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Convergence of Transonic Wind Tunnel Test Results of the AGARD-B Standard Model

AGARD-B is a widely-used configuration of a standard wind tunnel model. Beside its originally intended application for correlation of data from supersonic wind tunnel facilities, it was tested in a wide range of Mach numbers and, more recently, used for assessment of wall interference effects, validation of computational fluid dynamics codes and validation of new model production technologies. The researchers and wind tunnel test engineers would, naturally, like to know the "true" aerodynamic characteristics of this model, for comparison with their own work. Obviously, such data do not exist, but an estimate can be made of the dispersion of test results from various sources and of the probable "mean" values of the aerodynamic coefficients. To this end, comparable transonic test results for the AGARD-B model at Mach numbers 0.77, Mach 1.0 and Mach 1.17 from six wind tunnels were analyzed and average values and dispersions of the aerodynamic coefficients were computed.

Keywords: *wind tunnel, transonics, standard model, inter-facility correlation.*

1. INTRODUCTION

Standard wind tunnel models (reference models, calibration models or test check-standards) are important tools of experimental aerodynamics. They are objects of simple, precisely defined shapes (usually resembling a simplified form of an airplane or a rocket) that are tested in wind tunnels in order to verify the complete measurement chain, including wind tunnel structure, quality of the airstream, model positioning, transducers and force balances, data acquisition system and data reduction software. This verification is done by comparison of test results with previously obtained results.

Standard models are also used to provide baselines for correlation of results from different wind tunnels [1-3], to check data repeatability over time [4], for checkouts of wind tunnel systems after repairs or modifications, for the assessment of wall interference effects [5,6], for verification of new measurement techniques or devices [7], for the validation of new model manufacturing technologies [8-10], for training of wind tunnel personnel [11]. Besides, results from wind tunnel tests of standard models are used as test cases for the verification of computational-fluid-dynamics (CFD) computer codes [12].

The researchers and wind tunnel test engineers would, naturally, like to have access to "true" aerodynamic characteristics of the selected standard model configuration, with which to compare their own work. Obviously, such data do not exist because each set of test results is influenced by the differences in model production, differences in test conditions and the peculiarities of particular wind tunnel facilities and measurement systems used. There is also an unfortunate circumstance that standard models are usually tested during the commissioning of wind tunnel facilities, when the measurements systems have not yet been optimally tuned, so that the results are not always as good as they can be [3]. Therefore, a certain scatter of results from different tests of the same theoretical model configuration is inevitable.

It is of interest to quantify that scatter, so that a researcher can have an idea of the degree of the reliability of the "reference" which is used. Such an analysis is presented in the paper. It is based on the transonic test results of the AGARD-B standard model in six wind tunnels. The analysis is limited to the transonic speed range, which was selected as the "worst case" because transonic wind tunnel tests can be heavily influenced by the wall interference phenomena, model support interference and possible nonoptimality of ventilated test-section walls, while the results of tests in different wind tunnels in subsonic or supersonic speed ranges are expected to be in better agreement. Results of the analysis of tests at Mach numbers 0.77, 1.0 and 1.17 are presented.

An additional intention of the authors was to present a set of comparative results for the AGARD-B configuration in the transonic speed range that might be of help to other researchers, because, although sets of test results from various sources are available, the data are not always in easily legible form.

2. THE AGARD-B STANDARD MODEL

Among the standard wind tunnel models, AGARD-B configuration [13][14] is perhaps the most widely used. It is a simple wing-body configuration vaguely resembling a delta-winged high-speed airplane (Fig. 1).

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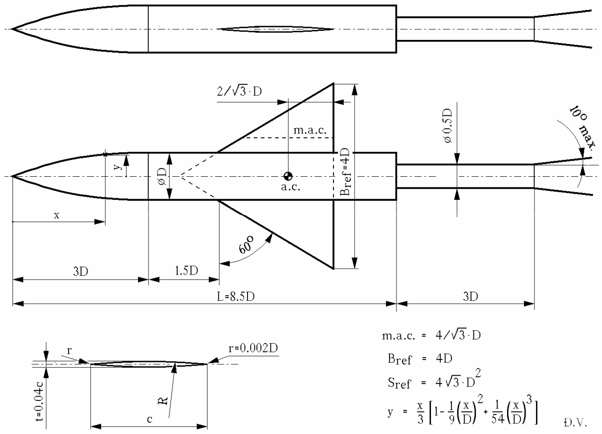

Figure 1. Theoretical geometry of the AGARD-B standard model and its support sting

Initially intended for correlation of data from supersonic wind tunnels [3], AGARD-B has since been tested in a wide interval of Mach numbers, ranging from subsonic [15] through transonic and supersonic [2], up to hypersonic [3] speed range.

3. COMPARATIVE DATA SETS

AGARD-B model configuration was selected as a check-test standard [4] at the wind tunnel site in VTI (Military Technical Institute, Belgrade, Serbia) so it is being periodically tested, every couple of years, and data [2,4] are available to perform an analysis of both short-term and long-term repeatability.

VTI is fortunate to be the custodian of a 115.8 mm-dia. AGARD-B/C model (Fig. 2), built by the Boeing Company. The same physical model had earlier been tested in the 5 ft trisonic wind tunnel [16-18] of NAE (National Aeronautical Establishment) in Canada, a division of the NRC (National Research Council), and the 1.2 m trisonic wind tunnel [19] of INCREST (National Institute for Technological and Scientific Creation) in Romania, now operating as INCAS (National Institute of Aerospace Research).

