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ON THE USE OF HIGH PITCH SWEEP RATES IN TIME-LIMITED SUPERSONIC WIND TUNNEL TESTS

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Abstract: *In high Reynolds number blowdown facilities with limited run time, such as the VTI's T-38 wind tunnel in Belgrade, tests at high stagnation pressure level often can not last long enough for execution of a sweep in the desired angle-of-attack range. Recently, during supersonic wind tunnel testing of a hypervelocity standard model it was investigated how angle-of-attack sweep range could be extended by increasing the pitch sweep rate up to 12° per second and whether the high sweep rates affected the test data. The optimum pitch sweep rate was investigated and established in the early stage of the VTI's T-38 facility exploitation period and a majority of reference wind tunnel data was obtained with the pitch rate of about 2° per second. The wind tunnel balance responses in the performed Mach 2 tests at all pitch rates of 2, 3, 4, 8 and 12° per second was excellent. The total axial force, normal force and the pitching moment were practically identical at all pitch rates. Unfortunately, the base pressure data showed a very high dependency on pitch rates because of the lag in pressure piping and, consequently, the forebody axial force, calculated on the basis of base pressure measurement, showed certain discrepancies. This should be important to all who deal with 'base drag corrected' supersonic data. Some recommendations and experience gained during tests are given.*

Keywords: *wind tunnel, supersonics, pitch sweep rate, base pressure, forces and moments.*

1. INTRODUCTION

In the situation of reduced time available for wind tunnel tests and constrained energy consumption, it is imperative that all wind tunnel systems and experimental setup be optimally set to achieve the parameters best matched with customer requirements. Today, when saving energy means saving time, as well as investments and environment, optimization of both facility operation and testing is a must for the wind tunnel community. First, accurate and complete wind tunnel calibrations have to be established, maintained, and placed under process control to avoid a risk of substantial investments in obtaining inaccurate wind tunnel data. Second, the optimization of the experimental setup has to be done by selecting the proper model scale, stagnation pressures, appropriate measuring equipment and model supports, as well as optimum sweep rates. All of these elements are emphasized in supersonic wind tunnel tests. The constraints related to model size, load range of available instrumentation versus transient and steady aerodynamic loads, and available run times, are often decisive in the selection of the conditions for a high-speed wind tunnel test [1].

Considering the above-mentioned trends, there is a surprising lack of research investigating the possibilities to reduce wind tunnel run times, thus also reducing the energy consumption, by increasing model sweep rates. The tests performed at subsonic Mach numbers from 0.3 to 0.75 in the NAE Canada trisonic wind tunnel demonstrated that pitch rates of up to 15°/s did not affect the force, moment and pressure data [2]. Apart from this research, there have not been found other published works on this subject. In the VTI T-38 wind tunnel, the possibilities to reduce run times by increasing pitch sweep rates have recently been investigated during supersonic testing of a hypervelocity standard model. The primary goal was to observe the possible effect of high pitch rates on the wind tunnel measurement data. The results and conclusions are summarized in this article.

2. EXPERIMENTAL FACILITY

The designed supersonic operating envelope of the VTI T-38 wind tunnel (Fig.1) in Belgrade, Serbia is limited by the minimum pressures needed to start and maintain a supersonic flow and by the structural safety limits [1].

Mach number is limited to an interval from 0.2 to 4 by the structural safety limits, and the mechanical design of both the choke flaps and flexible nozzle.

Stagnation pressure in the test section can be maintained between 1.1 bar and 15 bar, depending on the Mach number and regulated to 0.1% of nominal value. Run times range from 6 s to 60 s, depending on the Mach number and stagnation pressure. Models are usually 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 mechanism supports both step-by-step and continuous (pitch-sweep) movement of the model during measurements.

