AERODYNAMIC TESTS OF MODEL AIRCRAFT AGARD IN WIND TUNNEL

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Abstract. *Models of aircrafts are tested in wind tunnels in order to predict the performance of their full-scale counterparts during actual flight. A test campaign of a modified version of the AGARD model "B" has being carried out at the Brazilian Pilot Transonic Facility, TTP, of the Institute of Aeronautics and Space, IAE. The data from this campaign are compared to the model "B" test results obtained in other wind tunnel facilities. This campaign is part of a series of tests to be conducted in order to analyse the metrological reliability of the TTP circuit. The aerodynamic loads acting on the test article are measured by a six-component internal balance and lift, drag and pitching moment characteristics of the model are evaluated for Mach number regimes ranging from 0.5 to 1.0, at angles of attack varying from -12 to 12 deg. The tunnel blockage with the model at zero angle of attack is 0.82 %. Besides the aerodynamic loads, the measured parameters are total pressure, static pressure and total temperature of the airflow. The pressure at the rear of the fuselage is also measured to perform the adjustment for drag base zero. Hysteresis effects are analysed and are considered as uncertainty limits in the measurements. 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 force coefficient with the Mach number for angle of attack equal to zero is compared with specialized bibliograph. The test results behaved as expected and represent an important contribution to the evaluation of the methodology employed at TTP for aerodynamic load measurements.*

Keywords*: transonic wind tunnel, AGARD model, aerodynamic tests*

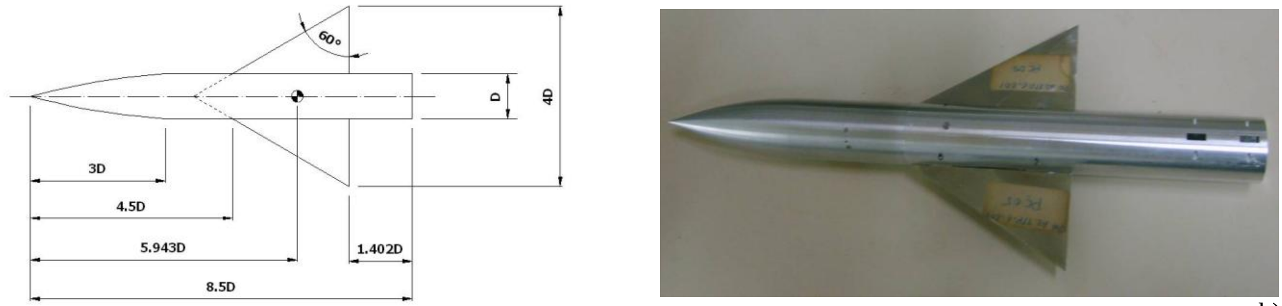
1. INTRODUCTION

In a wind tunnel, the air flows over the test article, simulating actual flight conditions. In order to design aerospace vehicles and their control systems, it is necessary to know the aerodynamic forces and moments acting on the body. Data originating from wind tunnel tests provide the needed information to predict flight performance of the full scale counterpart. Several test campaigns of sounding rocket vehicles developed by IAE have been carried out at TTP thereby supplying reliable wind tunnel data which has strategic importance for the Brazilian aerospace programs.

Experimental tests of a modified version of the AGARD model "B" have recently been carried out at the Pilot Transonic facility, TTP, located in São José dos Campos, São Paulo, Brazil, at the Aerodynamic Division of the Institute of Aeronautics and Space, IAE/ALA (Fig. 1). The purpose of the tests is to analyze the precision of the measured airflow parameters and to supply archival documentation of the tunnel's overall operating conditions, therefore maintaining the metrological reliability of the TTP data results.

Figure 1. The PilotTransonic facility.

The AGARD model "B" is an aeronautical standard model composed of an ogive-cylinder body and symmetrical delta wings. The delta wing is an equilateral triangle with a span four times its body diameter, *D* (Fig. 2a). Details of the model's geometry can be found in Khen and Victor (1991). It was originally designed for the calibration of supersonic wind tunnels but it has often been used for calibration of transonic facilities. The tunnel-to-tunnel data comparison detects possible errors arising from flow non-uniformity and is useful in identifying measurement problems in the wind tunnel circuit. This model was developed by the Advisory Group for Aeronautical Research and Development (AGARD) and has been used to compare the accuracy between wind tunnels. A picture of the test article used in this study is shown in Fig. 2b, where the length fuselage is around twice longer than the original one.



a) b)

Figure 2. AGARD model "B". a) Basic dimensions. b) Picture of the TTP version.

This study presents the experimental data originating from AGARD "B" model for Mach numbers in the subsonic and transonic regimes, at angles of attack ranging from -12° to +12°. The results of drag and lift force coefficients are compared to those reported by Anderson (1970). Pitching moment coefficients are presented but not compared, due to differences in moment reference.

