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USABILITY OF COMPARATIVE EXPERIMENTAL – NUMERICAL SUPERSONIC TEST CASES WITH THE HB REFERENCE MODEL

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Abstract

The HB reference wind tunnel models are used both to validate wind tunnels and as test cases for CFD tools. Wind tunnel tests of these models were performed in the Military Technical Institute (VTI) Belgrade. In analyzing the obtained data, issues appeared suggesting caution in the use of these models. A need is expressed for a more comprehensive database of test results.

1 Introduction

Reference wind tunnel models, also known as standard models, calibration models and test check-standards, are widely used tools of experimental aerodynamics. Among them is the *hypervelocity ballistic correlation model*, its two configurations known by their abbreviated names HB-1 and HB-2. It is of interest to researchers in the field of high-speed aero-dynamics, both as a means to validate the complete measurement and data reduction chain in an experimental facility and as a test case for examining the capabilities of different CFD (Computational Fluid Dynamics) aerodynamic analysis tools.

With increased requests for high-speed wind tunnel tests in the 1.5 m T-38 trisonic wind tunnel of VTI (Military Technical Institute Belgrade), it was felt that a verification of the quality of measurements in the high Mach number range through the use of a reference model was desirable. The high-Mach part of the operating envelope, ranging from Mach 2 to Mach 4, has hitherto been used without being verified by a reference model because the large supersonic starting loads experienced in this wind tunnel [1] prevented the use of available reference models above Mach 2. A recent analysis has shown, however, that, provided a suitable balance is used, the relatively short HB-1 and HB-2 models could be tested in the complete supersonic Mach number range of the T-38 wind tunnel without problems related to starting loads. Therefore, as a part of a VTI's programme for improvement of the T-38 testing capability in the upper supersonic speed range [2][3], comprising a number of upgrades and a recalibration of the supersonic test section, it was decided to build and test the HB models in this wind tunnel.

Two HB models, with forebody diameters of 75 mm and 100 mm, were produced in the VTI's model workshop for this purpose.

A number of wind tunnel tests of the two configurations (HB-1 and HB-2) of the smaller produced model were performed after the completion of the modifications to the wind tunnel and the recalibration of the supersonic test section. During the preparation and execution of the tests, as well as in the post-test correlation with reference results from other laboratories, some issues were observed questioning the usability of the HB model defined as it is, and the usability of available reference data. These observations, with some conclusions and suggestions, are presented here.

2 The HB Reference Model

The initiative for choosing a suitable configuration of a high velocity reference wind tunnel model was started at the joint meeting of AGARD (Advisory Group for Aeronautical Research and Development) and STA (Supersonic Tunnel Association) in the year 1959. This eventually resulted in adoption, into the AGARD family of reference models, of two model configurations, designated as HB-1 and HB-2 [4], Fig.1.

Both configurations of the model are axisymmetric cone-cylinders with 25° nose cone half-angle. The HB-2 configuration has a 10° tail flare, added to make the model less sensitive to viscous effects. The junctures of the nose and flare with the cylinder are smooth radius fairings. The unit length for the definition of model geometry is the diameter *D* of the cylindrical part of model forebody. Model length is defined as 4.9*D* for both configurations. Moments reduction centre is at 1.95*D* from the nose.

