

LIVING WITH SUPERSONIC STARTING LOADS IN THE T-38 TRISONIC WIND TUNNEL OF VTI

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Abstract

Unexpectedly high supersonic starting loads were initially an issue limiting the functionality of the T-38 trisonic wind tunnel in VTI, Beograd. Investigation of this problem began as soon as the wind tunnel became operational. Over the years, it was established that there was not a single remedy for the high starting loads. Instead, a number of devices, techniques and procedures were developed, to be used concertedly to alleviate the problem. Application of these measures enables routine testing at high Mach numbers in the T-38 wind tunnel, with the possible exception of very slender models, which may still present difficulties.

1 Introduction

The operation of many supersonic wind tunnels is characterized by transient phenomena occurring at the time of the establishing and stopping of the supersonic flow in the test section, when randomly developed systems of strong normal and oblique shock waves pass through the test section (Fig. 1). This can lead to large local variation in the pressure and flow direction in the test section, subjecting the tested model to high aerodynamic loads that can exceed several times the magnitude of loads expected in a steady supersonic flow. Starting loads can cause unacceptably high stresses in the model and the measuring devices such as force balances (Fig. 2).

The magnitude of starting loads is mostly dependent on Mach number and the stagnation pressure at the time of establishing or breakdown of the supersonic flow. It is of

particular importance in blowdown wind tunnels in which the supersonic flow becomes established at high values of stagnation pressures, thus inducing high starting loads. Among such wind tunnels is the 1.5 m × 1.5 m T-38 trisonic blowdown wind tunnel [1] in Military Technical Institute Beograd (VTI–Vojnotehnički institut Beograd).

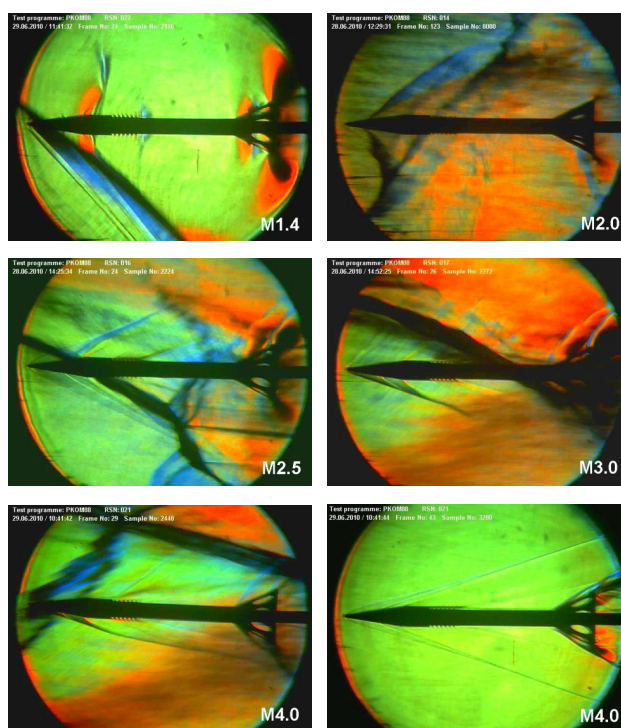


Fig. 1. Transient shock waves in the test section of the T-38 wind tunnel during the starting of the flow at Mach 1.4, 2, 2.5, 3 and 4; steady flow at Mach 4; 3-colour schlieren visualization

When the T-38 wind tunnel became operational about the year 1985, in the Aeronautical institute Žarkovo (VTI, at that time in Yugoslavia), it became evident that

minimum operating pressures were higher than anticipated, partially because of an oversized silencer in the exhaust of the wind tunnel, required because of the environmental noise restrictions. High minimum start pressures resulted in higher than anticipated starting loads. The T-38 does not have complex protection devices existing in some wind tunnels to guard the models during the starting phenomena, so the high starting loads were initially a significant problem limiting the functionality of the facility, and measures had to be taken to resolve this issue.

