UDK: 533.6.071.4
COSATI: 01-01

Testing of AGARD-B calibration model in the T-38 trisonic wind tunnel

Dijana Damljanović, BSc (Eng)[1)]
Aleksandar Vitić, BSc (Eng)[1)]
Đorđe Vuković, BSc (Eng)[1)]

In this article, test results of AGARD-B calibration model, performed at the beginning of 2006 in the T-38 trisonic wind tunnel of the Military Technical Institute, are presented. The test results are compared with the results of the tests of the same model performed in 1981 in the IAR (NAE) 5ft trisonic wind tunnel (Canada), and with the results of the test performed in 1986 during the commissioning of the T-38 wind tunnel. Analysis of the test results showed a good agreement with the results obtained in the distinguished IAR (NAE) 5ft wind tunnel, confirming a high quality of air stream in the test section of the T-38, good condition of instrumentation and the correctness of the data reduction algorithm.

Key words: **experimental aerodynamics, calibration model, trisonic wind tunnel.**

Abbrevations

C_x – drag force coefficient (wind axes system)
C_z – lift force coefficient (wind axes system)
C_m – pitching moment coefficient (wind axes system)
C_{pb} – base pressure coefficient
D − model diameter [m]
L − model length [m]
$L_{ref\,f}$ − model reference length [m]
B − wing span [m]
$B_{ref\,f}$ − model reference length [m]
S_{ref} − model reference area [m^2]
S_b − model base area [m^2]
α − aerodynamic angle of attack [^{o}]
β − aerodynamic sideslip angle [^{o}]
M – Mach number
P_b − base pressure [bar]
P_{st} − static pressure [bar]
P_0 − stagnation pressure [bar]
q − dynamic pressure [bar]
Re − Reynolds number for unit length [1/m]
M Re − Reynolds number for reference length [10^6]
T_0 − stagnation temperature [K]
X_{ref} – reference point position relative to balance center [m]
X – axis identification (wind axes system)
Y – axis identification (wind axes system)
Z – axis identification (wind axes system)
RSN – Run Sequence Number
$F.S$ – transducer full scale

1) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade

Introduction

AGARD calibration model B is an ogive-cylinder with a delta wing, originally designed for the calibration of supersonic wind tunnels, but it is also often used for calibrating transonic wind tunnels.

A series of wind tunnel tests of an AGARD calibration model B was performed in the trisonic wind tunnel T-38 of the Military Technical Institute. The tests consisted of forces and moments measurements on the model aiming at determining its aerodynamic coefficients in the Mach number range from 0.2 to 1.80, at complex angles of attack in the range of –4° to +10° and roll angle of 0°.

In this article, some results of the testing are presented in the form of graphs, with the coefficients reduced to the wind axes system.

The obtained test results are compared with the test results of the same model performed in 1981 in the IAR (NAE) 5ft trisonic wind tunnel (Canada), and with the results of the test performed in 1986 during the commissioning of the T-38 wind tunnel. The summary graphs present the comparison of the aerodynamic coefficients obtained in these model tests.

Analysis of the test results obtained through repeated tunnel runs is also given.

Model

AGARD calibration model B is a configuration consisting of a wing and body combination, [1]. The wing is a delta in the form of an equilateral triangle with a span four times the body diameter. The body is a cylindrical body of revolution with an ogive nose. Fig.1 is a sketch of the model with the pertinent dimensions given in terms of the body diameter *D*.

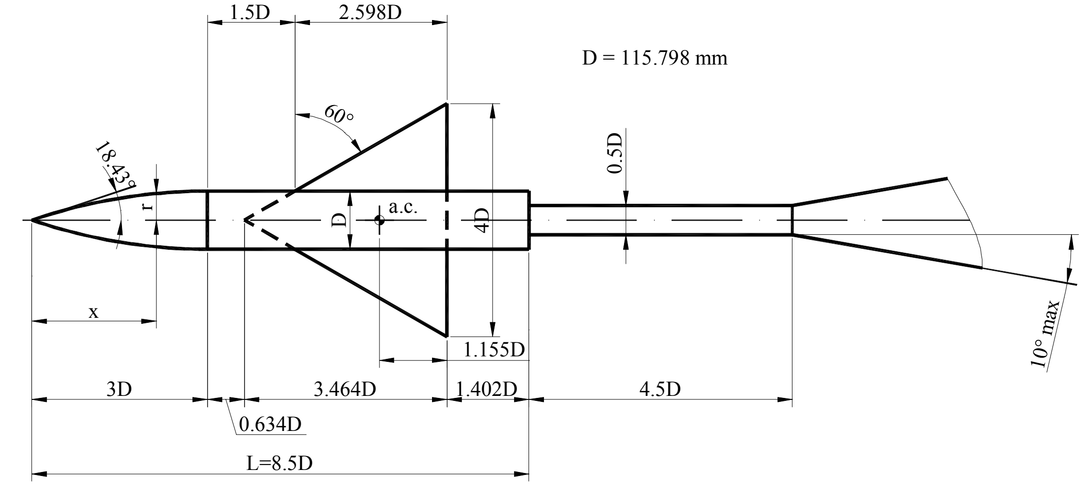

Figure 1. Basic dimensions of the AGARD-B model

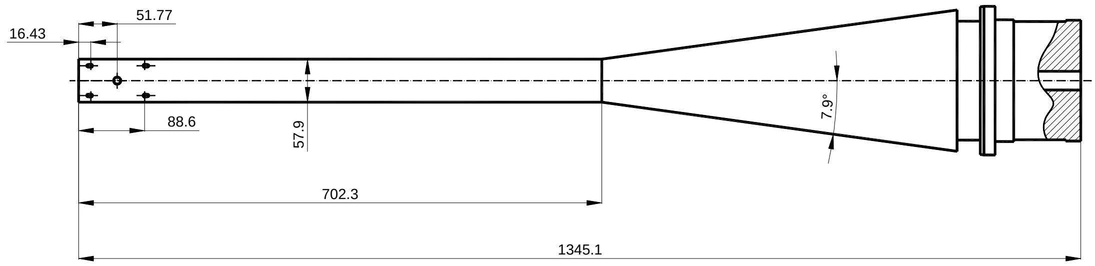

Figure 2. Basic dimensions of the AGARD sting

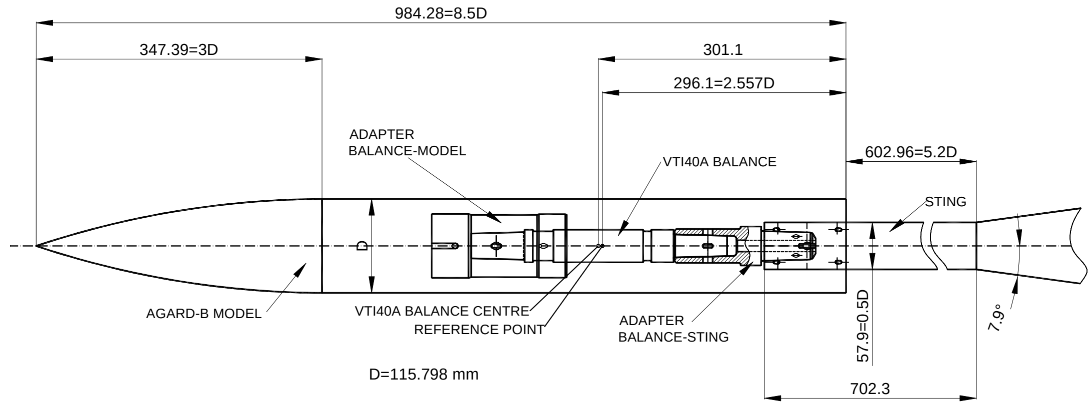

Figure 3. Relation of the sting and balance to the AGARD-B model

The AGARD-B wind tunnel calibration model used in the T-38 wind tunnel was supplied by BOEING, USA. Model size was chosen with respect to the tunnel test section size.