Figure 2. The 115.8 mm dia. AGARD-B model with 0.53% blockage in the T-38 wind-tunnel of VTI

Data from tests [11][20] of the model in those wind tunnels are available, so they can be compared to assess the facility-dependent variations, eliminating the uncertainties due to differences in model production.

Some test data [21] from the 1.2 m trisonic wind tunnel [22] of NAL (National Aerospace Laboratories) in India and the 1.5 m medium-speed wind tunnel [23] of CSIR (Council for Scientific and Industrial Research) in South Africa are included in the analysis as well. Results from these five wind tunnels are compared to a set [15] of results from the AEDC (Arnold Engineering Development Center) 4T 4 ft wind tunnel [24] in the USA, which differs from data sets [2][4][11][20] in that the model frontal blockage was very small (0.15%) so it can be considered that the test was practically wall-interference-free.

4. TEST FACILITIES

Table 1 shows the sizes of the test sections of the six wind tunnels in which the analyzed data were measured, as well as sizes of the models and the amount of frontal blockage they produced in the test sections.

4.1 NRC 5 ft trisonic wind tunnel

The 5 ft trisonic wind tunnel [16] of NRC in Ottawa, Canada is a pressurized, blowdown wind tunnel (Fig. 3, [17]). Mach number range is from 0.1 to 4.25 and achievable Reynolds number is above 60×10^6/m. The 5 ft × 5 ft test section has solid walls for measurements in the subsonic and supersonic Mach range. For transonic tests, a ventilated test section is used, with perforated walls within a plenum chamber with a controlled blow-off. At the time of the tests presented in this paper, walls had uniform, fixed porosity [18].

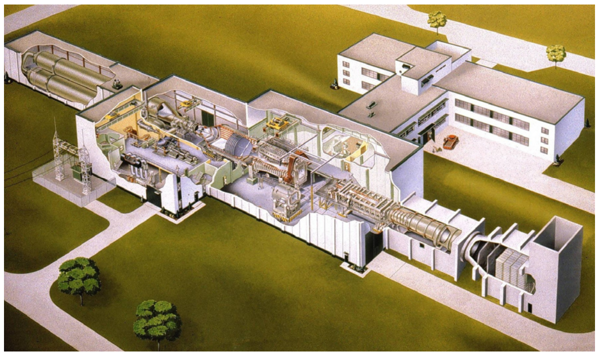

Figure 3. The 5 ft Trisonic wind tunnel of NRC, Canada

4.2 NAL 1.2 m trisonic wind tunnel

The 1.2 m × 1.2 m trisonic blowdown wind tunnel (Fig. 4) [22] of CSIR-NAL in Bangalore, India, is very

Table 1. Sizes of wind tunnel test sections and tested AGARD-B models

	NAE (NRC) Canada	NAL India	INCREST (INCAS) Romania	VTI Serbia	CSIR S. Africa	AEDC USA
Test section size	5 ft	1.2 m	1.2 m	1.5 m	1.5 m	4 ft
Model diameter	115.8 mm	34.3 mm	115.8 mm	115.8 mm	150 mm	49.8 mm
Blockage	0.53%	0.073%	0.83%	0.53%	0.78%	0.15%

similar to the NRC 5 ft wind tunnel. Mach number range is 0.2 to 4. Reynolds number can be up to 60×10^6/m. Transonic test section is ventilated and has uniformly perforated walls.

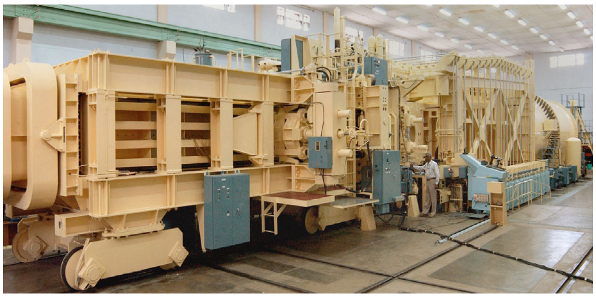

Figure 4. The 1.2 m Trisonic wind tunnel of NAL, India

4.3 INCAS 1.2 m trisonic wind tunnel

The 1.2 m × 1.2 m trisonic wind tunnel (Fig. 5) [19] of INCAS in Bucharest, Romania, is of the blowdown type and similar to the Canadian and Indian trisonic wind tunnels. Mach number range is from 0.1 to 3.5 and maximum Reynolds number is up to 100×10^6/m. Transonic test section has variable-porosity perforated walls with inclined holes.

Figure 5. The 1.2 m Trisonic wind tunnel of INCAS, Romania

4.4 VTI T-38 1.5 m trisonic wind tunnel

The 1.5 m T-38 trisonic wind tunnel [25] of VTI (Military Technical Institute) in Beograd, Serbia, (Fig. 6) is a blowdown facility of the same type and with similar characteristics as the Canadian, Indian and Romanian wind tunnels (all three wind tunnels were designed and built by the same company). Mach number range is from 0.2 to 4 and maximum Reynolds number is up to 115×10^6/m. Transonic test section of the wind tunnel has variable-porosity perforated walls with inclined holes and splitter plates.