2. WIND TUNNEL

The Pilot Transonic wind tunnel is one of a closed circuit kind, where the airflow is not in contact with the atmosphere. It operates continuously when driven by an axial compressor (also called main compressor). A schematic picture of the aerodynamic circuit is presented in Fig. 3, highlighting its main parts: the main compressor, cooler, stilling chamber, plenum chamber, high velocity diffuser and corners (numbered from 1 to 4). Arrows indicate the direction of the airflow in the aerodynamic facility. The test section, which receives the test article, is located in the plenum chamber (Falcão Filho and Mello, 2002). The height of the test section is 0.25 m and it is 0.30 m wide. The parameters total pressure, p_0, Mach number, M, and total temperature, T_0, are automatically controlled in order to guarantee stable values of Mach and Reynolds numbers. Flaps located at the test section end can be set at several angles in a continuous way, to provide air extraction through wall slots. The purpose of the extraction is to prevent a chocking in the transonic range, to diminish shock wave reflections from the walls and to guarantee a better uniform flow around the model being tested.

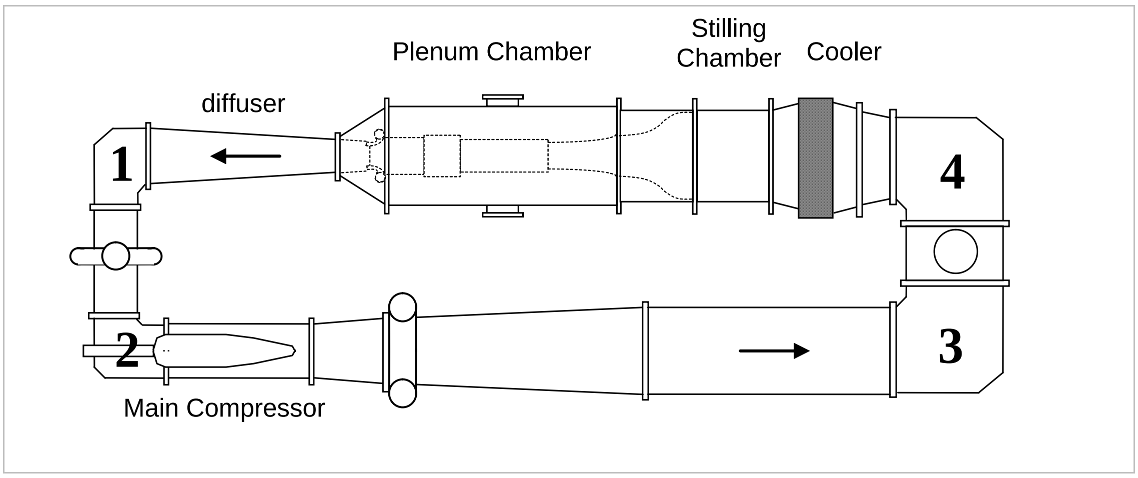
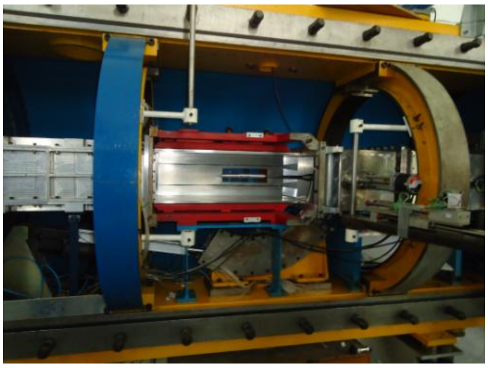


Figure 3. Schematic picture of the wind tunnel circuit.

A sting-type support was used to fix the model B inside the test section (Fig. 4). Some dimensions of the sting are shown in Fig. 5.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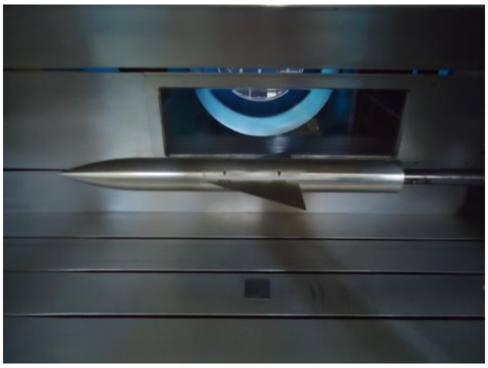
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Figure 4. a) The TTP test section. b) Detail of the AGARD model fixed inside the test section by a sting at the rear.