Figure 1. Pressurized air storage tanks of the VTI T-38 wind tunnel

In high Reynolds number blowdown facilities with limited run time, such as the VTI T-38 wind tunnel [3], tests at high stagnation pressure level often cannot last long enough for execution of a sweep in the desired angle-of-attack range. The optimum pitch sweep rate was established in the early stage of the facility exploitation period and a majority of reference wind tunnel data were obtained based on the pitch rate of 2°/s.

3. TEST MODEL

Test data on the HB hypervelocity standard models have been used to establish reference data for the correlation of the VTI T-38 experimental results with those from other aerodynamic facilities [4]. The compared data comprise the normal force curve slope and zero-lift total axial-force coefficient results at Mach numbers from 1.5 to 4.

Recently, during supersonic wind tunnel testing of the 100 mm dia. HB-2 standard model it was investigated how much sweep range during a run can be extended by applying high pitch rates. In addition, the effect of high pitch rates on the wind tunnel test data was studied.

HB standard model is an axisymmetric cone-cylinder with 25° nose cone half-angle [5][6]. The HB-2 configuration has a 10° tail flare, added to make the model less sensitive to viscous effects. The reference length for the definition of model geometry is the diameter D of the cylindrical part of model forebody. Model length is defined as 4.9D and moments' reduction centre is at 1.95D from the nose.

The 100 mm dia. HB-2 model (Fig.2), designed and produced in the VTI's workshop for the T-38 wind tunnel, is intended for measurement of forces and moments, and has been designed so that it can be tested on at least three different force balances, using suitable mounting adaptors for the model. The design enables simple assembly and disassembly of the model, which makes it suitable for use as a quick-check standard that could be easily installed in the wind tunnel instead of some currently tested model.

In the tests presented in this paper, the aerodynamic forces and moments acting on the model were measured by the VTI-produced 44 mm internal six-component strain gauge balance, labelled as VTI KV44. With the nominal axial force range of 2200 N, the balance has been designed specifically for supersonic wind tunnel tests. It has been calibrated to the accuracy better than 0.2% F.S. (based on 95% measurement certainty) for all components except for the axial force, for which the accuracy of 0.38% F.S. was achieved.

Figure 2. The 100 mm dia. HB-2 standard model in the VTI T-38 wind tunnel

Base pressure was measured on the model in the centre of the base area, at the entrance to the sting cavity at the rear side of the model. Base pressure coefficient (C_{pb}) and base axial force coefficient (C_{Ab}) are calculated as:

$$C_{pb} = \frac{p_b - p_{st}}{q}, \tag{1}$$

$$C_{Ab} = -C_{pb}\frac{S_b}{S_{ref}}, \tag{2}$$

where p_b is base pressure, p_{st} is freestream static pressure, q is dynamic pressure, while the reference area (S) and base area (S_b) are calculated as follows:

$$S = \pi(D)^2/4, \tag{3}$$

$$S_b = \pi(1.6D)^2/4. \tag{4}$$

Forebody axial force coefficient (C_{Af}) is calculated by subtracting the base axial force coefficient from the total axial force coefficient (C_A) obtained from the balance measurement:

$$C_{Af} = C_A - C_{Ab} \,. \quad (5)$$

4. RESULTS AND DISCUSSION

4.1. Uncertainty of measurements

In order to discuss wind tunnel data, it is necessary to determine uncertainty of measurements, outside of which any possible pitch rate effects can be detected [7].

The overall uncertainty of a measurement in wind tunnel tests is roughly proportional to a multiple of random error (estimated by standard deviation σ), which is latter often used to express the degree of the accuracy of measurements [8]. Based on the known accuracies of individual sensors in wind tunnel tests, it is possible to estimate the standard deviations of various quantities which are computed from several independently measured quantities. This estimation is done by varying the data for each directly measured quantity for a small amount (equal to the accuracy of the sensor used), performing the complete calculation of the aerodynamic coefficients, and by noting the changes in the calculated output values.