Figure 6. The T-38 1.5 m trisonic wind tunnel of VTI, Serbia

4.5 CSIR Medium-Speed Wind Tunnel

The 1.5 m × 1.5 m wind tunnel (Fig. 7) [23] of CSIR in Pretoria, South Africa, is a continuous, closed-circuit, variable-pressure facility with Mach number range from 0.1 to 1.4 and Reynolds number up to 31×10^6/m. Transonic test section of the wind tunnel has slotted walls.

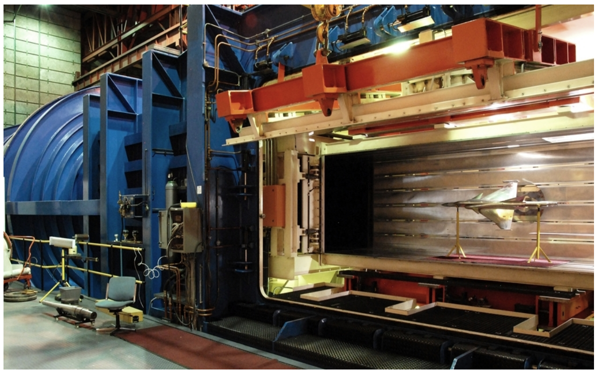

Figure 7. The 1.5 m Medium-speed wind tunnel of CSIR, South Africa

4.6 AEDC 4T wind tunnel

The 4T Aerodynamic Wind Tunnel [24], at the U.S. Air Force's Arnold Engineering Develop-ment Complex (AEDC) near Tullahoma, USA, is a continuous wind tunnel with a 4 ft × 4 ft test section and operating Mach number range from 0.2 to 2. Maximum Reynolds number is above 23×10^6/m. Test section of the wind tunnel has variable-porosity perforated walls with inclined holes.

5. RESULTS AND DISCUSSION

5.1 Wind tunnel data from the six sources

Results of wind tunnel tests of the AGARD-B model are presented in the form of non-dimensional aerodynamic coefficients in the wind axes system.

Reference area for the calculation of the lift and drag coefficients C_L and C_D was the theoretical wing area $S_{ref}=4\sqrt{3}\,D^2$ (Fig.1). Reference length for the pitching moment coefficient C_m was the mean aerodynamic chord (m.a.c.) equal to $4\sqrt{3}\,D/3$. According to specification [14], moments were reduced to a point in the plane of symmetry of the model, at the longitudinal position of 50% of the m.a.c, though results [15][20] were initially published with the moments reduced to a point at 25% m.a.c. Drag coefficient is presented as forebody drag C_{Df} obtained by subtracting, from the total measured drag C_D, the base drag C_{Db} computed from the measured base pressure on the model. Likewise, the lift coefficient is presented as forebody lift coefficient C_{Lf}.

The correlation of the test results and the magnitude of interfacility differences are illustrated in Fig. 8 to Fig. 16 which show the graphs of the forebody drag force, lift force and pitching moment coefficients vs. angle of attack from six available sources at Mach numbers 0.77, 1.0 and 1.17.

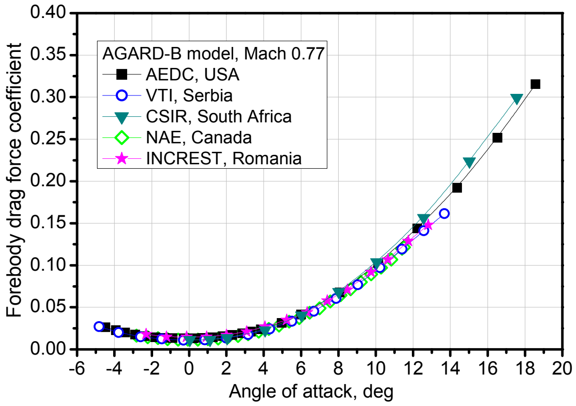

Figure 8. Correlation of the forebody drag force coefficients from five facilities, Mach 0.77

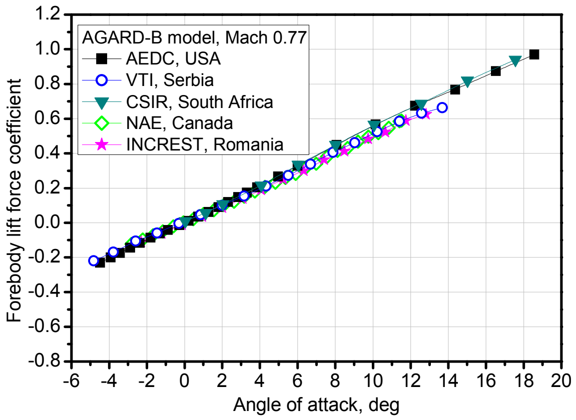

Figure 9. Correlation of the forebody lift force coefficients from five facilities, Mach 0.77

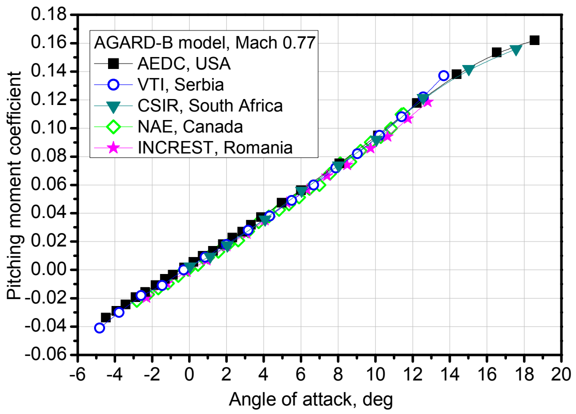

Figure 10. Correlation of the pitching moment coefficients from five facilities, Mach 0.77