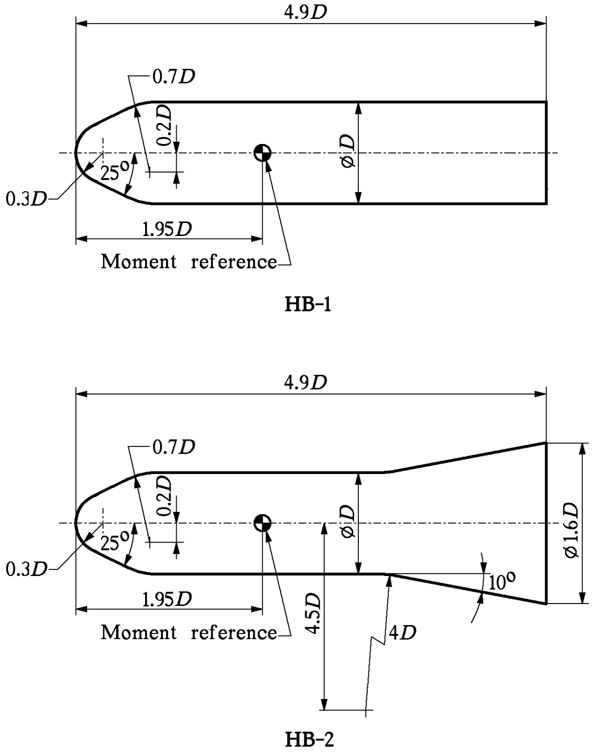

Fig. 1. Theoretical geometry of the HB standard wind tunnel models, [4][5]

A support sting (Fig. 2) for the HB models was also specified, with a constant diameter of no more than 0.3*D* and a length of at least 3*D* with a downstream fairing of 20° half-angle. The specified maximum diameter and minimum length of the sting were estimated as necessary to ensure negligible interference on the base pressure for turbulent flow.

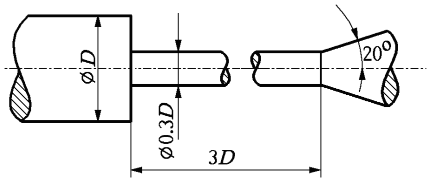

Fig. 2. Standard sting geometry for the HB models, [4][5]

3 The wind tunnel tests in VTI

Military Technical Institute (VTI) in Belgrade uses the AGARD-B model for periodical checkout and assessment [6][7] of overall state and quality of its T-38 trisonic wind tunnel, a blow-down type pressurized intermittent wind tunnel with Mach number range up to 4 and high Reynolds numbers capability. However, because of the high supersonic starting loads present in the T-38 wind tunnel, this model configuration, having fairly large lifting surfaces, could not be tested above Mach 2, which lead to a decision to perform tests of two HB models of different sizes (75 mm and 100 mm diameter) in the Mach number range 1.5 to 4. The lower part of the test Mach number range overlapped with the test range of the AGARD-B model, in which the T-38 wind tunnel installation was successfully verified [6][7] in correlation with other wind tunnel facilities, so that one variable (unknown reliability of the wind tunnel) could be removed from the comparative analysis of the results.

Force tests were conducted on the two configurations (HB-1 and HB-2) of the smaller (75 mm) model at Mach numbers 1.5, 1.75, 2.0, 2.25, 3.0, 3.5 and 4.0, at dynamic pressures of 150 to 160 kPa (depending on Mach number), except for tests at Mach 3.5 and 4 which were made at 130 kPa and 110 kPa, respectively, because sufficient wind tunnel run times could not be achieved at higher pressures. Reynolds number in the test (based on forebody diameter) ranged from 4.2×10^6 to 5.6×10^6, depending on Mach number. Relative diameter of the sting was 0.64*D*. A small number of preliminary wind tunnel runs were also made with the larger (100 mm dia.) model. Flow field around the model was visualized using the three-colour schlieren method.