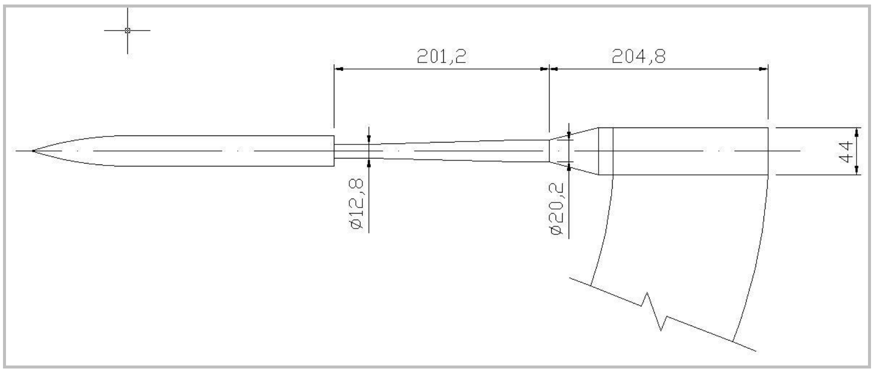
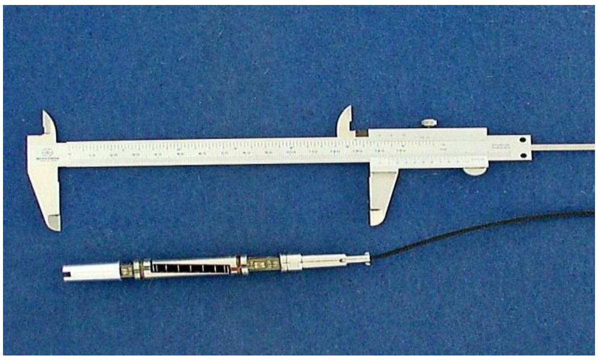


Figura 5. Dimensions of the sting support. Units (mm).

The tunnel blockage with the model at zero angle of attack is 0.82 %. The blockage is the ratio between the maximum cross-sectional area of the fuselage, which is 6.16×10^{-4} m^2, and the area of the test section, equal to 7.5×10^{-2} m^2. Davis (1973) carried out an investigation to determine wall interference effects in relation to tunnel blockage and the consequences in aerodynamic load measurements. However, Davis *et al.* (1986) state that for the conventional, ventilated type of transonic test section a model blockage ratio of about one percent should be applied to keep wall interference effects reasonably small.

3. INSTRUMENTATION

The instrument used to measure the aerodynamic loads acting on the model being tested was a six-component internal balance model MC-.36-.63-A, manufactured by Micro Craft (Fig. 6a). The balance is calibrated prior to the tests according to the methodology described in Reis *et al.* (2008). Two absolute pressure transducers (TESTO 525, 0 to 2000 mbar abs) were connected to the upper and lower parts of the sting, at the blunt end of the model fuselage, to measure the base pressure (Fig. 6b). As pointed out by Pope and Goin, (1978), the pressure acting on the blunt base of the model is an important part of the total drag in the transonic speed range.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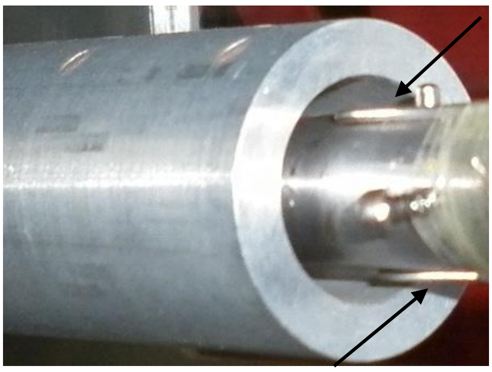
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Figure 6. Instrumentation. a) Internal aerodynamic balance. b) Details of the model's base. Arrows indicate the two pressure measurement locations.

4. TEST DESCRIPTION

The AGARD model "B" was tested at nominal Mach numbers M equal to 0.50, 0.60, 0.70, 0.90 and 1.0, at angles of attack α varying from -12 to 12 degrees. Hysteresis were verified ascending from 0^o to 12^o, returning to 0^o before running the negative values of angles and returning back to 0^o. Two tests were conducted for M = 0.50, one with the flaps closed and the other with the flaps opened at 10^o, in order to analyse the influence of the mass extraction on the results. A more detailed flap influence investigation was performed at the 0.70 Mach number value for flap apertures set at 0, 5, 10 and 15 degrees. For M = 0.60, 0.80, 0.90 and 1.0, the flaps were kept at 10^o.

5. DATA REDUCTION

5.1. Aerodynamic forces and moments

In this study, data reduction supplies the aerodynamic coefficients of the aircraft. Curves of force and moment coefficients are related to the angle of attack. The terminology employed for designating aerodynamic loads is: drag force (D), side force (SF), lift force (L), rolling moment (r), pitching moment (m) and yawing moment (y).

The force coefficients, C_{Force}, and the moment coefficients, C_{moment}, are evaluated through the expressions (1) and (2) respectively:

$$C_{Force} = \frac{Force}{qA} \quad (1)$$

$$C_{moment} = \frac{Moment}{qAl} \quad (2)$$

Force: aerodynamic force (drag, side or lift);
Moment: aerodynamic moment (rolling, pitching or yawing);
q: dynamic pressure;
A: reference area; and
l: reference length.

The reference area used, A, which corresponds to the wing area of the model, is equal to 5.432×10^{-3} m^2. The reference length, l, corresponds to the diameter of the fuselage and is equal to 2.8×10^{-2} m.