Model has been used in previous wind tunnel calibrations, including T-38, and therefore there is an already existing extensive database with which to compare the results obtained from the present test programme, [2, 5].

Basic model dimensions are given in Table 1.

Table 1

Model length (*L*):	0.9843 m
Model diameter (*D*):	0.1158 m
Wing span (*B*):	0.4632 m
Model reference length, mean aerodynamic chord (L_{ref}):	0.2674 m
Model reference length, wing span (B_{ref}):	0.4632 m
Model reference area (S_{ref}):	0.0929 m^2
Model base area (S_b):	0.01053m^2
Reference point position for moment calculation (X_{ref}):	0.005 m

Model was used to provide force and moment data and only one pressure sensor was used. The pressure in the cavity surrounding the sting at the model base (i.e. the base pressure) was sensed by a single orifice at the end of the tube, which was routed through the balance adaptor to the sensor located below the strut of the model support.

Basic dimensions of the tail sting used to support the model, are given in Fig.2. The male end of the sting was inserted into the model support boss, which was itself attached to the strut.

Sting diameter was 57.9 mm, the length of the straight part of the sting 702.3 mm and the included angle of conical transition of sting into support 7.9°.

The VTI40A six-component balance was supplied by VTI. The "live" side of the balance was fitted into a cylindrical adaptor rigidly attached to the model. The adaptor was needed because the model had originally been made for a larger diameter balance. The "ground" side of the balance was attached to the sting by an adaptor (from

1.5" to 2" diameter). Relation of the sting and balance to the AGARD-B model is presented in Fig.3.

The length of the straight part of the sting behind the model base was 603 mm. Sting vs. model base diameter ratio was 0.5 and sting length vs. model base diameter ratio was 5.2, which is a little above the recommended values for minimum sting interference (see Fig.1).

It can be seen from Fig.3 that the distance from the balance centre to model's downstream end is 301.1 mm. The reference point for force/moment calculation is located at 1.155*D* distance upstream of the downstream edge of the wings (see Fig.1) and 2.557*D* upstream of the model base, where *D*=115.798 mm. From the dimensions given in Fig.3 it is possible to calculate the distance between the reference point and balance centre. Hence, the balance centre is located at 5 mm distance upstream of the reference point.

Fig.4 presents AGARD-B model mounted in the T-38 test section.

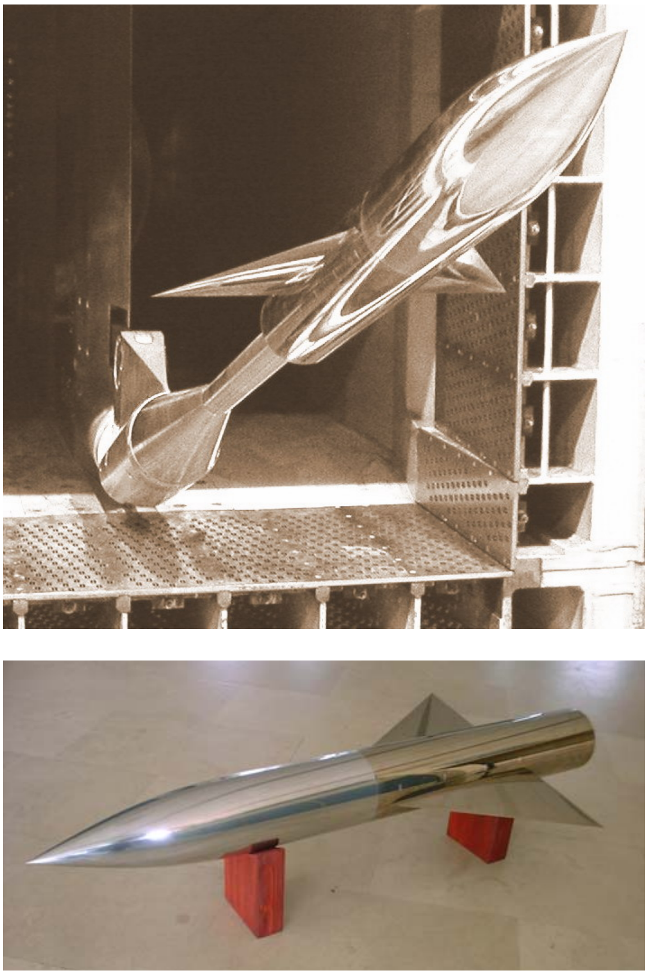

Figure 4. AGARD-B model mounted in the T-38 test section

Testing facility

The T-38 testing facility at the Military Technical Institute in Žarkovo is a blowdown-type pressurized wind tunnel with a 1.5m x 1.5m square test section, [3]. For subsonic and supersonic tests, the test section has solid walls, while for transonic tests a section with porous walls is inserted into the tunnel configuration. The porosity of the walls can be varied between 1.5% and 8%, depending on the Mach number, so as to achieve the best flow quality.

Mach number in the range 0.2 to 4.0 can be achieved in the test section, with Reynolds numbers up to 110 million per meter. In the subsonic configuration, Mach number is set by sidewall flaps in the tunnel diffuser. In the supersonic configuration, Mach number is set by the flexible nozzle contour, while in transonic configuration, Mach number is both set by sidewall flaps and the flexible nozzle, and actively regulated by blow-off system. Mach number can be set and regulated to within 0.5% of the nominal value.

Stagnation pressure in the test section can be maintained between 1.1 bar and 15 bar, depending on the Mach number and regulated to 0.3% of the nominal value. Run times are in the range 6s to 60s, depending on the Mach number and stagnation pressure.

The model is supported in the test section by a tail sting mounted on a pitch-and-roll mechanism by which the desired aerodynamic angles can be achieved. The facility supports both step-by-step model movement and continuous movement of the model (“sweep”) during measurements.

Positioning accuracy is 0.05° in pitch and 0.25° in roll.