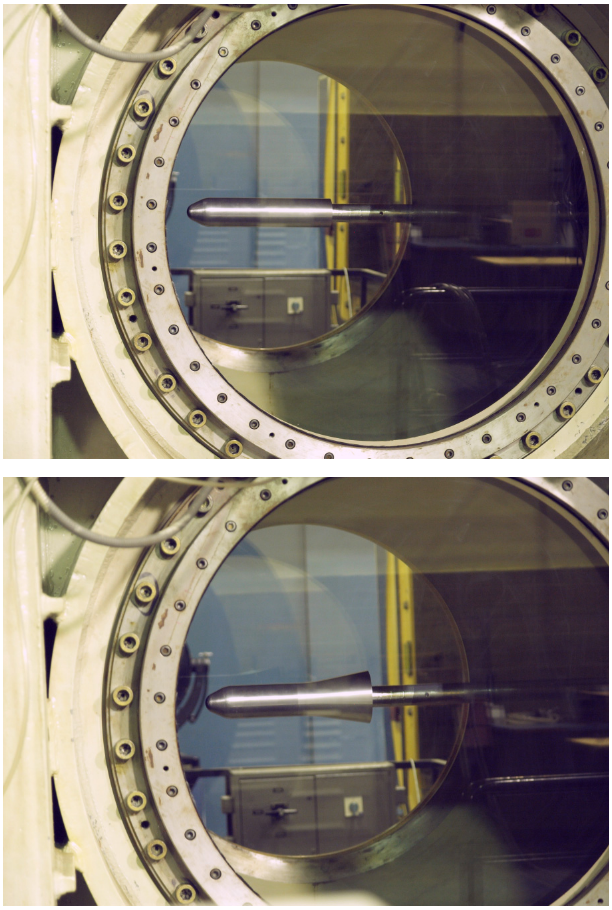

Fig. 3. HB-1 and HB-2 75 mm dia. models in the test section of the T-38 wind tunnel

Some representative supersonic test conditions were also numerically simulated in Fluent CFD software so that the database was extended with appropriate numerically calculated data.

4 Issues in using the HB models

In the analysis of the test results and the numerically obtained data for the HB-1 and HB-2 models, certain issues appear that limit the possibility of performing the wind tunnel tests of this models with a ‘standard’ support sting configuration and urge some caution in the use of the reference test results, both for verification of a wind tunnel facility, and for verification of numerical CFD tools.

4.1 Available reference test data

Inter-facility correlation of results is an important component of testing of reference wind tunnel models. A database of test results from various laboratories and a wide range of testing conditions are essential in this matter. However, upon preparing to perform comparison of VTI test results with those from other wind tunnels, it became evident that available test data for the HB models in the supersonic speed range are actually very few and quite old, mostly from the years 1963-1968. The only comprehensive, freely available wind tunnel test data for the HB models, covering a wide range of supersonic and hypersonic Mach numbers, seem to be those from tests performed in 1963/64 in the wind tunnels of the Von Karman facility at AEDC (Arnold Engineering Development Complex), presented in the reports [4][8], (report [4] also giving a small amount of otherwise unpublished data from other institutions). A number of accessible experimental reports and the authors of practically all CFD simulations of the HB models cite only this AEDC data as a reference.

There is also a limited amount of free-flight data at Mach 2 available from the NASA Ames ballistic range tests [9]. Test results from ONERA Chalais and Vernon facilities, e.g. [10] are not widely used and, besides, cover somewhat fewer Mach numbers and angles of attack. Reports from some other tests performed in the supersonic speed range, e.g. [11], seem to be not so easily accessible and are rarely cited.

From some newer publications it can be seen that the HB configurations have recently been used mostly for pressure distribution and heat-transfer tests, [12]-[15].

For the experiments performed so far in the VTI’s Experimental Aerodynamics Laboratory, data from force-measurements tests [4][8][9] [10] were used as references for comparison, in spite of much lower Reynolds numbers, ranging from 0.01×10^6 to 2.5×10^6 vs. the values of 4.2×10^6 to 5.6×10^6 in VTI tests.

4.2 Debatable reference data from AEDC

During the comparison of obtained experimental data with the reference values from other facilities it became evident that, while the results for the normal-force coefficient, the pitching-moment coefficient and the forebody axial-force coefficient for the HB-2 model from all sources correlated quite well, there was a substantial discrepancy between the total zero-lift axial-force coefficient C_{A0} data from AEDC tests [4][8] and all other available data, including the VTI data (Fig.4). On the other hand, the C_{A0} data from other sources correlated quite well. The situation was similar for the HB-1 model (Fig.5). This discrepancy was noted by other authors as well, e.g. [9].

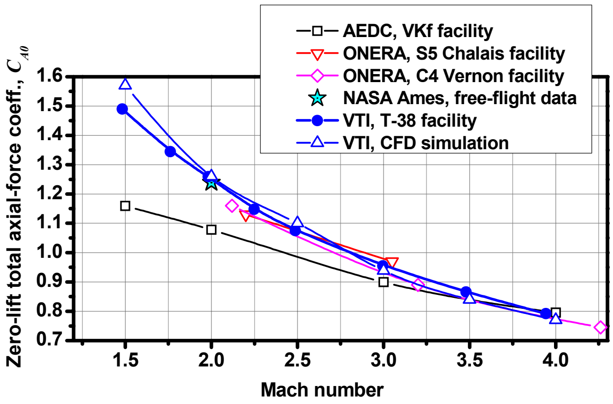

Fig. 4. Comparison of zero-lift total axial-force coefficient vs. Mach number from different sources, HB-2 model