5.2. Relation between the load components in the body and wind directions

Due to the variation of the angle of attack α of the AGARD model during the test, the axial and normal forces, AF and NF respectively, read by the strain gages of the balance must be related to the wind axis. The geometrical relation between the two sets of components is (Anderson, 2001):

$$D = NF_{balance} \sin\alpha + AF_{balance} \cos\alpha \quad (3)$$

$$L = NF_{balance} \cos\alpha - AF_{balance} \sin\alpha \quad (4)$$

5.3. Base pressure

According to Pope and Goin (1978), the axial force measured by the balance can be adjusted for the model base pressure by the equation:

$$AF = AF_{measured} - A_b(\, p - p_b \,) \quad (5)$$

$AF_{mesured}$ = measured axial force;
A_b = model base area;
p = freestream static pressure; and
p_b = model base pressure.

Consequently, one subtracts the drag due to the base from the total measured drag to obtain the drag acting on the model, denominated drag base zero. The reason for this adjustment is that comparisons with data from other wind tunnels are simplified. If not, the interferences with the sting have to be very well determined.

5.4. Mach number and dynamic pressure

To evaluate the Mach number M and the dynamic pressure q of the flow, respectively, Eqs. (6) and (7) are employed (Anderson, 1985):

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{p_0}{p}\right)^{\frac{(\gamma-1)}{\gamma}} - 1\right] \qquad (6)$$

$$q = \frac{\gamma}{2} p_0 \frac{M^2}{\left(1 - \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}}} \qquad (7)$$

where p_0 is the total pressure, p is the static pressure and $\gamma = c_p/c_v$, is the ratio of specific heat, equal to 1.4 for air.
The static pressure sensor is positioned on the upper part of the wall at the beginning of the wind tunnel test section and the total pressure sensor is located in the stilling chamber of the circuit.

6. RESULTS AND DISCUSSION

Despite the geometric difference in the fuselage rear length of the test article employed in this study, the data results were compared to specialized literature as a preliminary analysis of the quality of the TTP airflow and instrumentation. All the drag and lift forces coefficients, as a function of angle of attack or Mach number, were compared to AGARD "B" reference results obtained by Anderson (1970), which are considered as reference because they are assumed to be free from wall interference due to the low blockage ratio of the test. Influence of flap opening and hysteresis effects on the data are analyzed as well.

6.1. Drag force coefficient

The drag force coefficient of the AGARD model "B" at the Mach number value equal to 0.50 is presented in Fig. 7 as a function of the angle of attack, α. The flaps were set at 0^o and 10^o. Base pressure adjustment not applied to data. No significative influence was observed due to the test section flap condition.
The same test configuration results after applying the base pressure adjustment (Eq. 5) to the data can be seen in Fig. 8. One can notice a decrease in the C_D values due to the adjustment. For example, at $\alpha = 0^o$ the relative difference between the adjusted and not adjusted results is 37%.

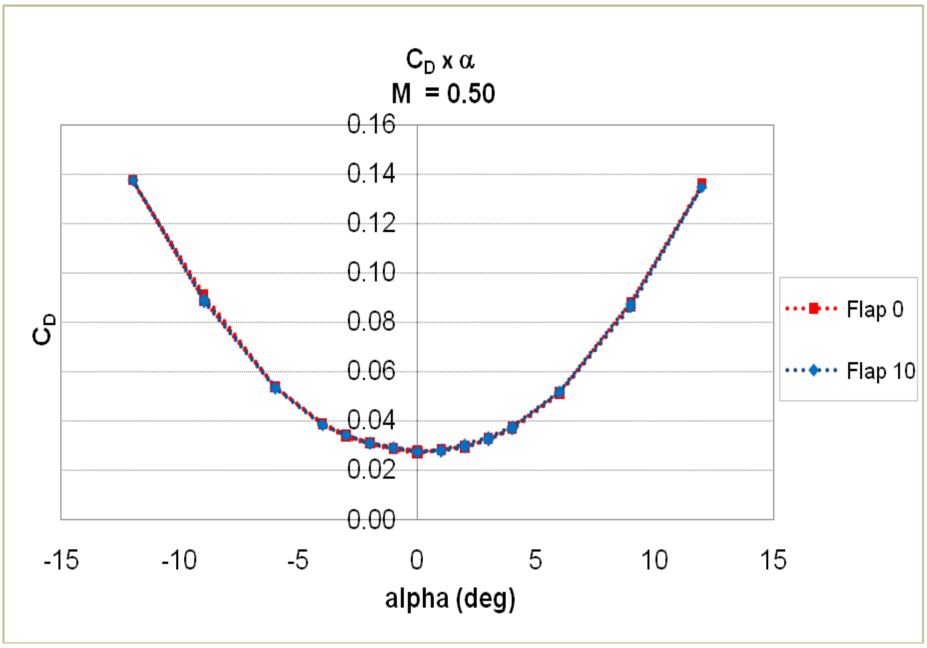

Figure 7. Analysis of flap aperture influence on Drag coefficient. Mach number 0.50.