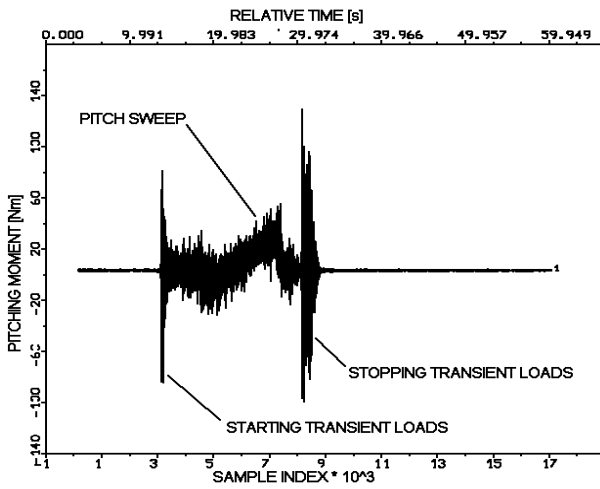


Fig. 2. Plot of a typical unfiltered output from the pitching-moment component of an internal wind tunnel balance in a supersonic wind tunnel run; transient loads exceed maximum test loads by more than a factor of 2; recorded at Mach 2.5

2 Initial investigations

Investigation of the starting loads problem in the T-38 wind tunnel was started [2] during the commissioning of the wind tunnel.

An important result of these investigations was that they showed that the supersonic starting loads, when properly scaled according to the normal-shock theories [3][4], were of similar magnitude as in other wind tunnels, and their large absolute magnitude was due to high minimum starting pressure of the T-38 wind tunnel. It was also established that the minimum stagnation pressure required to start a supersonic flow was considerably higher than the pressure at which the established flow broke down at the end of a run.

Another important result was an establishment of an empirical method for estimating the starting loads, based on the Boeing method [5]. Maximum starting loads for missile-like models in the T-38 wind tunnel (axial force F_{TX} , side force F_{TY} , normal force F_{TZ} , rolling moment M_{TX} , pitching moment M_{TY} and yawing moment M_{TZ}) have, since then, been estimated using the relations (1):

$$\begin{aligned} F_{TX} &= k_X S_X \\ F_{TY} &= k_Y S_Y \\ F_{TZ} &= k_Z S_Z \\ M_{TX} &= k_L S_Z B \\ M_{TY} &= k_M S_Z L \\ M_{TZ} &= k_N S_Y L \end{aligned} \quad (1)$$

where S_X , S_Y and S_Z are the model contour areas projected in the directions of the respective load components, B and L are the wing span and model length, respectively, and k_X , k_Y , ..., k_N are the empirically derived, Mach number dependent, 'starting-loads pressure differentials' as in Fig. 3. Curves in graphs in this figure should be thought of as upper limits, i.e. the starting pressure differentials for a model are not likely to be above the curves, but can be below them.

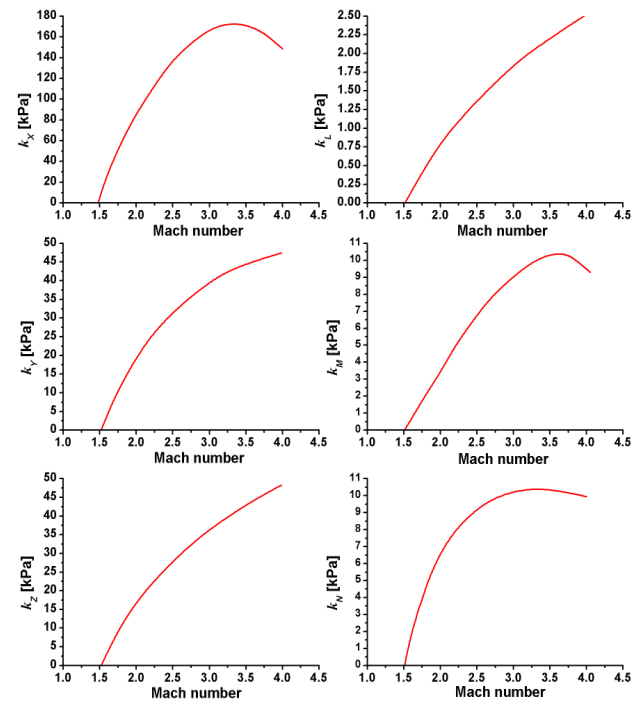


Fig. 3. Pressure differentials for calculation of supersonic starting loads

Beside the quantification of the starting loads, two important techniques for the reduction of the starting loads were introduced, the use of the sidewall flaps to create a second throat and the use of deliberate model-sting contact to relieve loads on the balance.