Table 1 presents estimates of maximum expected errors in determining the aerodynamic coefficients from the main six-component balances, expressed for each quantity as two standard deviations (2σ) with approximately 95% confidence level. Estimates are presented for Mach 2, and for the model attitude defined by +10° angle of attack and 0° rolling angle, including the sting deflection. It is assumed that the dimensions of the model are exact. The test results obtained using the VTI KV44 six-component balance are compared with the results from reference runs performed using the ABLE Mk18 six-component balance.

Table 1. Measurement uncertainties of relevant aerodynamic coefficients for Mach 2 tests

HB-2 100 mm standard model		
Measurement uncertainties	Wind tunnel balance	
	ABLE Mk18	VTI KV44
$2\sigma\ C_A$	±0.0036	±0.017
$2\sigma\ C_N$	±0.022	±0.0067
$2\sigma\ C_m$	±0.017	±0.0089
$2\sigma\ C_{Ab}$	±0.00087	±0.00087

By performing two runs with identical flow conditions, a level of repeatability can be obtained and together with measurement uncertainties, the scatter of data can be established. For reference, the main balance and pressure data from two identical runs, performed one after the other, are shown in the figures in the following sections.

4.2. Averaging the wind tunnel test data

Model support mechanism in the VTI T-38 wind tunnel enables control of model position in pitch and roll planes. Position of the model support in these two planes is measured by high-accuracy encoders. The mechanism's pitching angle is calculated for each sample from the encoder output using the third-order polynomial function that was determined in the previous calibration.

Since the model was moving continuously in pitching angle range from −5° to +19° during the measurement, it was necessary to select certain model positions for which the data were to be reduced. For this purpose, a list of 25 pitching angles at approximately 1° intervals was prepared for each run. During data reduction process, the data were segmented in such a manner that for each model position only the data lying in the interval of approximately ±0.25° from the selected pitching angles were averaged, thus giving the 25 "steps" for which the results are listed in the tables and graphs.

Generally, the averaging interval at each model position is a little narrower, as the software automatically adjust it so as to obtain an average of a whole number of periods of the model/sting oscillation at natural frequency.

The average values of measured angles are calculated for each data segment (desired model position) using the n samples lying in the averaging interval:

$$pit = \frac{1}{n}\sum_{i=1}^{n} pit_i \quad (6)$$

The average values of the pressures, temperature, Mach number, Reynolds number and main balance data in the run are calculated using the equivalent relations.

In these HB-2 model tests it was necessary to sample the data at a rate high enough to allow the averaging of sufficient samples over the desired range of angle-of-attack. Not the same numbers of raw data samples were averaged for all runs, but raw samples were averaged from within the same range of angle-of-attack for all runs at all pitch rates, see Table 2.

Table 2. High pitch sweep rate tests parameters

HB-2 100 mm standard model testing Mach 2, Stagnation pressure 2.5 bar Pitch sweep range −5° to +19°			
Pitch rate, °/s	Channel sampling rate, 1/s	Data acquisition time, s	Number of samples in the averaging interval
2	250	12	62
2	250	12	62
3	250	8	41
4	250	6	31
8	500	3	31
12	500	2	20

4.3. Measurement of the base pressure

The accurate measurement of the base pressure in the supersonic wind tunnel tests is complicated by the lag in the measured values, caused by the combination of the low pressure levels and the relatively long pneumatic piping. In the VTI T-38 wind tunnel, the piping from the sensing port to the transducer is about seven meters long, and the time needed for establishing the pressure in the pneumatic installation is not negligible. This time lag particularly complicates the measurement of the base pressure in the pitch sweep tests. In order to realize measurement as accurately as possible, limited pitch rates are used, allowing for the base pressure establishment in the piping. On the other side, low pitch rates extend the required run time, thus directly increasing energy consumption. Decreasing run time is an obvious course of action that is needed in order to achieve energy savings.