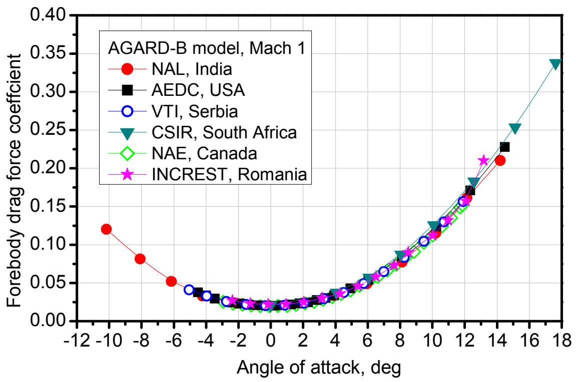

Figure 11. Correlation of the forebody drag force coefficients from six facilities, Mach 1

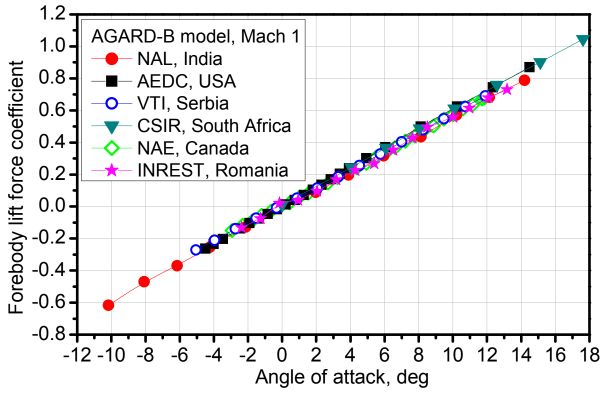

Figure 12. Correlation of the forebody lift force coefficients from six facilities, Mach 1

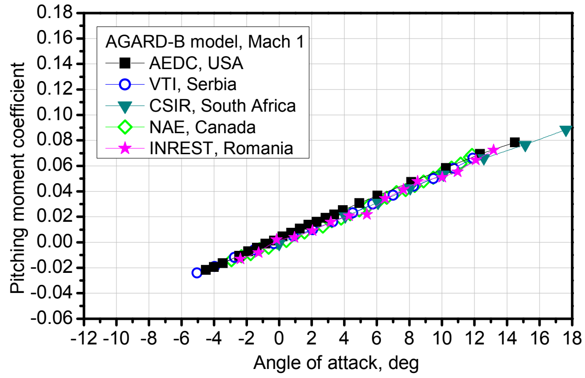

Figure 13. Correlation of the pitching moment coefficients from five facilities, Mach 1

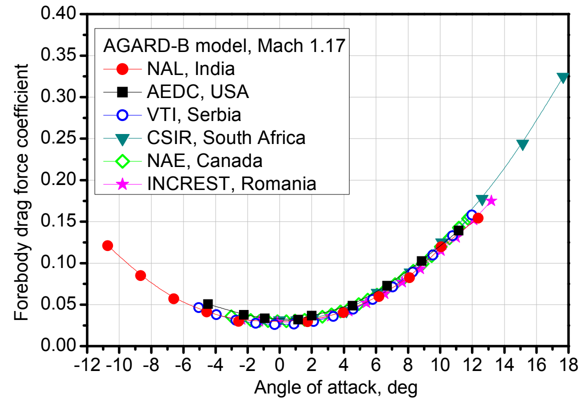

Figure 14. Correlation of the forebody drag force coefficients from six facilities, Mach 1.17

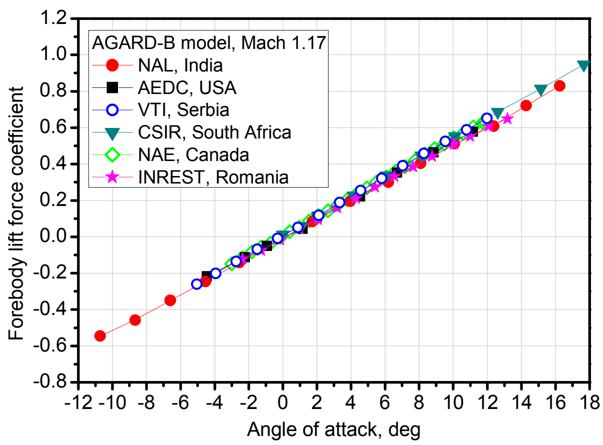

Figure 15. Correlation of the forebody lift force coefficients from six facilities, Mach 1.17

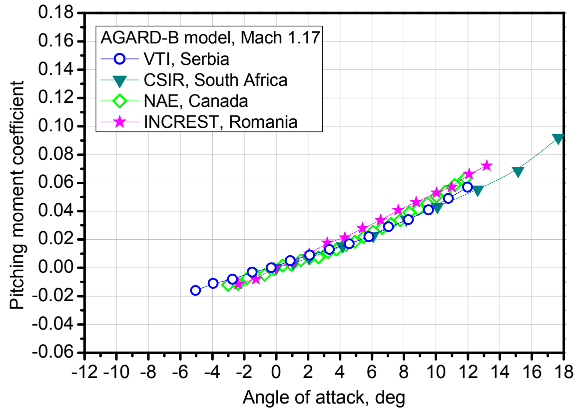

Figure 16. Correlation of the pitching moment coefficients from four facilities, Mach 1.17

NAL tests data for Mach 0.77 and for the pitching moment coefficients at other Mach numbers were not available. Also, data for Mach 0.77 and Mach 1.17 from NAL, AEDC and CSIR, where available, were acquired at a slightly higher Mach numbers than other data (at Mach 0.8 and 1.2 vs. 0.77 and 1.17, respectively).