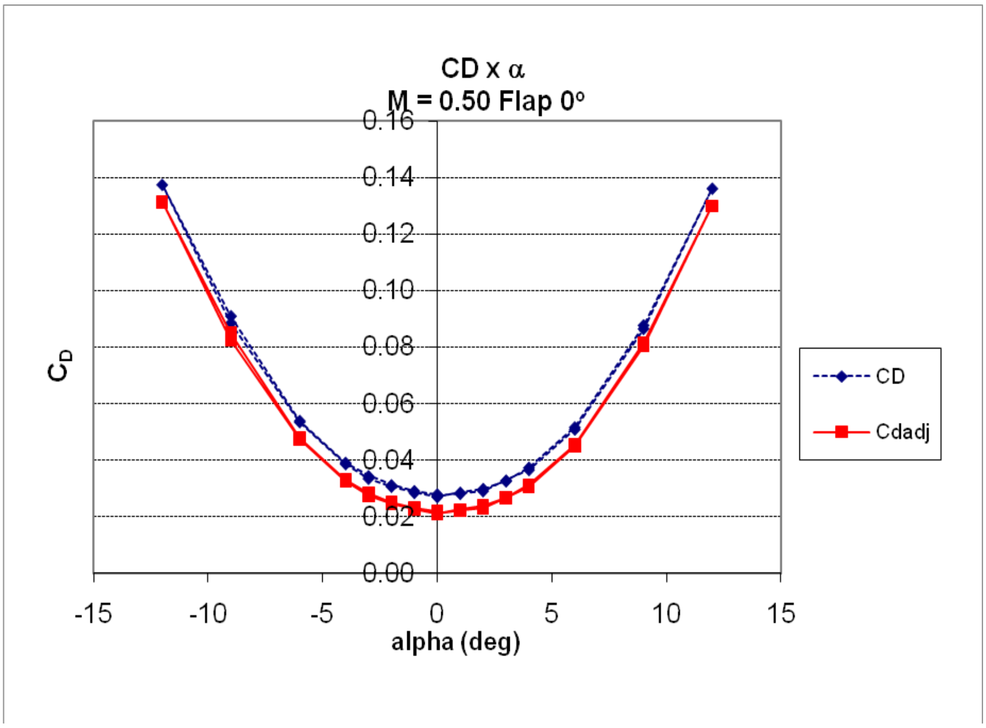

Figure 8. Effect of the base pressure adjustment on Drag coefficient. Mach number 0.50.

The hysteresis presented in the experiment is an important source of error to the overall test uncertainty. Its contribution on the drag coefficient uncertainty is shown in Fig. 9, for Mach number equal to 0.70. Only the positive range of α is shown. The uncertainties were determined for a confidence level of 95 %.

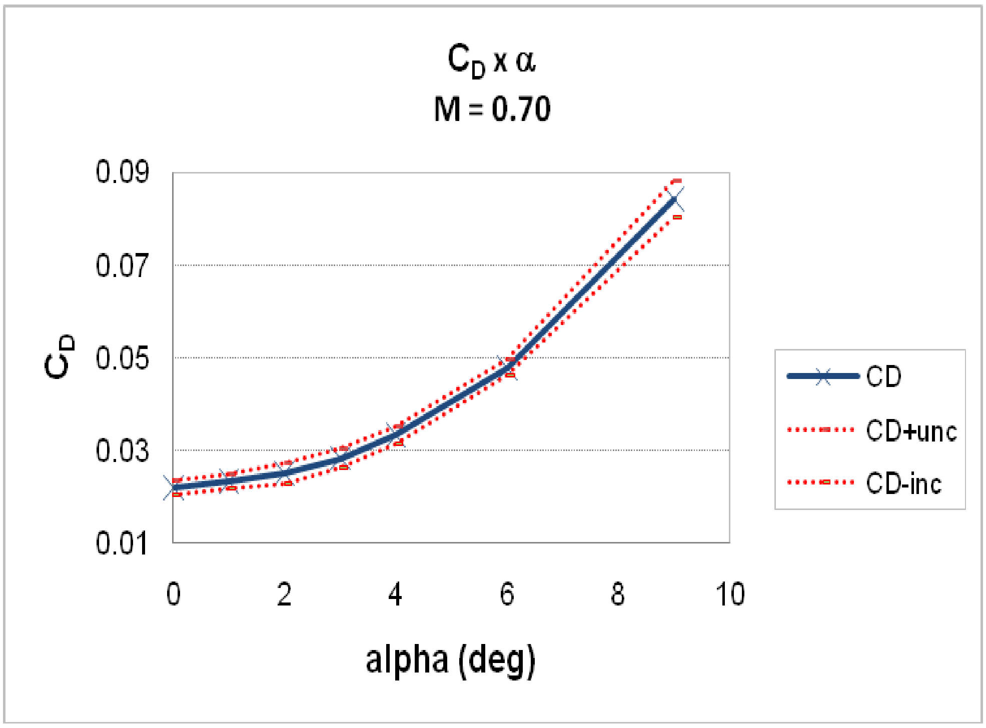

Figure 9. The uncertainty in C_D due to the hysteresis effect.

Family curves C_D versus α for the Mach number range covered in this study are shown in Fig. 10. Second degree polynomials were fit to the data through the least squares method.