The effect of higher pitch rates on the base pressure measurement is analyzed in the VTI T-38 wind tunnel, the goal of the study being to determine the maximum pitch rate that will not have an adverse effect on the measurement accuracy with the existing base pressure pneumatic piping. As anticipated, wind tunnel tests of the HB-2 model at Mach 2 showed a significant effect of the pitch rates on the base pressure measurement. Significant discrepancies in the base pressure data are present for pitch rates above 3°/s, and they become more prominent for higher pitch rates, as is shown in Tables 3 and 4, as well as in Fig. 3.

Table 3. High pitch rate tests: Base pressure

HB-2 100 mm standard model testing, Mach 2 Stagnation pressure 2.5 bar, Pitch angle +19°			
Pitch rate,°/s	*Pb*, bar	*ΔPb*, mbar	*ΔPb*, %FS
2	0.08845	0.00	0.000
2 (repeat run)	0.08874	0.29	0.016
3	0.09083	2.38	0.136
4	0.09452	6.07	0.347
8	0.10338	14.93	0.853
12	0.10796	19.51	1.115
$2\sigma Pb$ = 0.038%FS, $2\sigma Pb$ = ±0.665 mbar			

Table 4. High pitch rate tests: Base pressure coefficient

HB-2 100 mm standard model testing, Mach 2 Stagnation pressure 2.5 bar, Pitch angle +19°		
Pitch rate,°/s	*Cpb*	*ΔCpb*
2	–0.25880	0.00
2 (repeat run)	–0.25798	0.00082
3	–0.25767	0.00113
4	–0.25377	0.00503
8	–0.24291	0.01589
12	–0.24068	0.01812
$2\sigma Cpb$ = ±0.00087		

Based on the results, it is clear that pitch rates higher than 3°/s in the wind tunnel tests requiring the base pressure measurement would not be possible without improving the base pressure response, i.e., without modifications of the transducer placement, its type or the corresponding pneumatic piping. Thus, for the supersonic tests in the VTI T-38 wind tunnel in the future, the recommended course of action is to move the base pressure transducer to a more suitable place. It has to be close enough to the model, mounted on a stable support and isolated from the wind tunnel vibrations. In the past, some trials were performed with the base pressure transducer placed in a service cavity in the vertical strut of the model support system, reducing the piping length by about 4 m. A significant reduction in lag was observed, but thermal stabilization of the transducer, as well as accessibility of pressure tubing for venting against moisture condensation remained issues to be solved in the future.

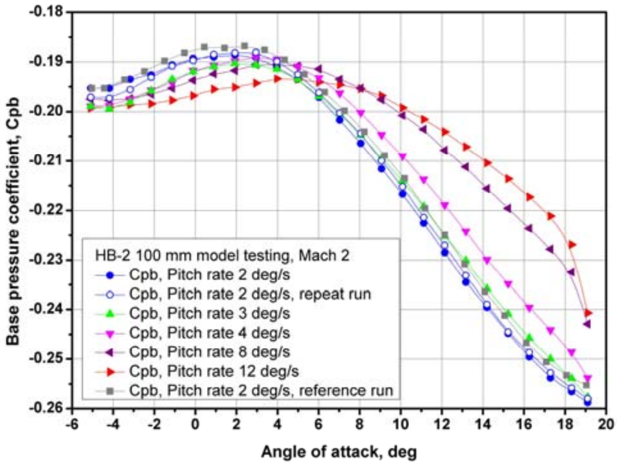

Figure 3. Base pressure coefficient for different pitch rates in the HB-2 model Mach 2 tests

On a case to case basis, depending on the model size and design, it would be possible for a transducer to be placed inside the model. The transducer diaphragm then must be aligned with the pitch plane to eliminate the effects of gravitational and other accelerative forces [2].

In addition, when selecting the transducer type for the base pressure measurement, it should be careful to choose the one with relatively low internal volume and fast response. Some high accuracy digital transducers have the response time from 0.10 s to 0.25 s. It is not satisfactory for measurement of the base pressure, which tends to change fast during model movement.

