure $q$ is the free stream dynamic pressure of the airflow measured by a Pitot tube located at the entrance of the TA-2 test section. The area $A$ and the length $l$ are reference values related to the geometry of the model.

The law of propagation of uncertainty is applied to equation (1) to estimate the associated uncertainties of aerodynamic forces and moments $F_i$, $\beta_i$ [5]. Similarly, the law is applied to equations (2) and (3) for the aerodynamic coefficient uncertainties. As an example, for force coefficients $C_F$, the positive square root of expression (4) is the combined uncertainty $u_{CF}$:

$$u_{CF}^2 = \left(\frac{1}{qA}\right)^2 u_F^2 + \left(\frac{-F}{q^2 A}\right)^2 u_q^2 + \left(\frac{-F}{qA^2}\right)^2 u_A^2$$

(4)

Least squares method with matrix formalism is applied to reduce both balance calibration and test data [6, 7].

4. Results and discussions
Codes in MatLab® and Excel® worksheets were elaborated to present curves $C_F\times\beta$ and $C_m\times\beta$ for the flow regimes covered by the tests. In this study we present results which correspond to a nominal velocity of 200 km/h.
Table 1 shows the coefficient values for the drag and lift forces, $C_{F1}$ and $C_{F3}$, respectively, and the pitching moment coefficient, $C_{F5}$. The associated uncertainties, $u_{CF1}$, $u_{CF3}$ and $u_{CF5}$, are also presented in Table 1; they are the combined uncertainties resulting from the type A and type B evaluation. The dominant contribution comes from the type A evaluation, due to hysteresis. This can be seen in figures 3 and 4. Figure 3 shows the $C_{F1} \times \beta$ curve for a one-cycle test which is comprised of the increasing and decreasing values of $\beta$. Error bars represent the uncertainties related to the calibration of the external balance. In figure 4, data correspond to the average value of both ascending and descending runs; in this figure, the contribution of the hysteresis to the uncertainty associated with the drag coefficient is also considered, combined with that related to the balance calibration. The curves for the drag, lift and pitching coefficients are shown together in figure 5.

**Table 1.** Load coefficients and associated uncertainties estimated at the 200 km/h airflow regime.

| $\beta$ (°) | $C_{F1}$ | $u_{CF1}$ | $u_{CF1}/C_{F1}$ (%) | $C_{F3}$ | $u_{CF3}$ | $u_{CF3}/C_{F3}$ (%) | $C_{F5}$ | $u_{CF5}$ | $u_{CF5}/C_{F5}$ (%) |
|-------------|---------|-----------|----------------------|---------|-----------|----------------------|---------|-----------|----------------------|
| -5          | 0.03442 | 0.00016   | 0.5                  | 0.2505  | 0.0020    | 0.8                  | 0.0378  | 0.0021    | 5.6                  |
| -4          | 0.03301 | 0.00015   | 0.5                  | 0.2521  | 0.0020    | 0.8                  | 0.0400  | 0.0013    | 3.3                  |
| -3          | 0.03201 | 0.00028   | 0.9                  | 0.248   | 0.004     | 1.6                  | 0.043   | 0.003     | 7.0                  |
| -2          | 0.03127 | 0.00016   | 0.5                  | 0.2467  | 0.0024    | 1.0                  | 0.0439  | 0.0023    | 5.2                  |
| -1          | 0.03068 | 0.00022   | 0.7                  | 0.2461  | 0.0027    | 1.1                  | 0.0451  | 0.0015    | 3.3                  |
| 0           | 0.03056 | 0.00017   | 0.6                  | 0.2449  | 0.0026    | 1.1                  | 0.0451  | 0.0005    | 1.1                  |
| 1           | 0.03088 | 0.00016   | 0.5                  | 0.2459  | 0.0018    | 0.7                  | 0.0442  | 0.0021    | 4.8                  |
| 2           | 0.03132 | 0.00017   | 0.5                  | 0.2503  | 0.0022    | 0.9                  | 0.0399  | 0.0006    | 1.5                  |
| 3           | 0.03206 | 0.00016   | 0.5                  | 0.2534  | 0.0029    | 1.1                  | 0.0355  | 0.0019    | 5.4                  |
| 4           | 0.03308 | 0.00019   | 0.6                  | 0.2559  | 0.0013    | 0.5                  | 0.0308  | 0.0010    | 3.2                  |
| 5           | 0.03434 | 0.00012   | 0.3                  | 0.2595  | 0.0009    | 0.3                  | 0.02670 | 0.00014   | 0.5                  |

**Figure 3.** The drag force coefficient variation with sideslip angle, $C_{F1} \times \beta$, for the ascending and descending runs.
5. Conclusions
The results of the wind tunnel campaign employing the M5/ONERA/IAE aeronautical standard model were presented. Curves of drag, lift and pitching coefficients versus the sideslip angle were supplied. Data reduction revealed that the uncertainty component related to the hysteresis is the dominant
contribution. The pitching moment coefficient presented the highest associated uncertainty. The test campaign has just started and the tests with varying the angle of attack $\alpha$ are under progress.

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