Instrumentation, data recording and reduction

The stagnation pressure P_0 in the test section was measured by Mensor quartz bourdon tube absolute pressure transducer pneumatically connected to a pitot probe in the settling chamber of the wind tunnel. The range of the transducer used was 7 bar. The nonlinearity and hysteresis of this transducer is typically 0.02% F.S. An end-to-end calibration of the transducer and data acquisition channel was performed using a Mensor quartz secondary pressure standard.

The difference $P_{st} - P_0$ between the stagnation and static pressure in the test section was measured in subsonic speed range by a Mensor quartz bourdon tube differential pressure transducer pneumatically connected to the P_0 pitot probe and an orifice on the test section sidewall. In transonic and supersonic speed range an absolute pressure transducer of the same type and range was used. The range of these transducers was 1.75 bar; nonlinearity and hysteresis was about 0.02% F.S. Transducers were calibrated in the same manner as the P_0 transducer.

The stagnation temperature T_0 was measured by a RTD probe in the settling chamber. The accuracy of this transducer is approximately ±0.5K.

The pitching angle of the model support was measured by a resolver mounted onto the mechanism. The accuracy of the pitching angle reading was 0.05°.

The base pressure P_b was measured by a Druck PDCR42 piezoresistive differential pressure transducer (actually, $P_b - P_{st}$ was measured). The range of this transducer was 0.35 bar, with 0.05% F.S. nonlinearity and hysteresis.

Aerodynamic forces and moments acting on the model were measured by VTI40A internal six-component strain gauge balance. The range of the balance was 1130 N for axial force, 5000 N for side force, 10150 N for normal force, 184 Nm for the rolling moment, 530 Nm for the pitching moment and 256 for the yawing moment; the accuracy was approximately 0.20% F.S.

The balance was checked by applying dead weights at known locations immediately prior to testing and accuracy within nominal limits was confirmed.

The output of a precision digital clock was sampled synchronously with other channels, in order to serve as a time base for the segmentation of data.

The data acquisition system consisted of a Teledyne 64 channel "front end" controlled by a PC computer. The front-end channels for flow parameters transducers (i.e. P_0, $P_{st} - P_0$ and T_0) were set, with 10 Hz, fourth-order low pass Butterworth filters and appropriate amplification.

In order to minimize the differences in time lags on various channels during model sweep, the channels for six balance components and base pressure were set with 30 Hz low pass filters of the same type. In order to compensate for the poorer filtering on these channels, these signals were additionally filtered during the data reduction by a 3 Hz non-casual low pass digital filter.

The data from all analog input channels were digitized by a 16-bit resolution A/D converter with the overall accuracy of the acquisition system being about 0.05% F.S. of the channel signal range. All channels were sampled with the same 200 samples/s rate.

Digitized data were sent through the network to a COMPAQ Alphaserver DS20E computer and stored on disk for later reduction.

Data reduction was performed after each run, using the standard T38-APS software package in use with the wind-tunnel facility. It was done in several stages, i.e.:

- Data acquisition system interfacing and signals normalization;
- Determination of flow parameters;
- Determination of model position (orientation);
- Determination of aerodynamic coefficients.

Each stage was performed by a different software module.

Several axes systems were used in data reduction. These were: the wind tunnel axes system, balance, body, and wind axes systems. The tunnel, balance and body axes systems were used only for calculating the intermediate data and they do not appear in results presented in this article. Balance and wind axes systems were defined as follows:

Balance axes system: The origin of this axes system was in the centre of the balance VTI40A. For this model, the *X* axis was parallel to the model longitudinal axis and positive towards the end of the model. The *Z* axis lay in the model's plane of symmetry, and the *Y* axis was directed towards the left side of the model and completed a left-handed axes system.

Wind axes system: The origin of this axes system was in the model reference point. The *X* axis was parallel to the air velocity vector and in the same direction (toward the end of the model). The *Z* axis lay in the flow plane and was normal to the *X* axis. The *Y* axis completed the left-handed axes system. The aerodynamic angle of attack α was the angle between the projection of the air velocity vector on the model plane of the left-right symmetry and the model axis. The aerodynamic sideslip angle β was the angle between the air velocity vector and its projection on the model plane of the left-right symmetry.

Fig.5 shows the relative positions of these axes systems.

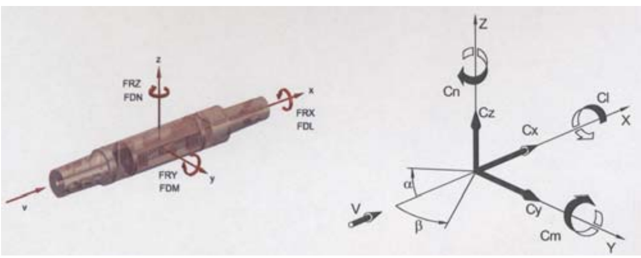

Figure 5. Axes systems used in data reduction

Test programme

The objective of the testing was to obtain the characteristics of the AGARD-B model at Mach numbers 0.2 to 1.80, angles of attack α in the interval –4° to +10° and roll angle 0°, [4]. The angle of attack range was covered by a continuous pitching movement of the model during the run with a 2°/s rate of change.

A list of some performed runs, which are compared with results from the Canadian tunnel and previous T-38 wind tunnel calibrations, is given in Table 2.

Table 2

RUN number	TEST section	MACH number	*M*Re	Stagnation pressure P_0, bar	Roll angle ϕ, [°]
17	Subsonic	0.60	7.80	2.3	0
5	Transonic	0.85	9.6	2.3	0
7	Transonic	1.00	10.26	2.3	0
10	Transonic	1.27	10.54	2.3	0
22	Supersonic	1.40	10.44	2.3	0
24	Supersonic	1.60	10.02	2.3	0

Some runs were performed in order to check test repeatability. List of those runs is given in Table 3.

Table 3

RUN number	TEST section	MACH number	*M*Re	Stagnation pressure Po, bar	Roll angle ϕ, [°]
8	Transonic	1.07	10.40	2.3	0
28	Transonic	1.07	9.04	2.0	0
29	Transonic	1.07	8.85	2.0	0
11	Transonic	1.40	10.40	2.3	0
26	Transonic	1.40	10.42	2.3	0
27	Transonic	1.40	10.43	2.3	0
30	Transonic	1.40	10.27	2.3	0

Test results

The test results of AGARD-B calibration model, performed at the beginning of 2006 in the T-38 trisonic wind tunnel of the Military Technical Institute are compared with the results of tests of the same model performed in 1981 in the IAR (NAE) 5ft trisonic wind tunnel (Canada), [5]. Test results obtained from the latest test programme are also compared with the results from previous T-38 wind tunnel calibrations, [2]. In those tests ABLE 2.0" Mk XVIII internal six-component balance was used.

The tests results are presented in the form of graphs in Figures 6-11. Compared graphs show C_x (drag force coefficient), C_z (lift force coefficient), C_m (pitching moment coefficient) and C_{pb} (base pressure coefficient) in relation to the angle of attack α in the wind axes system. Test results are given for model aerodynamic centre located a 2.557*D* distance upstream of the model base. Reynolds numbers for each Mach number are also given. Model reference length for *M*Re Reynolds number calculation is mean aerodynamic chord L_{ref}.