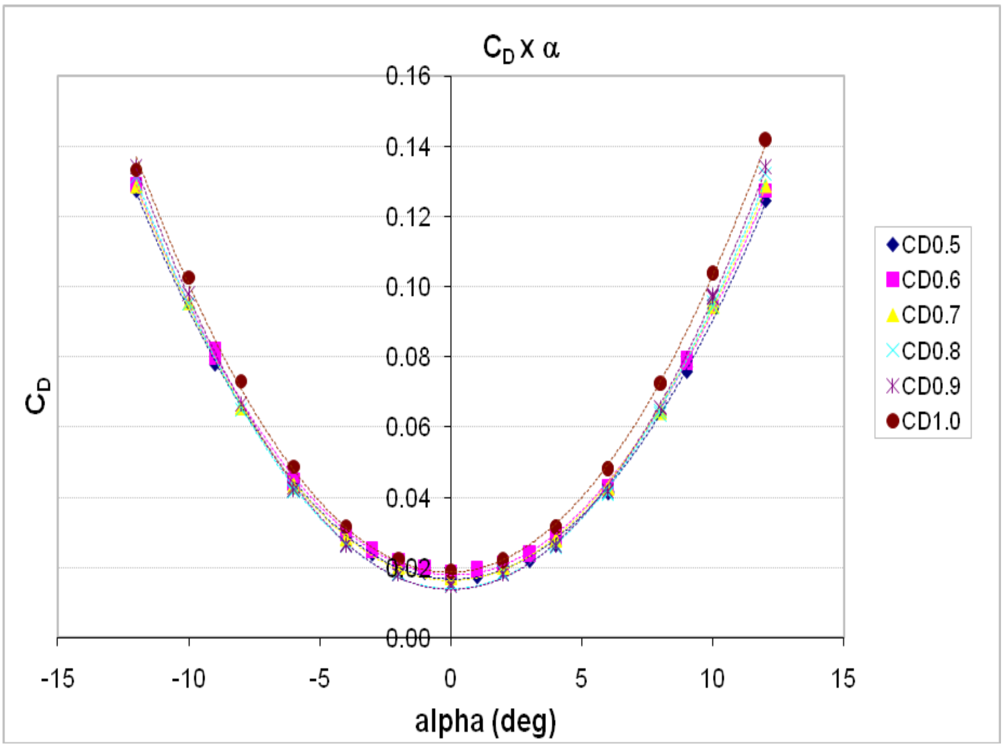

Figure 10. Curves C_D versus angle of attack for Mach number varying from 0.50 to 1.00.

6.2. Lift force coefficient

Figure 11 relates lift force coefficient, C_L, as a function of the angle of attack. The values of C_L increase when the Mach number increases. The dependence of C_L on α is of third degree order. The least squares method was used to fit third degree polynomials to the data.

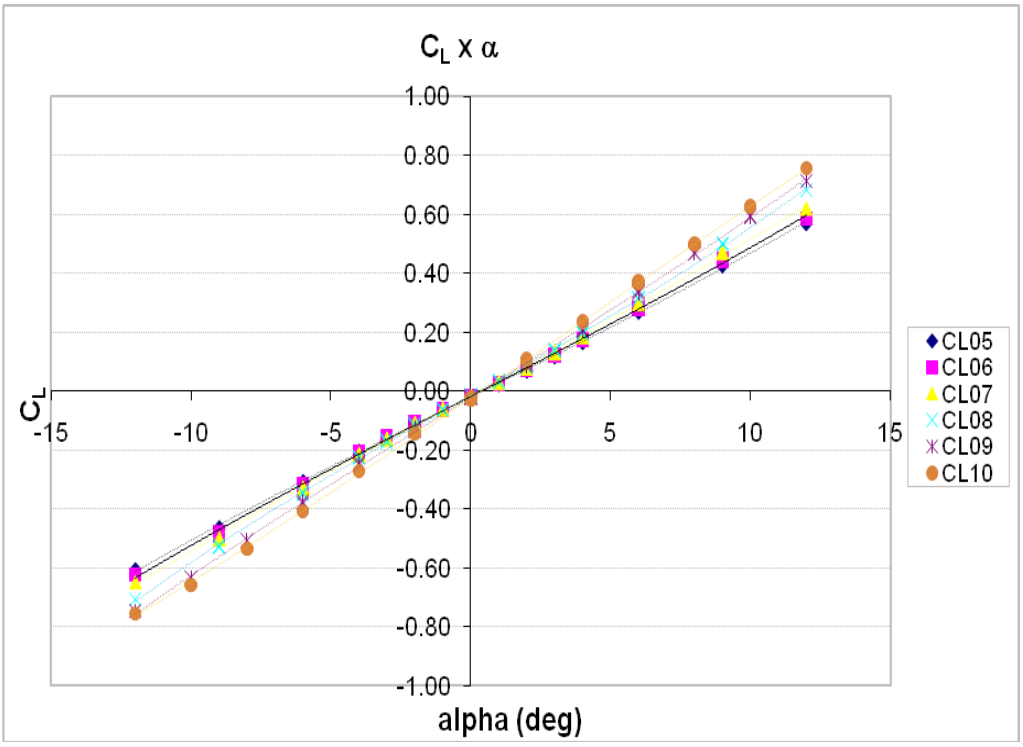

Figure 11. Lift force coefficient family curves for M = 0.50 to 1.00.