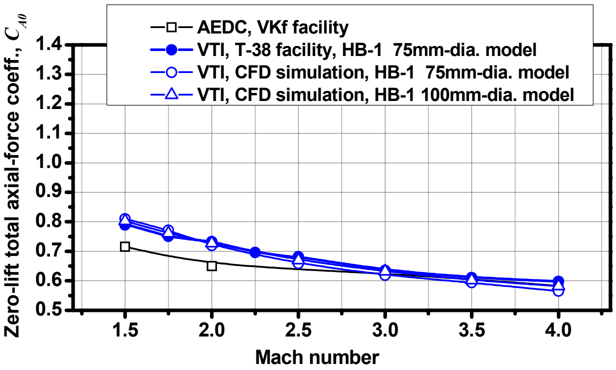

Fig. 5. Comparison of zero-lift total axial-force coefficient vs. Mach number from different sources, HB-1 model

A satisfactory explanation for the discrepancy between the AEDC test values and other values for the total C_{A0} was not found, but the problem obviously originated in the determination of the base axial-force coefficient. The AEDC data [4][8] are presented in the forms of the forebody axial-force coefficient and the base axial-force coefficient which must be summed to obtain total C_{A0}. While the forebody axial-force coefficient from AEDC correlates well with other data, there is a large difference in the base axial-force coefficient. Source [9] suggests a possibility of unexpectedly large sting interference. On the other hand, a possibility comes to mind that the base area was calculated differently in AEDC than in other facilities (this calculation was not documented in [4][8]).

4.3 CFD test cases

A number of CFD simulations of the flow around HB-1 and HB-2 models at zero angle of attack and Mach numbers 1.5 to 4.0 were performed in VTI, using Fluent 6.1 CFD software tool. An unstructured mesh composed of tetrahedral elements was used. The 3D coupled explicit solver with Spalart-Allmaras viscous model was applied for numerical calculation of the flow. Simulated flow conditions were identical to those in the wind tunnel test. The CFD simulations showed good agreement with the VTI T-38 experimental data (Fig.4 and Fig.5) and with the reference experimental data from ONERA [10] and NASA Ames [9], but not with the AEDC reference data [4][8]. This corroborates the observations that AEDC data are apart from all other data sets with regard to total axial-force coefficient.

4.4 Other data sources

Similar to VTI results, both the experimental [9][10] and the CFD results (e.g. [16]) for axial-force coefficient results from some other researchers tend to give significantly higher values for total axial-force coefficient C_A than reference [4]. These values are in much better accordance with T-38 test data (Fig.4). The correlation of the normal-force coefficient C_N and the pitching-moment coefficient C_m from all sources is much better, though there are some small deviations in C_m between the sets of results.

4.5 Repeatability of measurement

Both the experimental and the CFD data for C_A from various facilities show noticeable scatter (e.g. in Fig.4), and do not correlate nearly as well as the results for the same variable from the tests of e.g. the AGARD-B reference model. Such scatter is inconvenient to a researcher intending to confirm his experimental or numerical work as precisely as possible. The scatter of experimental data is partly due to the nature of the test facilities in which most of the experiments were performed, i.e. in the short-run-duration wind tunnels [12]-[15],[17] where special measurement techniques had to be applied and the accuracy of measurement was necessarily lowered.

4.6 Model support sting limitations

During the preparation of the wind tunnel test in VTI, it became evident that the ‘standard’ sting for the HB models, as defined in Fig.2, was too slender for the expected aerodynamic loads, in particular regarding the HB-2 model.