Test results obtained in repeated wind tunnel runs are presented in similar form of graphs in Figures 12 and 13.

Comparison of results with NAE AGARD-B test

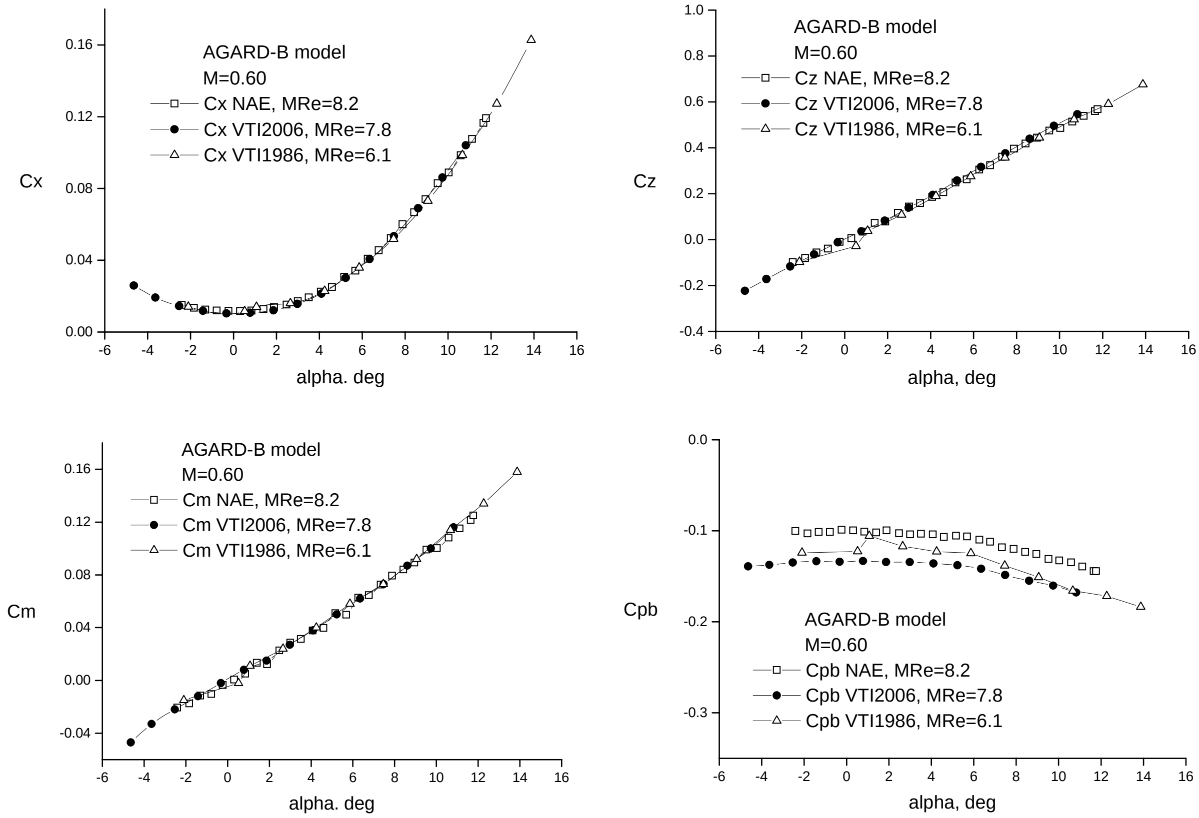

Figure 6. Aerodynamic coefficients of the model at M=0.6