3 Cooperative loads-reduction techniques

As the customers' interest in supersonic testing increased over the years, means were sought to circumvent the starting loads problem and expand the capabilities of the wind tunnel. Gradually, it was established that there was no single remedy for high starting loads. Instead, a number of devices, techniques and procedures was developed, to be used concertedly to alleviate the problem. These measures are presented here.

3.1 Use of sidewall flaps in the diffuser

Initially, the sidewall flaps at the upstream end of the diffuser in the T-38 wind tunnel were intended as a means to control Mach number in the subsonic and lower transonic speed range. When the starting loads problem became evident, designers of the wind tunnel suggested using these sidewall flaps in the supersonic configuration as well, to form a second throat [3] in the wind tunnel duct and so reduce the minimum operating pressure. Although the sidewall flaps in the T-38 were not designed to create an aerodynamically clean second throat, this technique was moderately successful.

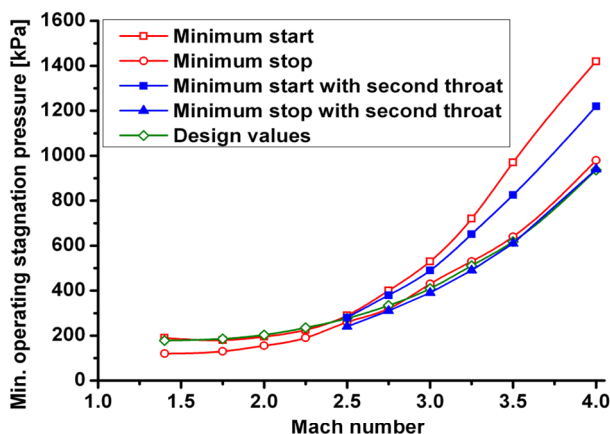


Fig. 4. Reduction of the minimum operating pressures of the T-38 wind tunnel by the use of the second throat

Minimum starting pressures were decreased by more than 10 % (Fig. 4, [2]), but, on the other hand, minimum stopping (flow breakdown) pressures remained almost unchanged.

3.2 Management of model-sting clearance

An important technique that was developed early in the operational life of the T-38 wind tunnel was the management of the model-sting clearance. Models for supersonic tests in this wind tunnel, that are always sting-mounted, are designed in such ways that model-sting clearance at model base is just sufficient to allow deflections in the steady-flow tests without model-sting contact. Whenever possible, this clearance is made so small that model-sting contact is sure to occur during the supersonic start phenomena, when large pitching and yawing moments cause large deflections of the model and the sting. During the contact, part of the aerodynamic load is transferred from the model directly to the sting, bypassing the sensitive wind tunnel balance. In this way the transient pitching and yawing moments on a force balance can be reduced by about 50 % which is a significant improvement. When this technique is applied, the force loads on the balance are actually slightly increased, but this is usually far less critical than the large reduction of bending moments.

A drawback of the technique lies in the difficulty to judge the necessary model-sting clearance before the actual wind tunnel runs. In actual model design, model-sting clearance is sometimes adjusted by an installation of a ring made of a relatively soft material (e.g. aluminum) inside the model base. The ring can be replaced with one having a different diameter, to adjust the gap, if necessary.

Another drawback of this technique is that it relieves only the wind tunnel balance, but not the model or the support sting.

3.3 Design and production of wind tunnel balances with specific characteristics

For supersonic tests, VTI designs and produces monobloc wind tunnel balances (Fig. 5) using high-strength maraging steels such as the Vascomax C-300 and C-350 [6]. Balances are

designed for high specific loads [7] of up to $1300\text{--}1400\text{ N/cm}^2$ and have relatively long, slender bodies for large moments-to-forces ratios. They are designed with stiff flexures, and high-impedance $2\text{ k}\Omega$ and $5\text{ k}\Omega$ strain gauges, with up to 24 V excitation, are applied to obtain useful signal magnitudes even from the small strain levels in the stiff sensing elements. When used in the lower half of their design load range, these balances are convenient for tests in which large starting loads are expected.