6.3. Pitching moment coefficient

The pitching moment coefficient curves are shown in Fig. 12. Third degree polynomials are fitted to the data. Values increase with the Mach number.

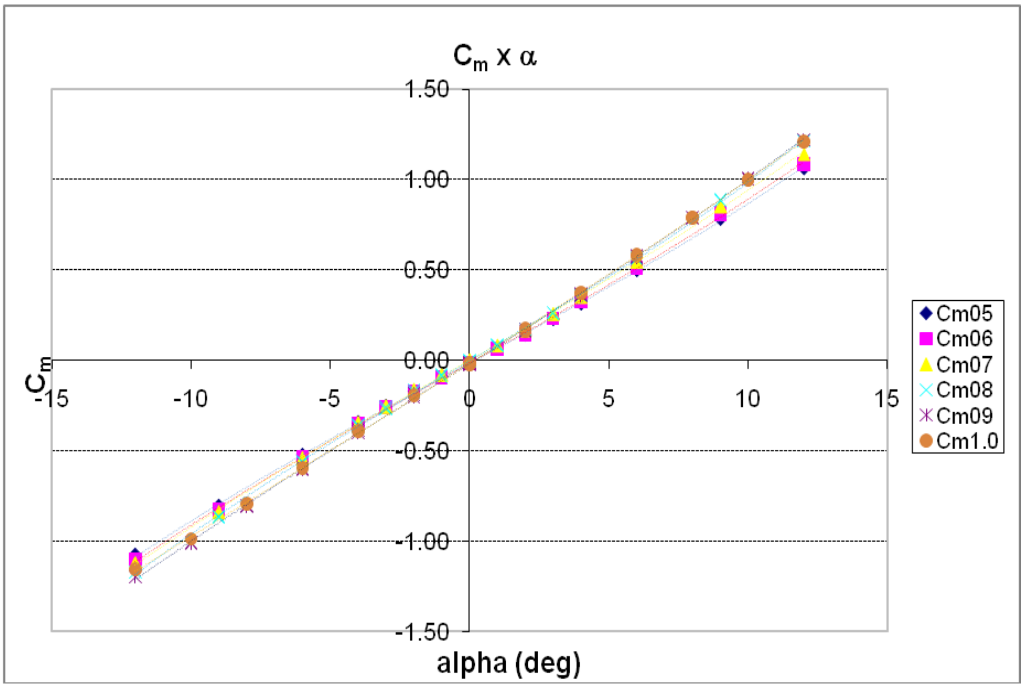

Figure 12. Family curves for pitching moment coefficient.

6.4. Flap opening

Table 1 presents the drag coefficient values, C_D, obtained in the Mach number equal to 0.70, for flaps opened at 0, 5, 10 and 15 degrees. One can notice that, in general, the flap openings equal to 5° and 10° yield the lowest drag coefficients results in this Mach number regime. However, the diferences are not considered important.

Tabel 1: C_D for several flap configurations.

Deg	Flap 0°	Flap 5°	Flap 10°	Flap 15°
0	0.022	0.021	0.021	0.022
2	0.025	0.024	0.024	0.025
4	0.032	0.032	0.032	0.033
6	0.047	0.046	0.046	0.047
8	0.068	0.068	0.068	0.069
10	0.098	0.096	0.098	0.099
12	0.132	0.131	0.132	0.134

6.5. Comparing TTP data to literature

6.5.1. Drag coefficient at angle of attack equal to zero

Values of zero drag force coefficients from several wind tunnels are shown in Fig. 13. The zero drag force coefficient is the value obtained at angle of attack equal to zero and it is denoted by C_{Dzero}. They are adjusted for the base pressure effect and therefore are forebody drag coefficients. These data were obtained in different percentages of blockage ratios. The results at the lowest blockage condition, 0.15 %, are considered reference and can be found in Anderson (1970). The model blockage at TTP is 0.82 %, and the data of the three other configurations, 0.75 %, 1.83 % and 2.77 %, were extracted from Davis (1973).

It can be noticed that the TTP values are higher than that presented in literature, except for M = 1.00. At this point, where a large drag rise can be observed, there are strong discrepancies between data. Differences in the TTP data may be caused by disturbances in the airflow whose tunnel corrections were not still fully implemented as well as the model's different geometrical influences.