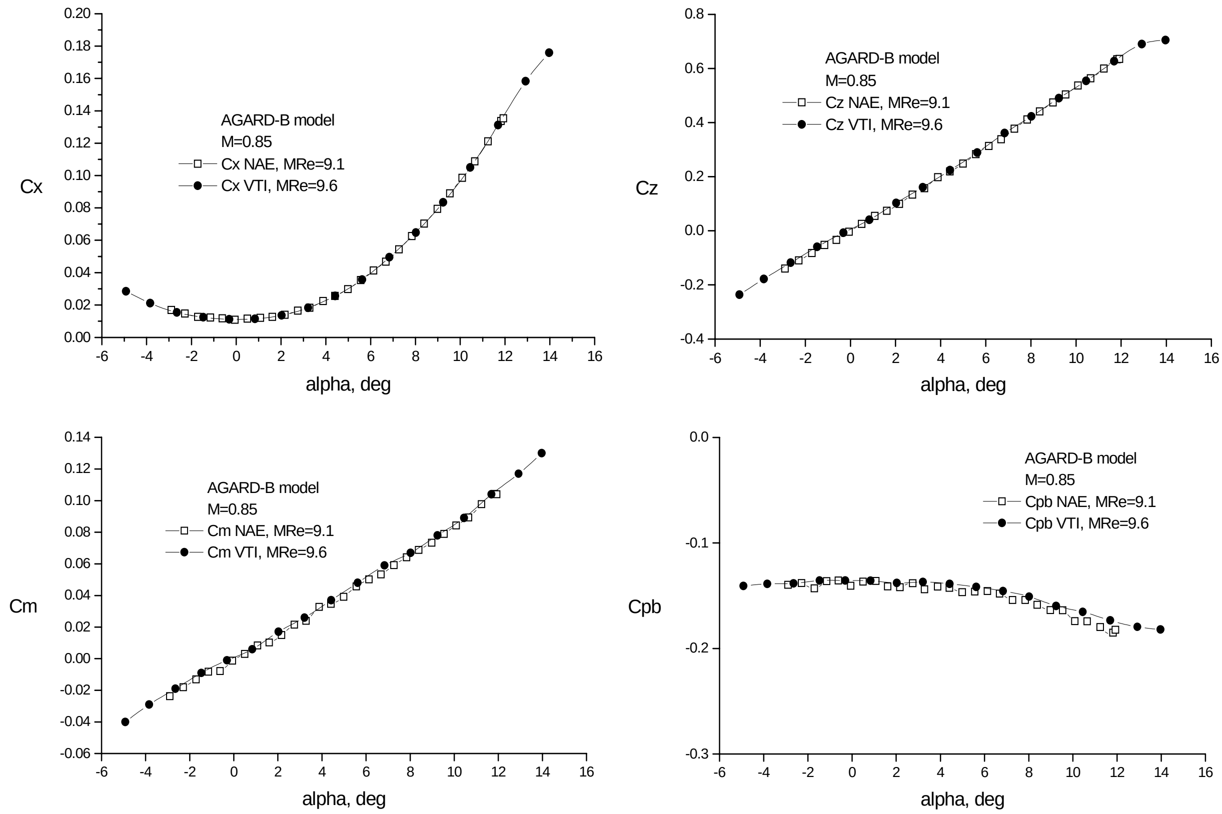

Figure 7. Aerodynamic coefficients of the model at M=0.85

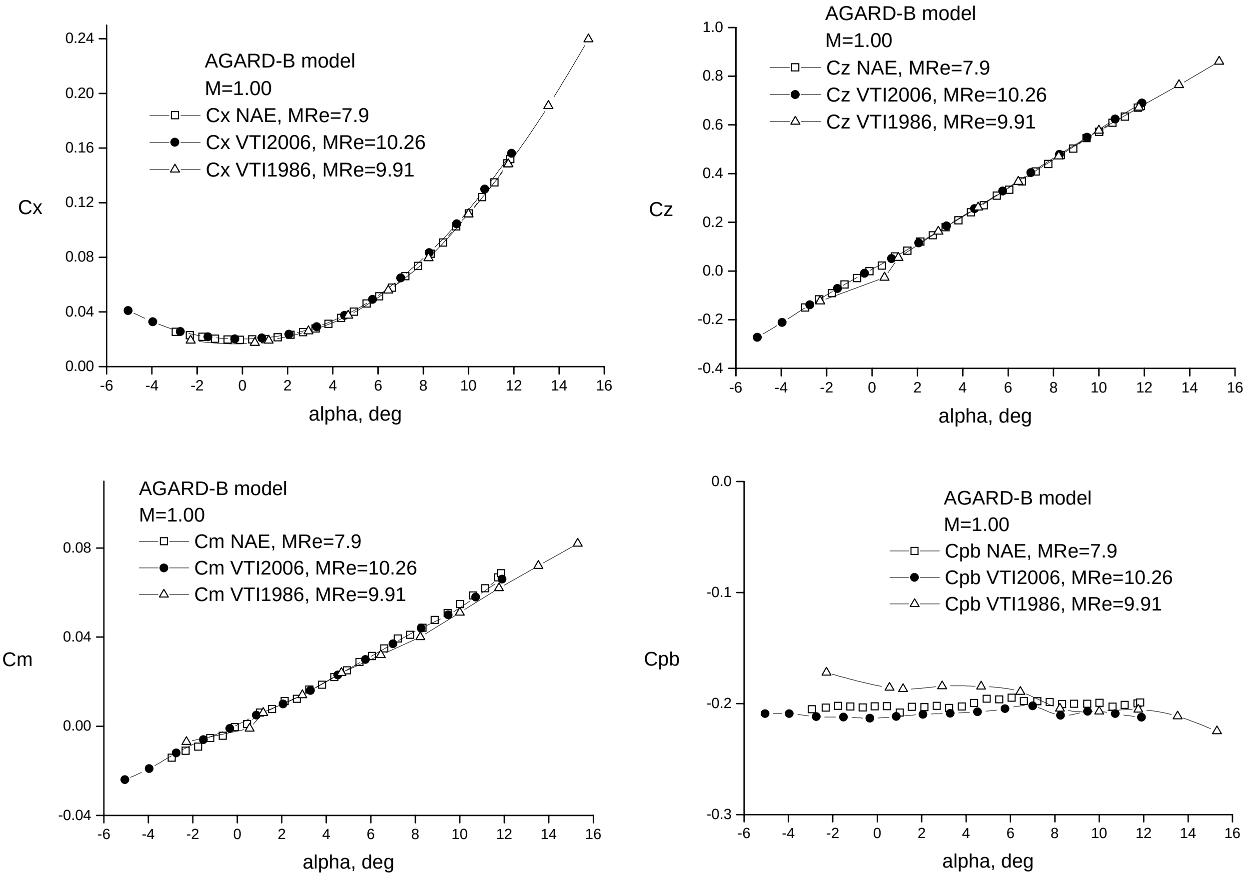

Figure 8. Aerodynamic coefficients of the model at M=1.0