From reference test results it can be seen that, at angles of attack of about 15° (the maximum angle of attack in tests [8]), the centre of pressure of the HB-2 model would be about $2D$ forward of the model base. Therefore, the $3D$-long support sting could be analyzed as a cantilevered beam having a length of $5D$, with the normal force F_N acting at the free end of the beam. Normal-force can be computed from the dynamic pressure q, the reference area $S_{ref} = \pi D^2/4$ and the normal-force coefficient C_N using the well-known elementary relation:

$$F_N = qS_{ref}C_N \qquad (1)$$

By expressing all model and sting geometrical data in terms of model forebody diameter D, and by applying the relations of the elementary theory of elasticity, it can be shown that the maximum normal stress σ in the ‘standard’ sting of a HB-2 model can be approximated by:

$$\sigma \approx 1481\, q\, C_N \qquad (2)$$

At a given normal-force coefficient C_N (or at a given angle of attack, as the normal-force curve slope $C_{N\alpha}$ of the HB-2 model does not change much with Mach number) maximum stress in the ‘standard’ sting would be proportional to the dynamic pressure q at which the wind tunnel test is performed. The stress would not depend on model size.

On the other hand, maximum permissible stress in a sting is limited by the strength of the material, which effectively limits the maximum dynamic pressure at which a HB-2 model can be tested with a ‘standard’ sting. Assuming a minimum safety factor $\nu=2$ relative to yield strength $\sigma_{0.2}$, this is illustrated in Fig.6 for two often-used high-quality steels. The graphs show that, if the safety factor is not to be compromised at angles of attack up to 15°, the use of the ‘standard’ sting is limited to dynamic pressures not higher than approximately 0.3 MPa (3 bar). This value of dynamic pressure is achievable in the T-38 wind tunnel of VTI and in other wind tunnel facilities; therefore, stress in the ‘standard’ sting can be a limiting factor in testing of HB models.

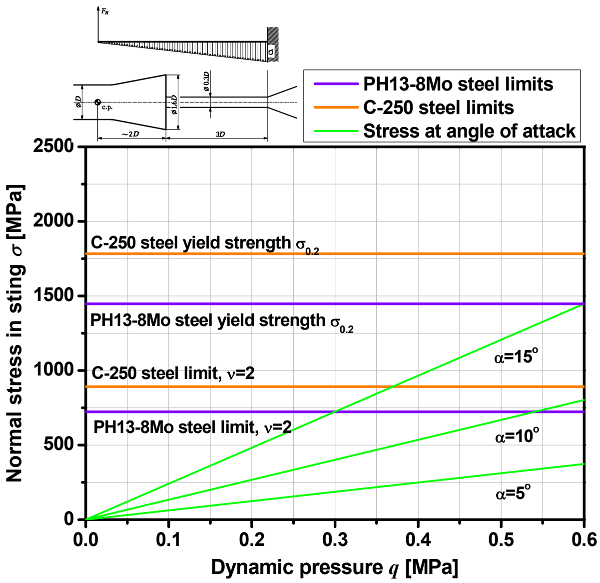

Fig. 6. Maximum stress in the standard sting of a HB-2 model at Mach 2, at various dynamic pressures and angles of attack vs. strength limits of two high-strength steels used for model support stings

A similar analysis can be performed for the supersonic starting loads. In VTI’s experience, supersonic start transient force loads F_{NT} can be estimated by the modified normal shock theory [18] as:

$$F_{NT} = p_{o\,min} S_p C_S \qquad (3)$$

which is analogous to (1) except that the minimum operating pressure p_{omin} of the wind tunnel is used instead of the dynamic pressure q, and the starting-load coefficient C_S is used instead of the normal-force coefficient C_N. Instead of the reference surface S_{ref}, a plan projection $S_p \approx 5.197D^2$ of the model contour is used. C_S is a function of model shape and Mach number. In a relation analogous to (2) the dependence of the stress in a 'standard' sting to these variables then takes the form:

$$\sigma \approx 9800\, p_{omin}\, C_S \qquad (4)$$

The limits in the use of a support sting of 'standard' dimensions at supersonic start are illustrated in Fig.7 for a range of wind tunnel starting pressures and Mach numbers. Additionally, as an example of actual wind tunnel conditions, the graph shows the stresses that would occur at minimum starting pressures of the T-38 wind tunnel in which VTI tests of the HB models were performed.