The values of the minimum forebody drag force coefficient vs. Mach number, as available from the six sources, are given in the graph in Fig. 17.

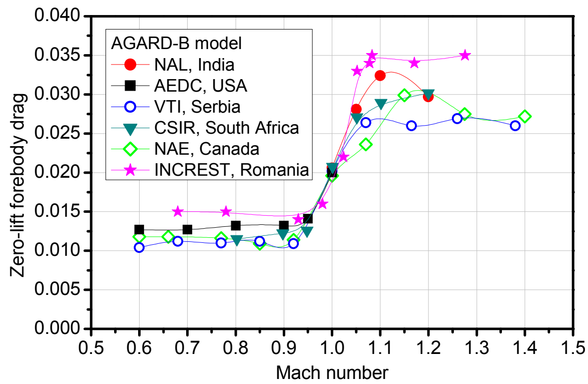

Figure 17. Interfacility correlation of zero-lift drag force coefficient vs. Mach number

5.2 Averaged data

Figure 18 to Figure 26 and Table 2 to Table 10 show the values of aerodynamic coefficients of AGARD-B at Mach numbers 0.77, 1.0 and 1.17 averaged from the six data sources.

As the data from different sources were not acquired at identical angles of attack, all data were interpolated at 0.5° intervals using cubic splines in the angle-of-attack range from –2° to +12° which was common to all datasets, and averaging was performed on interpolated data.

Averaged zero-lift forebody drag coefficient is presented vs. Mach number in the graph in Figure 27 and Table 11.

Scatter of the data is indicated in the graphs by error bars corresponding to ±1 standard deviation σ.

Averaged aerodynamic coefficients in the tables are shown at 1° intervals. Besides, for each aerodynamic coefficient, an overall standard deviation was determined for all interpolated datapoints at each Mach number.

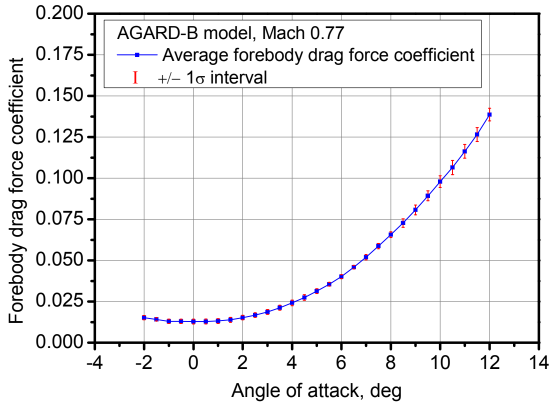

Figure 18. Average forebody drag force coefficients given with ±1σ error bands, Mach 0.77

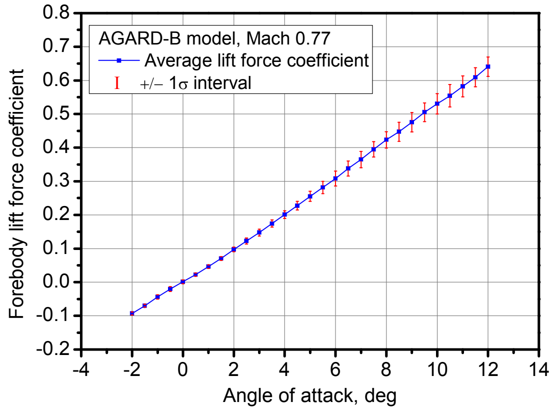

Figure 19. Average forebody lift force coefficients given with ±1σ error bands, Mach 0.77

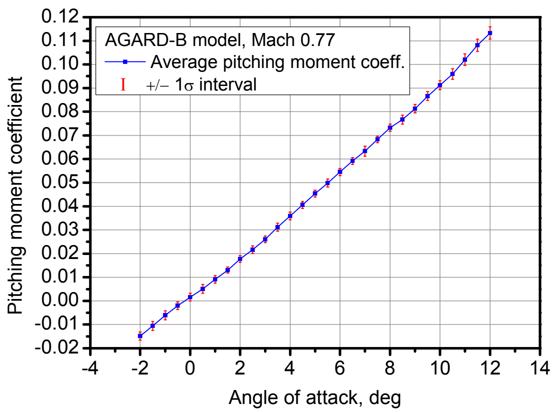

Figure 20. Average pitching moment coefficients given with ±1σ error bands, Mach 0.77