4.4. Measurement of the forces and moments

Contrary to the base pressure measurement, the VTI KV44 balance response in the high pitch rate tests of the 100 mm dia. HB-2 model was excellent. The coefficients of the axial force, the normal force, and the pitching moment are given in Fig.4-Fig.6, respectively.

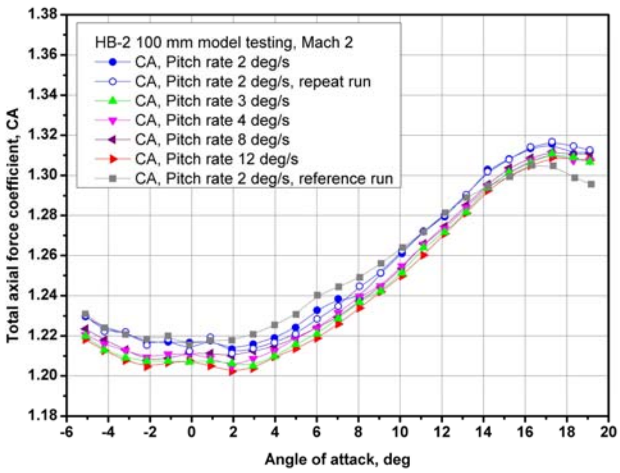

Figure 4. Total axial force coefficient for different pitch rates in the HB-2 model Mach 2 tests

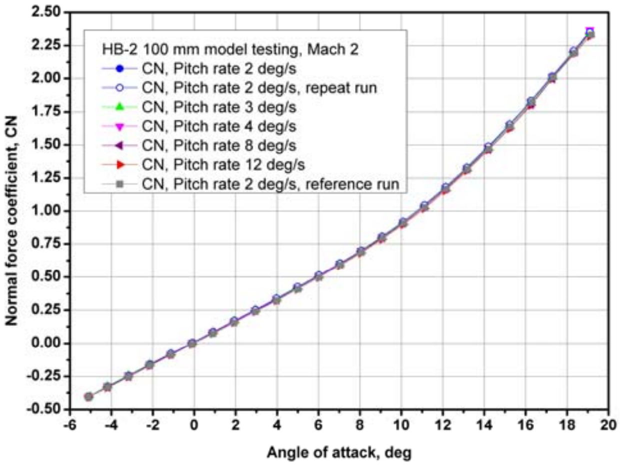

Figure 5. Normal force coefficient for different pitch rates in the HB-2 model Mach 2 tests

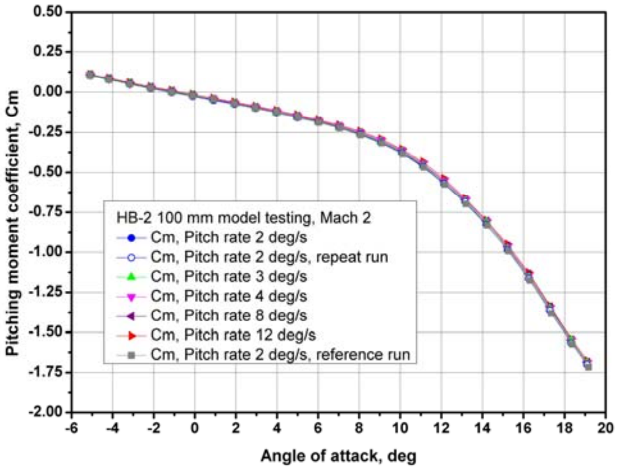

Figure 6. Pitching moment coefficient for different pitch rates in the HB-2 model Mach 2 tests

Force and moment data were in good agreement with data from the reference run performed using the ABLE Mk18 balance, and well within measurement uncertainties. The forebody axial force, however, depends on the base pressure, as in (5), and it is shown in Fig. 7. It is clear that pneumatic lag in the base pressure measurement for pitch rates higher than 3°/s introduces the error in the base axial force results (Fig.8).