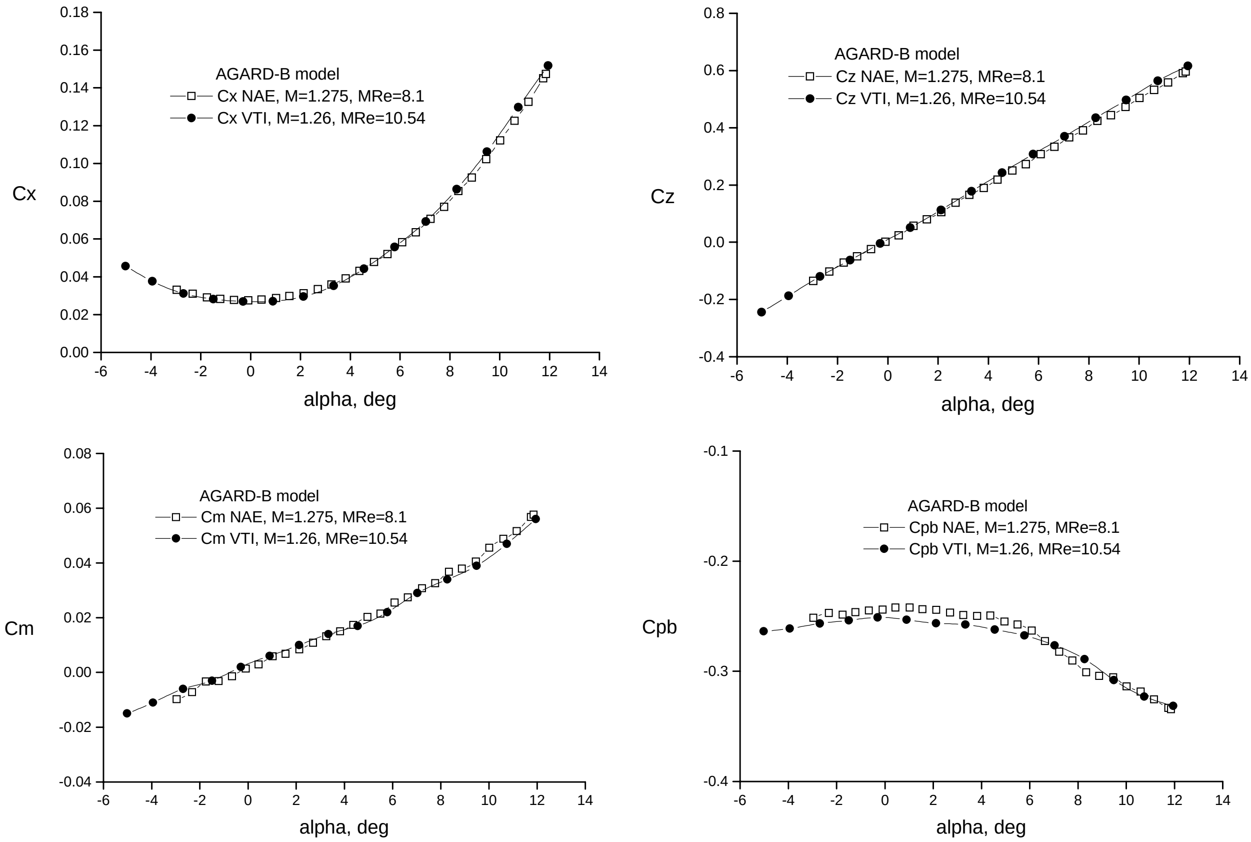

Figure 9. Aerodynamic coefficients of the model at M=1.27

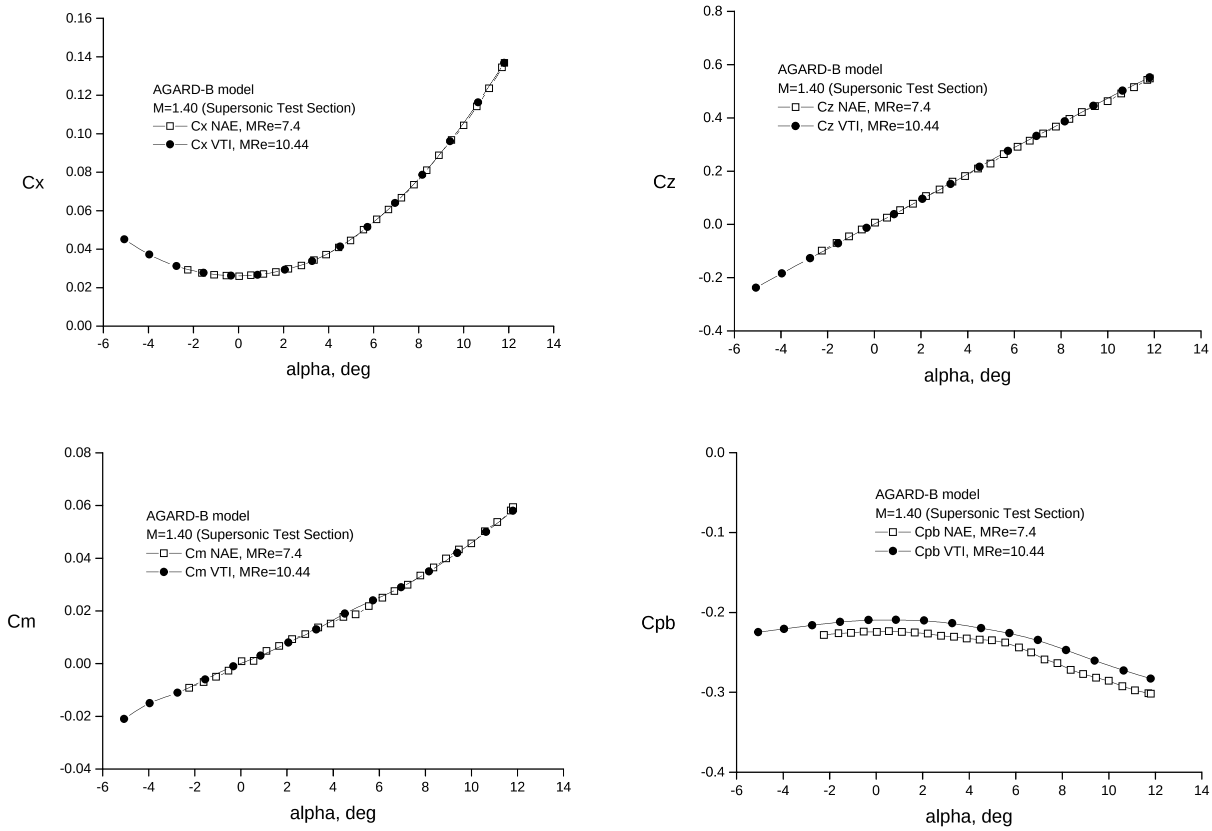

Figure 10. Aerodynamic coefficients of the model at M=1.40

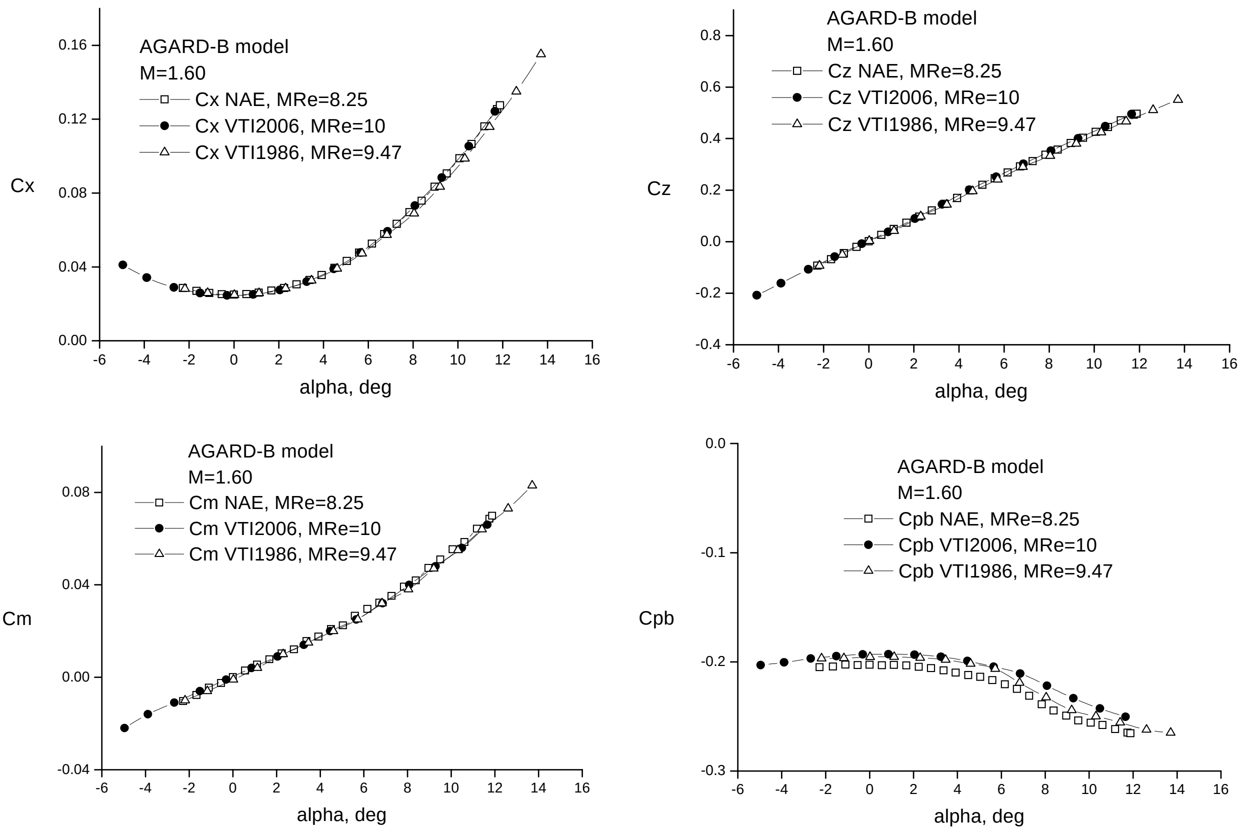