Two load ranges are defined for the balances: a measurement load range, in which the balance is calibrated, and a (higher) transient load range, which the balance can safely withstand, but without performing accurate measurements.

Generally, the VTI-produced monobloc balances have proved themselves to be more convenient for the supersonic tests in the T-38 wind tunnel than purchased assembled balances of Able/Task type which suffered from significantly higher hysteresis, especially after prolonged supersonic tests campaigns.

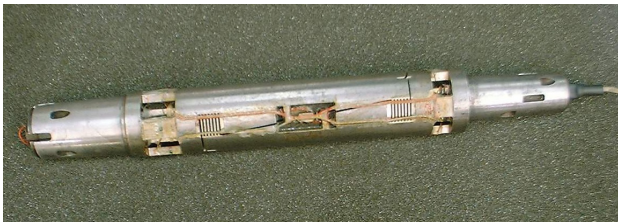


Fig. 5. A 40 mm VTI-produced monobloc wind tunnel balance used in supersonic tests; transient load range up to 6 kN , 600 Nm

3.3 Development of very stiff wind tunnel balances

For some time, efforts have been made to develop, produce and test several very stiff wind tunnel balances with semiconductor strain gauges. High sensitivities of semiconductor gauges (about 70 times higher than that of the foil strain gauges) make possible unconventional balance designs with very stiff sensing elements, the overall stiffness and load range for a given balance size being approximately twice that of a balance of conventional design. One of the balances, a 40 mm , 10 kN , five-component design with

semiconductor strain gauges on all sensing elements, is in successful use in the dynamic derivatives testing rig [8] at Mach numbers up to Mach 2. The other two balances, with semiconductor strain gauges on the axial force elements only, are intended for supersonic static force tests. One of them, the 40 mm , 3 kN , balance design [9] (Fig. 6) has become indispensable in the tests of some high drag models, e.g. [10], up to Mach 4, including the recent verification tests with the HB-2 reference model [11].



Fig. 6. The 40 mm VTI-produced high-stiffness monobloc balance with semiconductor strain gauges on the axial-force component

Another design, a 44 mm balance based on the experience with the 40 mm balance, is being finished (Fig. 7) and is awaiting calibration.

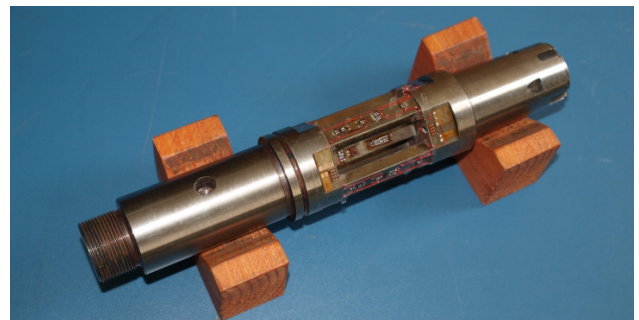


Fig. 7. The 44 mm high-stiffness six-component wind tunnel balance with semiconductor strain gauges on the axial-force component, photographed during the application of the gauges

Both balances with the semiconductor strain gauges on the axial-force component comprise simple compression-type elements for the axial force with strain gauges in T-patterns.

While an experimental verification [11] in wind tunnel tests of a standard model has shown

that the accuracy of the prototype 40 mm semiconductor-gauges balance [9] was somewhat inferior to that of a conventional-design balance with foil strain gauges, the semiconductor-gauges balances are anyway a solution of choice in some specific tests, in which no other available wind tunnel balance would be convenient. Among such uses are the precursor supersonic wind tunnel runs to establish the magnitude of supersonic starting loads on unconventional model configurations for which the empirical estimates seem to be unreliable, therefore helping in a selection and check of an appropriate load range of a balance for an extensive wind tunnel test.

3.4 Finite-element analysis of balances

Finite-elements (FE) analyses is used on VTI-designed balances to verify that stresses induced by transient loads estimated for a particular supersonic test would be within the safe limits even if the nominal load range of some balance component may be exceeded, but the other components are not loaded up to design limits. Therefore, the nominal load ranges of a balance are considered in a relatively flexible way, and can be redefined to suit a particular load configuration. Advancements, over the years, in software tools and computational resources make this type of analysis easy to perform. FE models of the often-used balances have been prepared, so that only the particular load cases have to be created when needed. In this way, the confidence in the selection of a particular balance for a high-Mach wind tunnel test is increased.