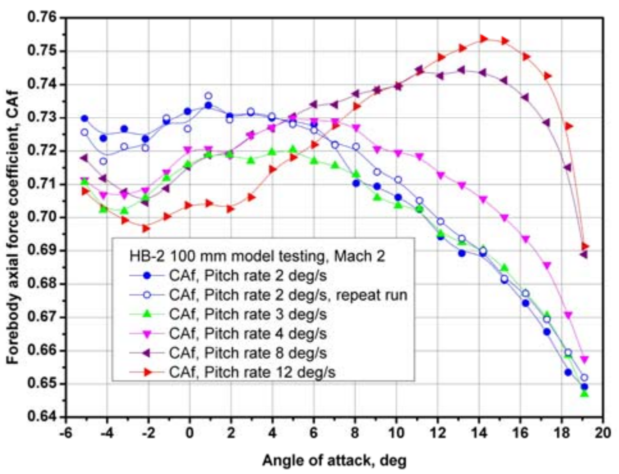

Figure 7. Forebody axial force coefficient for different pitch rates in the HB-2 model Mach 2 tests

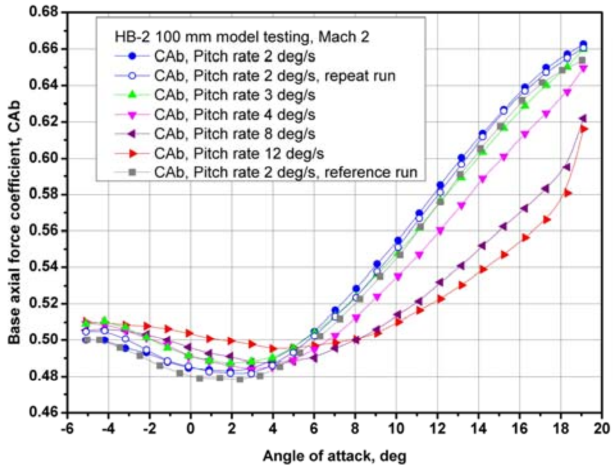

Figure 8. Base axial force coefficient for different pitch rates in the HB-2 model Mach 2 tests

The differences in the wind tunnel data between repeated runs at 2°/s sweep rate are small and well within the measurement uncertainties.

It is evident that differences in the base pressure and all related quantities between runs at the different sweep rates increase with the angles of attack, because of the higher rate of change of the base pressure and pneumatic lag in the installation.

5. CONCLUSION

The tests performed in the VTI T-38 wind tunnel with the goal to observe the possible effect of high pitch rates on the wind tunnel measurement data were useful and resulted in the following recommendations, aimed to improve the facility testing practice in the future:

- For the currently employed base pressure measurement system, the pitch rates higher than 3°/s have an adverse effect on measurement accuracy of the base pressure and, consequently, the forebody drag. The discrepancies in the forebody axial force observed for high pitch rates are of interest to those who deal with ’base drag corrected’ supersonic wind tunnel data.
- The base pressure measurement system should be modified in the manner to improve the pneumatic lag. It is expected that it could be accomplished by mounting the transducer closer to the model and by minimizing the volume of the required piping. The issue with thermal stabilization of the transducers has to be solved.
- The measurement of the forces and moments do not show any dependency on the pitch rates up to 12°/s at Mach 2. The correlations of the force and moments data using the Able and VTI balances are in a very good agreement and within the measurement uncertainties.
- The run time limitation in the VTI T-38 high supersonic range can be overcome by using pitch rates of 3°/s for the currently employed base pressure measurement system.
- The tests were performed using the no-wing-cylinder-tail-flared model and it is recommended to continue research using models of different aerodynamic forms.

Winged forms would be of particular interest.

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