Figure 11. Aerodynamic coefficients of the model at M=1.60

Repeatability check of VTI AGARD-B test

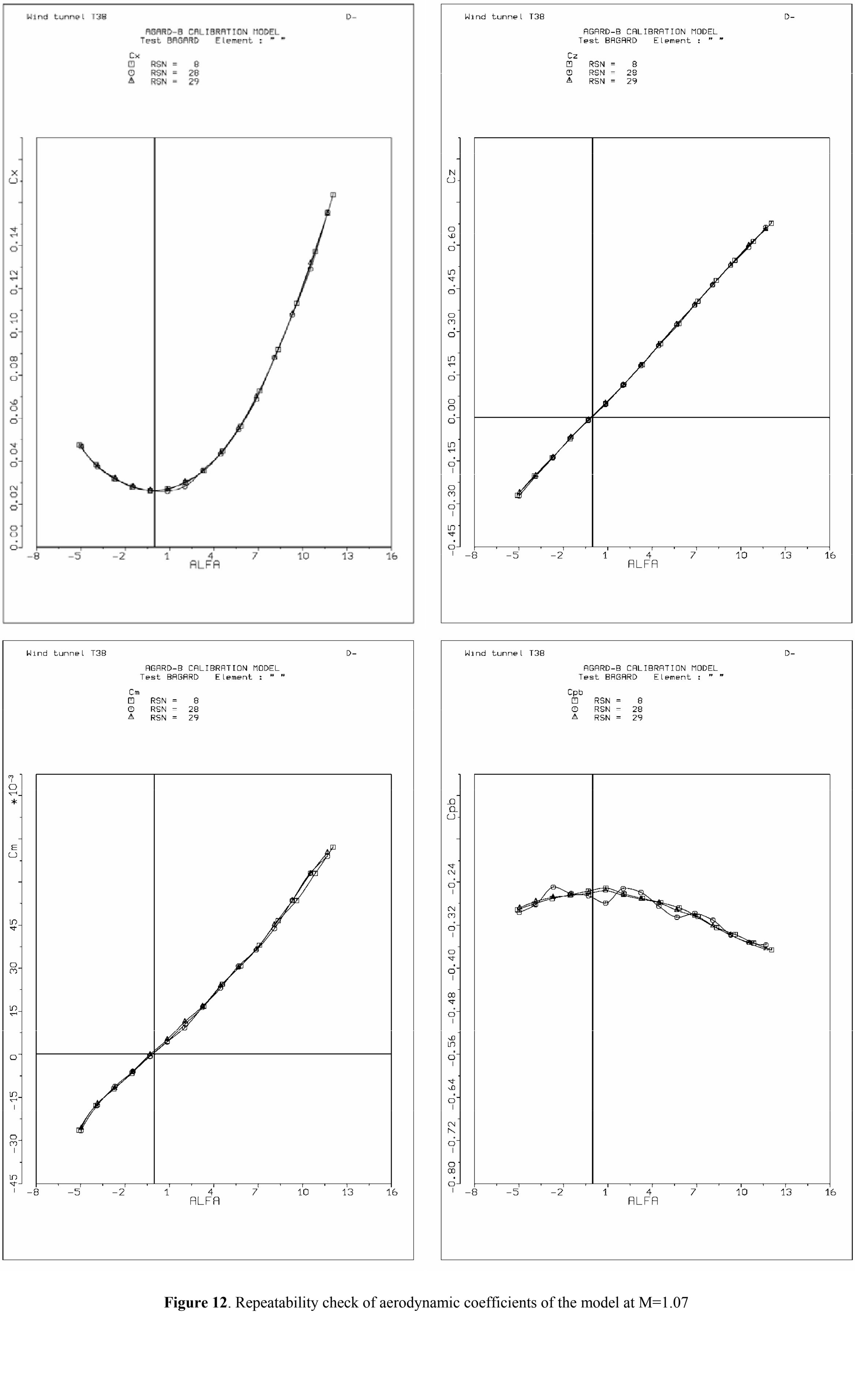

Figure 12. Repeatability check of aerodynamic coefficients of the model at M=1.07