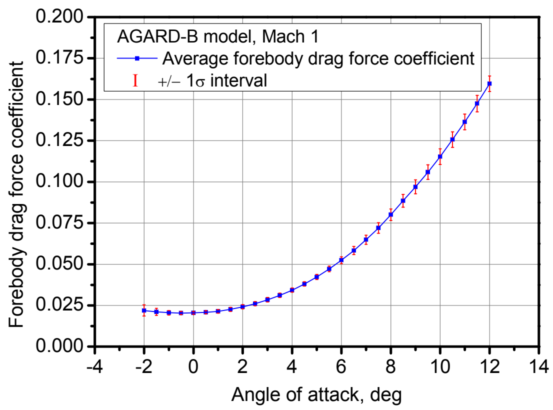

Figure 21. Average forebody drag force coefficients given with ±1σ error bands, Mach 1

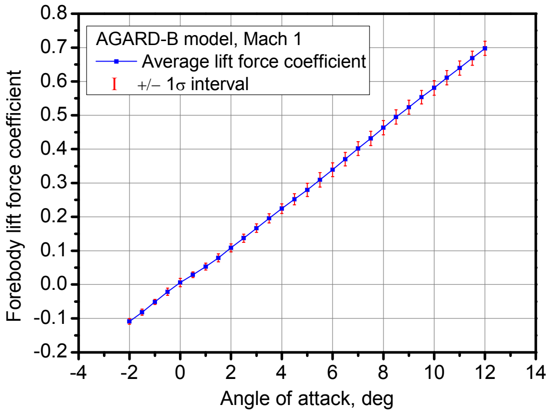

Figure 22. Average forebody lift force coefficients given with ±1σ error bands, Mach 1

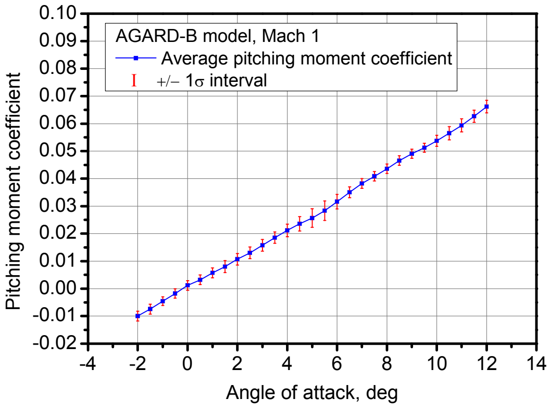

Figure 23. Average pitching moment coefficients given with ±1σ error bands, Mach 1

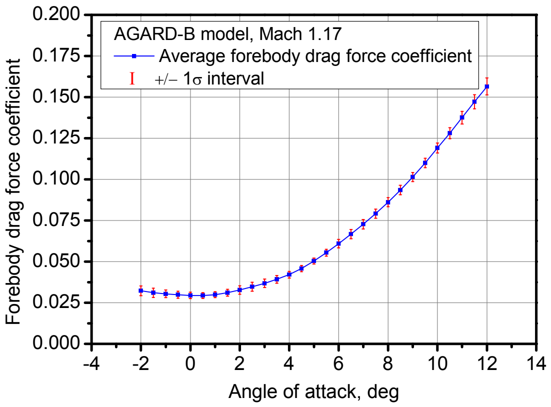

Figure 24. Average forebody drag force coefficients given with ±1σ error bands, Mach 1.17

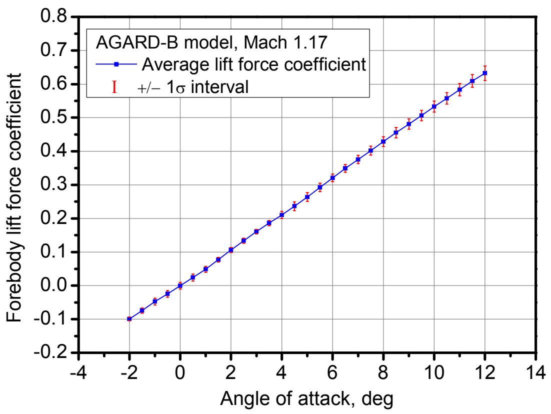

Figure 25. Average forebody lift force coefficients given with ±1σ error bands, Mach 1.17

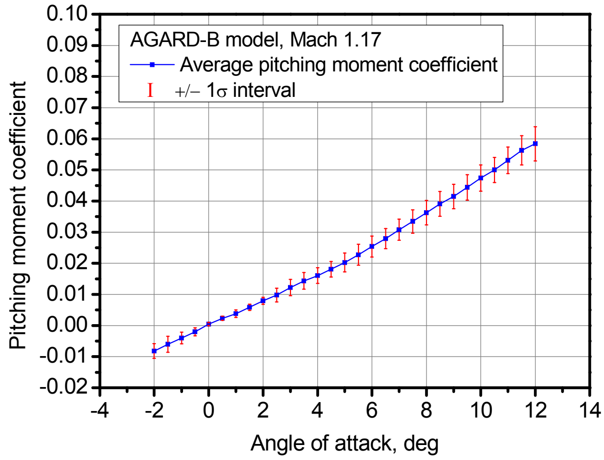

Figure 26. Average pitching moment coefficients given with ±1σ error bands, Mach 1.17

Table 2. Average forebody drag force coefficient calculated on the basis of five datasets, Mach 0.77