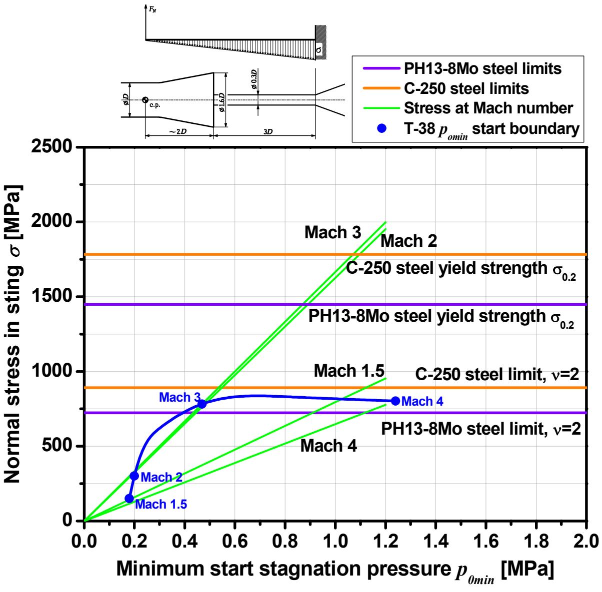

Fig.7 Maximum stress due to transient normal force in the standard sting of a HB-2 model at various wind tunnel starting pressures and Mach numbers vs. strength limits of two high-strength steels used for model support stings

It can be observed that, at Mach 3 and above, stresses in a standard sting in the T-38 (and, most likely, in other similar wind tunnel facilities) would exceed reasonable safety limits for a sting produced from the PH13-8Mo steel and come very close to the safety limit of the C-250 steel. Besides, the theory [18] predicts only the transient force loads and ignores the transient pitching/yawing moments. Using the method [1] that is applied in VTI to predict supersonic starting loads, and which agrees fairly well with VTI's measurements on the HB-2 model, it can be estimated that the transient moment loads can increase, by additional 25% (approximately), the stresses caused by transient normal forces as predicted using the equation (4). More realistic transient stresses in the sting could, therefore, be estimated as:

$$\sigma \approx 12250\, p_{o\,min}\, C_S \qquad (5)$$

which, regarding Fig.7, would put most of the tests of a HB-2 model on a standard sting above (approximately) Mach 2.5 in the dangerous zone.

It is obvious, therefore, that a 'standard' sting for the HB models can not be used in the experimental facilities similar to the T-38 wind tunnel of VTI.

An additional cause of concern is that the supersonic transient loads are pure dynamic loads so the fatigue strength limit σ_D of the sting material should not be ignored.

It can be concluded that it can be very risky to use the 'standard' sting in the tests of the HB models in wind tunnels with high-dynamic pressures because of the high stresses in the model support sting, primarily during the wind tunnel starting loads. If, however, relative sting diameter were increased from 0.3D to 0.5D, stresses in the sting would be reduced proportional to the ratio of the section moduli of the two stings, i.e. proportional to the third power of the sting diameters ratio or $(0.5/0.3)^3 = 4.63$ times. This modification of the standard geometry would eliminate or greatly reduce the problems related to the stresses in the support sting.

The existence of the sting-related problems in testing of the HB-2 standard models can be confirmed from e.g. [13][14][17] where non-standard stings of various relative diameters and lengths were used, without any consensus about a particular alternative ‘standard’. Even some of the *de-facto* reference tests [4][8] were performed with non-standard sting configurations.

On the other side, as the sting diameter can have a noticeable influence on the flow around model base, the deviation from the ‘standard’ setup should be had in mind when analyzing the results. Especially affected would be the results for the total axial-force coefficient.

4.7 Availability of a suitable force balance

In wind tunnels exhibiting high supersonic starting loads, the availability of a suitable force balance for the high-drag HB-2 model may be a problem if good accuracy in the measurement of the axial-force is desired. The ratio of the axial-force load to normal-force load is relatively large for the HB-2 model and a high-drag balance of a special design may be needed for a test of this model.

Beside the large ratio of the axial-force component to other load components, a balance for the HB models must have a sufficient load range to withstand not only the steady aerodynamic loads at the test Mach number, but also the supersonic starting loads which are characterized by large oscillatory forces and moments on the model. Some designs of wind tunnel balances for similar configurations of supersonic models (e.g. for lifting-body and reentry-body models) are quite complex [19].