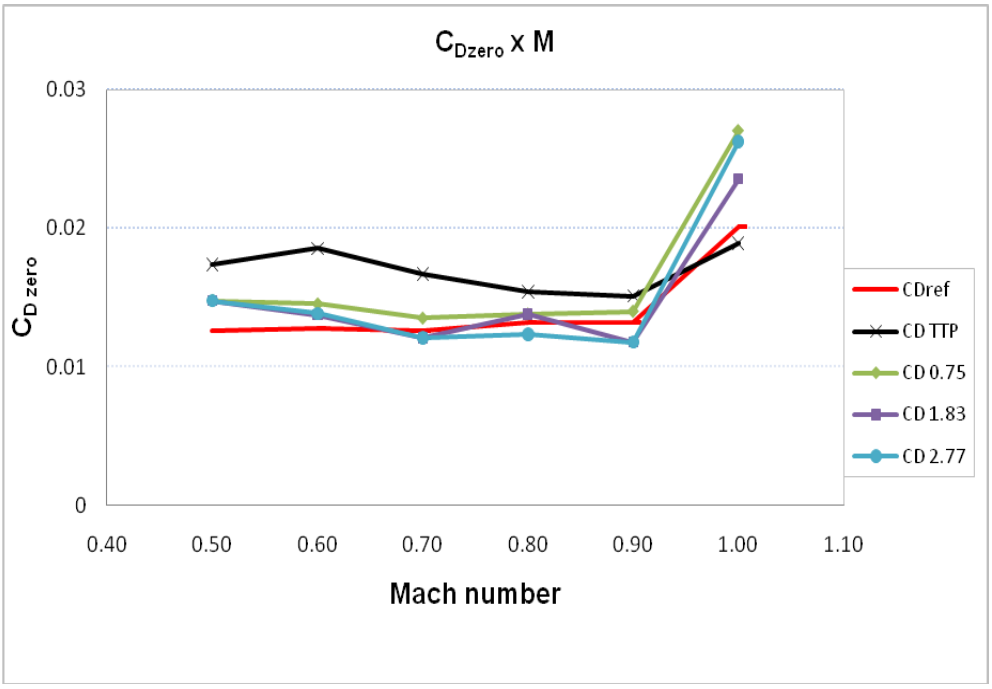

Figure 13. Comparison of Drag force coefficient with literature.

6.5.2. Lift force coefficient

Lift force coefficient results, C_L, at angles of attack of 4 degrees versus Mach number are presented in Fig. 14. Data obtained by Anderson (1970), are also plotted for comparison. Reference curves are above the TTP results but both approach each other at M higher than 0.80.

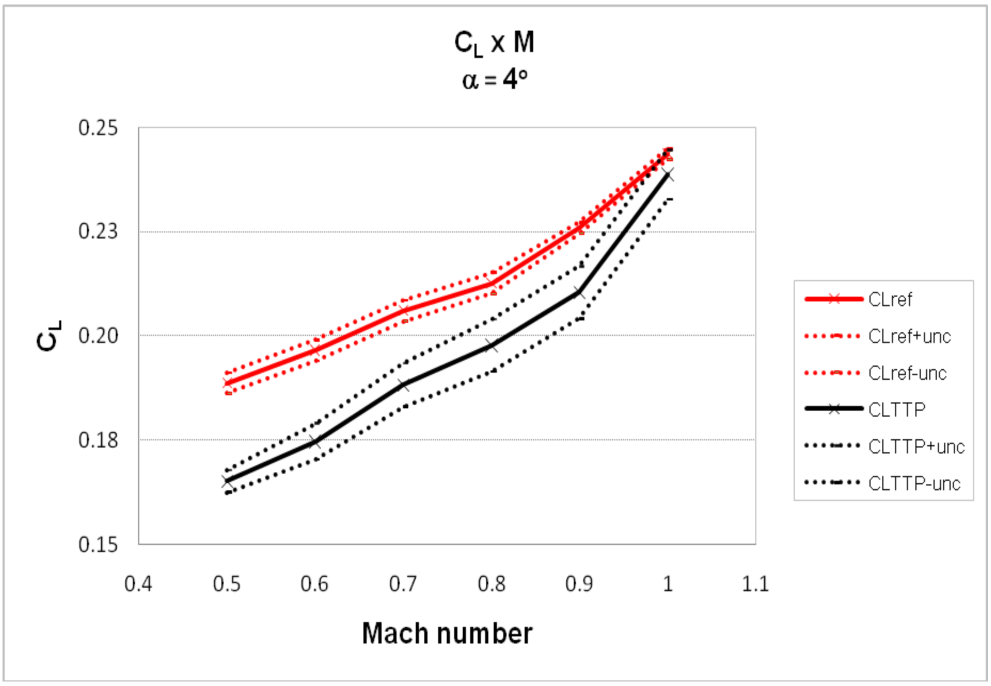

Figure 14. Lift coefficient versus Mach number for angle of attack equal to 4 degrees. Uncertainty limits correspond to a 95 % confidence level.

7. CONCLUSIONS

A modified AGARD "B" model was tested at the transonic wind tunnel TTP as a preliminary analysis of the overall condition of the airflow, instrumentation and measurement methodology.

The measurement precision was estimated sweeping up and down the sting-model system in relation to the angle of attack. The resulting hysteresis was considered as the uncertainty in the load coefficients.

An attempt to study the flow extraction effect on the aerodynamic loads was performed but more tests must be conducted before the optimum flap opening can be settled.

The zero drag force coefficients obtained at TTP are higher than the reference values due to the model's increased area exposed to the airflow.

Although this text campaign used a different configuration of AGARD model "B", it was useful to evaluate the aerodynamic loads measurements at TTP as a first approach.

Next steps of the campaign are to test AGARD models manufactured according to specification.

8. REFERENCES

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9. RESPONSIBILITY NOTICE

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