AGARD-B model, Mach 0.77		
Angle of Attack, deg	Average Forebody Drag Force Coeff.	Standard Deviation
-2	0.0152	0.0013
-1	0.0129	0.0013
0	0.0127	0.0014
1	0.0131	0.0015
2	0.0152	0.0014
3	0.0186	0.0015
4	0.0241	0.0017
5	0.0313	0.0014
6	0.0401	0.0012
7	0.0519	0.0017
8	0.0656	0.0018
9	0.0807	0.0029
10	0.0978	0.0035
11	0.1163	0.0042
12	0.1386	0.0039
Overall standard deviation		0.0023

Table 3. Average lift force coefficient calculated on the basis of five datasets, Mach 0.77

AGARD-B model, Mach 0.77		
Angle of Attack, deg	Average Lift Force Coeff.	Standard Deviation
-2	-0.093	0.004
-1	-0.044	0.006
0	0.001	0.006
1	0.046	0.005
2	0.097	0.007
3	0.148	0.010
4	0.201	0.011
5	0.255	0.015
6	0.308	0.022
7	0.365	0.024
8	0.423	0.024
9	0.476	0.029
10	0.530	0.030
11	0.582	0.031
12	0.641	0.029
Overall standard deviation		0.017

Table 4. Average pitching moment coefficient calculated on the basis of five datasets, Mach 0.77

AGARD-B model, Mach 0.77		
Angle of Attack, deg	Average Pitching Moment Coeff.	Standard Deviation
-2	-0.0148	0.0017
-1	-0.0060	0.0019
0	0.0016	0.0016
1	0.0091	0.0016
2	0.0177	0.0014
3	0.0260	0.0014
4	0.0359	0.0016
5	0.0454	0.0014
6	0.0545	0.0016
7	0.0633	0.0021
8	0.0733	0.0015
9	0.0813	0.0018
10	0.0912	0.0019
11	0.1020	0.0025
12	0.1133	0.0026
Overall standard deviation		0.0018

Table 5. Average forebody drag force coefficient calculated on the basis of six datasets , Mach 1

AGARD-B model, Mach 1		
Angle of Attack, deg	Average Forebody Drag Force Coeff.	Standard Deviation
-2	0.0220	0.0033
-1	0.0206	0.0013
0	0.0205	0.0007
1	0.0215	0.0011
2	0.0242	0.0012
3	0.0285	0.0014
4	0.0343	0.0013
5	0.0423	0.0015
6	0.0524	0.0021
7	0.0649	0.0028
8	0.0801	0.0035
9	0.0970	0.0042
10	0.1152	0.0048
11	0.1364	0.0047
12	0.1595	0.0047
Overall standard deviation		0.0029

Table 6. Average lift force coefficient calculated on the basis of six datasets, Mach 1

AGARD-B model, Mach 1		
Angle of Attack, deg	Average Lift Force Coeff.	Standard Deviation
-2	-0.109	0.008
-1	-0.051	0.008
0	0.006	0.012
1	0.053	0.010
2	0.108	0.012
3	0.167	0.013
4	0.224	0.014
5	0.280	0.020
6	0.339	0.020
7	0.402	0.020
8	0.463	0.021
9	0.524	0.021
10	0.581	0.021
11	0.640	0.021
12	0.698	0.021
Overall standard deviation		0.020

Table 7. Average pitching moment coefficient calculated on the basis of six datasets, Mach 1

AGARD-B model, Mach 1		
Angle of Attack, deg	Average Pitching Moment Coeff.	Standard Deviation
-2	-0.0010	0.0018
-1	-0.0046	0.0016
0	0.0012	0.0017
1	0.0057	0.0018
2	0.0107	0.0021
3	0.0157	0.0021
4	0.0211	0.0023
5	0.0257	0.0034
6	0.0316	0.0026
7	0.0382	0.0018
8	0.0436	0.0017
9	0.0491	0.0016
10	0.0537	0.0020
11	0.0594	0.0024
12	0.0667	0.0023
Overall standard deviation		0.0021

Table 8. Average forebody drag force coefficient calculated on the basis of six datasets, Mach 1.17

AGARD-B model, Mach 1.17		
Angle of Attack, deg	Average Forebody Drag Force Coeff.	Standard Deviation
-2	0.0322	0.0029
-1	0.0304	0.0023
0	0.0297	0.0020
1	0.0298	0.0017
2	0.0328	0.0026
3	0.0368	0.0025
4	0.0420	0.0021
5	0.0503	0.0019
6	0.0609	0.0026
7	0.0727	0.0029
8	0.0861	0.0028
9	0.1014	0.0028
10	0.1190	0.0030
11	0.1375	0.0039
12	0.1564	0.0052
Overall standard deviation		0.0028

Table 9. Average lift force coefficient calculated on the basis of six datasets, Mach 1.17

AGARD-B model, Mach 1.17		
Angle of Attack, deg	Average Lift Force Coeff.	Standard Deviation
-2	-0.099	0.005
-1	-0.047	0.010
0	-0.000	0.010
1	0.049	0.009
2	0.106	0.008
3	0.161	0.007
4	0.211	0.011
5	0.264	0.013
6	0.321	0.012
7	0.376	0.012
8	0.429	0.015
9	0.481	0.015
10	0.533	0.016
11	0.584	0.019
12	0.632	0.021
Overall standard deviation		0.013

Table 10. Average pitching moment coefficient calculated on the basis of four datasets, Mach 1.17