VTI resorted to the use of a simpler, specially-designed balance [20] (Fig.8) with semi-conductor strain gauges for the tests of the HB-2 model at Mach numbers above 2.5, but at the cost of slightly reduced accuracy in the measurement of the axial-force.

4.8 Positive VTI’s experience with HB models

VTI’s overall experience with the use of HB models is positive, in spite of the issues discussed in this paper. The two models, with the 75 mm (Fig.8) and 100 mm (Fig.9) forebody diameters, being simple bodies of revolution, were easy to produce. The models are intended for measurements of forces and moments and were designed so that each of them could be tested on several force balances, using suitable adaptors common to both models. Besides, the 100 mm dia. model can be tested on the VTI’s dynamic derivatives testing rig [21], though with some limitations in Mach number (imposed by the starting loads). Also, some space in the 100 mm model was provided for hypothetical future modifications to enable measurement of pressure distributions.

The models were designed so that they could be quickly assembled and disassembled. The design intent was to make the models suitable for use as quick-check standards that could be easily installed in the wind tunnel instead of some currently tested model, should a need for such checkout arise in any future wind tunnel test.

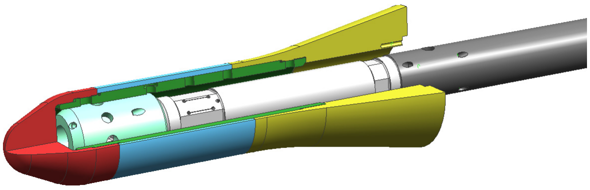

Fig. 8. CAD section view of the HB-2 75 mm dia. model mounted on VTI’s high-drag wind tunnel balance with semiconductor strain gauges

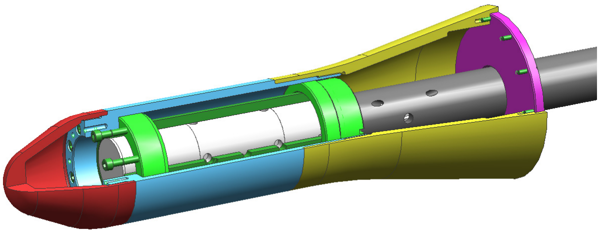

Fig. 9. CAD section view of the HB-2 100 mm dia. model mounted on a 2-inch Able wind tunnel balance

The models have provided important confirmation of the validity of measurements in the high-Mach part of the operating envelope of the T-38 wind tunnel. VTI intends to continue the use the two HB models for periodic check-ups and to build an extensive database of test results at high Reynolds numbers in the Mach number range from 1.5 to 4. Having in mind the possibility of using the models for quick-check of setups for other tests, plans are considered for extending the test envelope of the models into the transonic range. A local standardization of sting diameter to 0.5*D* is planed for future tests of these models.

5 Conclusions

The existing reference experimental results for the HB models were few, and of somewhat debatable usability. Because of the stress issues, it is almost impossible to test HB models on a 'standard' sting in high-dynamic-pressure facilities, so that a wind tunnel test of these models is likely to be performed at conditions differing in some important aspects from those in the reference tests which, too, deviated from the 'standard' setup in a nonsystematic manner. Therefore, the correlation between test results may not be as good as desired. Besides, the usefulness of a 'standard' that can not be fully applied is questionable.

In most cases, the *de-facto* authoritative reference for an experimental or CFD-simulation work with HB models, seems to be a set of wind tunnel tests which were shown to have some results different than data from other sources, which group very well. Therefore, a degree of caution is suggested in correlating one's experimental or computational results for the HB models with the reference data.

In view of the stated issues it is felt necessary to obtain a wider correlation-database of test results for the HB-1 and HB-2 models at realistic test conditions, so that the results could be used with more confidence, both in experimental and CFD work. A sting diameter of 0.5*D* is proposed for future tests.

Experimental results from VTI, a sample of which is given in the paper, are intended to be a part of this effort. VTI intends to continue tests of the HB models, as opportunity permits, and make results available to the community. These results should be of interest primarily for the experimenters in the high-Reynolds-number, high-dynamic-pressure facilities.

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