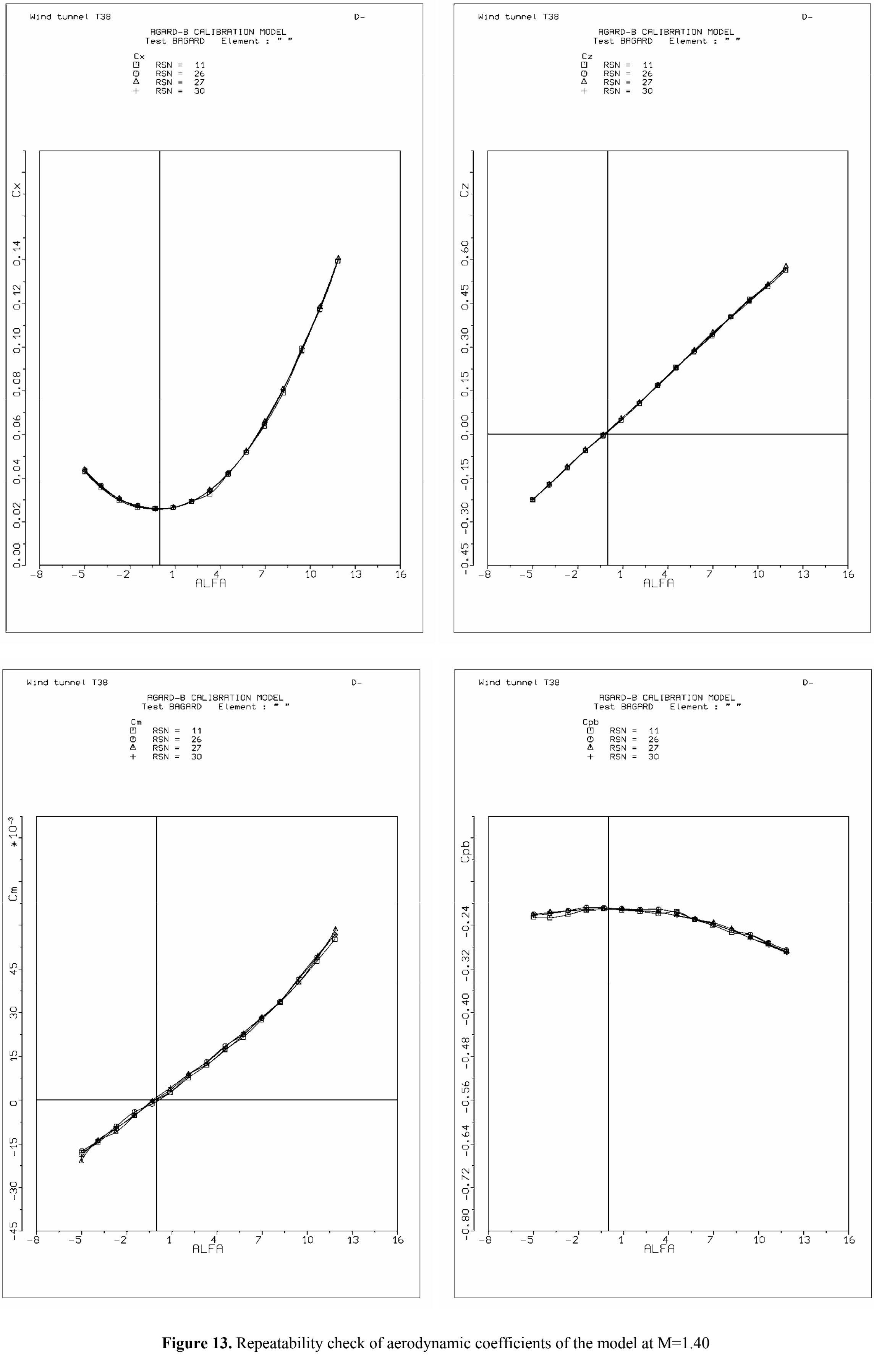

Figure 13. Repeatability check of aerodynamic coefficients of the model at M=1.40

Tables 4 and 5 present aerodynamic coefficients at a certain angle of attack obtained in repeated wind tunnel Mach 1.07 and 1.40 runs. Average values of aerodynamic coefficients and their dispersions are also given.

Table 4. Aerodynamic coefficients for model at M=1.07 and alpha=-0.31°

RSN	C_x	C_z	C_m	C_{pb}
8	0.0264	-0.008	-0.001	-0.2569
28	0.0264	-0.010	-0.001	-0.2657
29	0.0265	-0.007	0.000	-0.2612
Average	0.0264	-0.008	-0.001	-0.2613
Dispersion	0.0001	0.003	0.001	0.0088

Table 5. Aerodynamic coefficients for model at M=1.40 and alpha=-5.00°

RSN	C_x	C_z	C_m	C_{pb}
11	0.0431	-0.224	-0.018	-0.2255
26	0.0437	-0.223	-0.017	-0.2197
27	0.0439	-0.227	-0.021	-0.2215
30	0.0432	-0.223	-0.019	-0.2221
Average	0.0435	-0.224	-0.019	-0.2222
Dispersion	0.0008	0.004	0.004	0.0058

Conclusion

This article presents test results of AGARD-B calibration model, performed at the beginning of 2006 in the T-38 trisonic wind tunnel of the Military Technical Institute. The obtained test results are compared with the test results of the same model performed in 1981 in the IAR (NAE) 5ft trisonic wind tunnel (Canada) and with the results of the test performed in 1986 during the commissioning of the T-38 wind tunnel.

Analysis of the test results showed good agreement with the results obtained in the distinguished IAR (NAE) 5ft wind tunnel.

There is some disagreement in the obtained test results for the base pressure coefficient in these tests. This can be explained by the fact that the absolute pressure transducers of relatively high range measured base pressure in previous tests (IAR (NAE), VTI 1986) and the latest VTI test were performed using differential pressure transducers of lower range and higher accuracy.

Small differences between the aerodynamic coefficients in latest and previous (1986) measurements in T-38 wind tunnel are explained by not taking into account deflections of tail sting due to the model weight (about 0.2°).

Analysis of the test results obtained in repeated tunnel runs showed a good run-to-run agreement, confirming a high quality of tunnel repeatability. For example, the maximum dispersion of C_x drag force coefficients on M=1.07 in repeated runs is 0.0001 and on M=1.40 is 0.0008 (results are not as good as at Mach 1.07 because of unsteady Mach number in Mach 1.40 runs, caused by a malfunctioning ejector valve). Good test repeatability is declared by dispersion of C_x coefficient of no more than 0.0002.

Analysis of the test results confirms a high quality of air stream in the test section of the T-38, good conditions of wind tunnel instrumentation and the correctness of the data reduction algorithm. T-38 wind tunnel of the Military Technical Institute can rightfully be classified alongside top facilities of similar type worldwide.

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Received: 27.05.2006.

Ispitivanje kalibracionog modela AGARD-B u trisoničnom aerotunelu T-38

U ovom radu su prikazani rezultati ispitivanja kalibracionog modela AGARD-B koji je izvršen početkom 2006. godine u trisoničnom aerotunelu T-38 Vojnotehničkog instituta Vojske Srbije. Rezultati ispitivanja su upoređeni sa rezultatima ispitivanja istog modela izvršenog 1981. godine u IAR (NAE) 5ft trisoničnom aerotunelu (Kanada), i sa rezultatima ispitivanja izvršenog 1986. godine tokom primopredaje aerotunela T-38. Analiza rezultata je pokazala dobro slaganje sa rezultatima dobijenim u poznatom IAR (NAE) 5ft aerotunelu, potvrđujući visok kvalitet vazdušne struje u radnom delu aerotunela T-38, dobro stanje instrumentacije i korektnost algoritma za obradu podataka.

Ključne reči: **eksperimentalna aerodinamika, kalibracioni model, trisonični aerodinamički tunel.**

Испытывание калибровочной модели АГАРД-Б в трёхзвуковой аэродинамической трубе Т-38

В настоящей работе показаны результаты испытывания калибровочной модели АГАРД-Б, проведённого в начале 2006-ого года в трёхзвуковой аэродинамической трубе Т-38 Военно-технического института Армии Сербии. Результаты испытывания сравнены со результатами испытывания такой же модели проведённого в 1981-ом году в ИАР (НАЕ) 5 фт в трёхзвуковой аэродинамической трубе (в Канаде), а также и со результатами испытывания проведённого в 1986-ом году в течении приёмо-передачи аэродинамической трубы Т-38. Анализ результатов показал хорошее согласовывание со результатами полученными в известной ИАР (НАЕ) 5 фт аэродинамической трубе, потверждая высокое качество потока воздуха в рабочей части аэродинамической трубы Т-38, хорошее состояние приборов и правильность алгорифма для обработки данных.

Ключевые слова: экспериментальная аэродинамика, калибровочная модель, трёхзвуковая аэродинамическая труба.

Essai du modèle de calibrage AGARD-B dans la soufflerie trisonique T-38

Dans cet article on a présenté les résultats des essais du modèle de calibrage AGARD-B effectués au début de l'an 2006 dans la soufflerie trisonique T-38 à l'Institut militaire technique de l'Armée de Serbie. Les résultats obtenus ont été comparés avec les résultats des essais du même modèle, effecués en 1981. à IAR (NAE) 5ft dans la soufflerie trisonique (Canada) et avec les résultats des essais réalisés en 1986. L'analyse des résultats a démontré qu'il y a un bon accord avec les résultats obtenus dans la fameuse soufflerie IAR(NAE) 5ft, en confirmant excellente qualité de circulation d'air dans la chambre d'expérience de la soufflerie T-38, bon état d'instrumentation et l'algorithme correct pour le traitement des données.

Mots clés: **aérodynamique expérimentale, modèle de calibrage, soufflerie trisonique**