AGARD-B model, Mach 1.17		
Angle of Attack, deg	Average Pitching Moment Coeff.	Standard Deviation
-2	-0.0082	0.0024
-1	-0.0040	0.0019
0	0.0005	0.0004
1	0.0038	0.0012
2	0.0079	0.0011
3	0.0122	0.0026
4	0.0161	0.0025
5	0.0203	0.0030
6	0.0254	0.0034
7	0.0308	0.0034
8	0.0363	0.0039
9	0.0415	0.0040
10	0.0474	0.0042
11	0.0531	0.0043
12	0.0584	0.0055
Overall standard deviation		0.0031

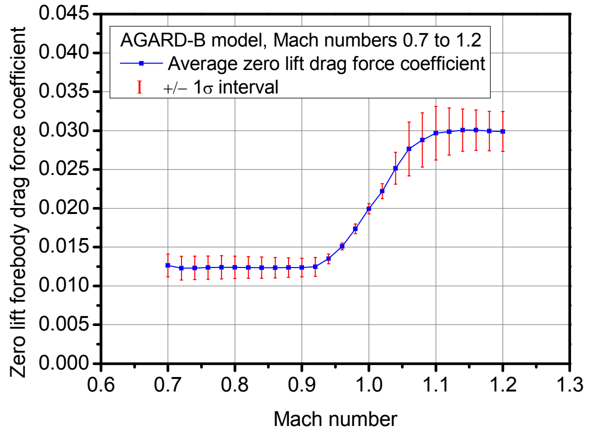

Figure 27. Average zero-lift forebody drag coefficients given with ±1σ error bands, Mach numbers 0.7 to 1.2

Table 11. Average zero-lift forebody drag force coefficient calculated on the basis of six datasets

AGARD-B model, Mach 0.7 to 1.2		
Mach number	Zero-lift Forebody Drag Force Coeff.	Standard Deviation
0.70	0.0127	0.0015
0.75	0.0123	0.0015
0.80	0.0124	0.0014
0.85	0.0123	0.0014
0.90	0.0124	0.0012
0.95	0.0140	0.0007
1.00	0.0204	0.0007
1.05	0.0269	0.0033
1.10	0.0297	0.0035
1.15	0.0302	0.0026
1.20	0.0298	0.0024
Overall standard deviation		0.0022

It can be observed from the presented graphs and tables that, somewhat contrary to expectations, the correlation of the zero-lift drag coefficient from the six wind tunnels seems to be better at Mach 1 than at other Mach numbers below and above Mach 1. In particular, there seems to be a considerable scatter of the drag-force and pitching moment coefficients from various datasets at Mach numbers between 1.05 and 1.2.

It was also noted that the agreement between the results from the NAE/NRC and VTI 1.5 m (5 ft) wind tunnels was slightly better than their agreement with other data, while the correlation between the data from the almost identical NAL and INCREST/INCAS 1.2 m wind tunnels was slightly better than their agreement with other data, in spite of different sizes of the models tested in NAL and INCREST. This suggests an unexplained small influence of the wind tunnel characteristics on test results. Also, lift curve slopes from CSIR and AEDC were slightly steeper than those from other sources.

Standard deviations of the aerodynamic coefficients averaged for four different models in six different wind tunnels are about an order of magnitude larger than the stringent between-the-test-campaigns repeatability requirements [4,26] desired with a model in one wind tunnel.

6. CONCLUSION

Results of transonic wind tunnel tests of AGARD-B models at three Mach numbers in four trisonic wind tunnels and two transonic wind tunnels, all in the 1.2 m to 1.5 m test-section-size range, were compared and an analysis was made of the dispersion of results. Tests were performed with four AGARD-B models, and one of the models was tested in three wind tunnels.

The analysis indicated that a scatter of transonic-tests results can be expected to be about an order of magnitude larger than the desired between-tests in-facility repeatability, which may be of interest when comparing other standard-model data from different laboratories.

A set of data for the aerodynamic coefficients of the AGARD-B model, averaged from the six experimental-data sets is presented, along with estimates of the expected scatter of results. These data may facilitate evaluations of future transonic test results of the AGARD-B standard model.

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КОНВЕРГЕНЦИЈА РЕЗУЛТАТА ТРАНСОНИЧНИХ АЕРОТУНЕЛСКИХ ИСПИТИВАЊА СТАНДАРДНОГ МОДЕЛА АГАРД-Б

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АГАРД-Б је најчешће коришћена конфигурација стандардног аеротунелског модела. Поред своје основне намене, корелације резултата испитивања у суперсоничним аеротунелима, користи се у широком опсегу Махових бројева, и од недавно, за процену утицаја зидова, валидацију кодова нумеричке динамике флуида, валидацију нових технологија за производњу модела. Истраживачи и аеротунелски тест инжењери су природно заинтересовани да располажу „правим“ аеродинамичким карактеристикама овог модела ради верификације сопственог рада. Очигледно да овакви подаци не постоје, али расипање података из различитих извора и вероватне средње вредности аеродинамичких коефицијената могу да се процене. У складу са тим упоредни резултати трансоничних испитивања модела АГАРД-Б на Маховим бројевима 0.77, 1.0 и 1.17 из шест аеротунела су анализирани и одређене су средње вредности и расипање аеродинамичких коефицијената.