3.5 Relaxation of safety factors

VTI has come to accept relatively low safety factors for finite-elements-checked monobloc wind tunnel balances of its own designs to be used in supersonic high-Mach tests. Safety factors between 1.7 and 2.0 for starting loads, based on computed Von Mises stresses and yield strengths of the balance materials are considered acceptable.

On the other hand, as the supersonic starting loads are pure dynamic, oscillatory, loads, consideration of the dynamic strength and

fatigue of the balance material is important. A balance in a high-Mach run in the T-38 wind tunnel typically suffers about 100 periods of full-range dynamic loads at frequencies between 10 and 20 Hz (depending on the mass of the model and stiffness of the sting and balance used). At the accepted stress levels which are high relative to the dynamic strengths of the materials used, a limited balance life, possibly not longer than a few years of extensive use, is a reality. As the percentage of supersonic runs in the T-38 wind tunnel increases, a replacement policy for 'worn out' balances is to be started.

3.6 Use of high-stiffness hybrid stings

A research is currently in progress in VTI on the possibility of producing model support stings from materials with high moduli of elasticity. The reasoning behind the research is that a very stiff sting would deflect less when subjected to loads, which would be very beneficial in testing of slender wind tunnel models. Deflections caused by the supersonic starting loads would be reduced as well, so that they would not contribute to the starting loads by increasing the angle of attack. Besides, increased stiffness of the sting would raise the natural frequency of the model-balance-sting assembly, which would be an advantage. Suitable high-stiffness materials are generally based on heavy metals such as tungsten and its carbides. Unfortunately, these materials are difficult to machine and are relatively brittle, so that they are not convenient for producing fine details of the sting-balance interface. Instead, a hybrid design, comprising steel and tungsten carbide components, appeared optimum. An experimental hybrid 43 mm diameter sting was produced along these lines (Fig. 8). The sting comprises an outer shell made of PH13-8Mo precipitation-hardened high-strength stainless steel and a core sintered from 90WC-10Co tungsten-carbide hard-alloy powder.

Static test of this sting, in assembly with the high-stiffness balance [9], has shown that the deflections under loads were reduced by more than 25 % relative to a steel sting of an identical size and a conventional wind tunnel balance.

A possibility of producing a complete sting from ferro-titanit [12] (a family of materials also known as ferro-tic, consisting of titanium-carbide particles in a matrix of maraging steel) has also been considered. However, it seems that it is not currently possible to economically obtain ferro-titanit in the form factors convenient for the production of such stings.

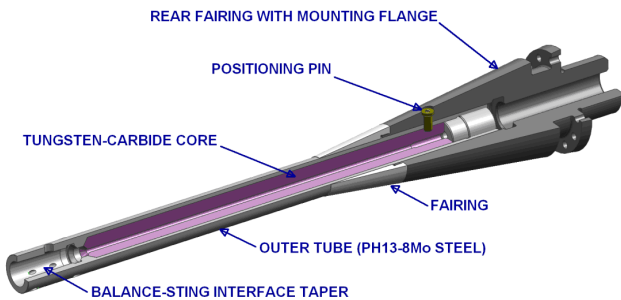


Fig. 8. A CAD-model cutout of the produced 43 mm-dia. hybrid sting with hard-metal core

An alternative approach to producing high-stiffness model support stings was attempted as well. A sting, with dimensions identical to the one produced with tungsten-carbide core but having a steel core and an outer layer of unidirectional carbon-fibre composite was produced and tested. Possibly because of a lack of experience with designs using composite materials, this prototype was not successful. Still, composite stings remain an option for future development because of advantageous vibration-damping properties.

The produced high-stiffness sting with the tungsten-carbide core has been tested in actual wind tunnel runs, but its contribution to the reduction of starting loads has yet to be determined.

3.7 Increase of the test dynamic pressure

Having in mind the operating envelope and the maximum dynamic pressures achievable in the T-38 wind tunnel, the designers of the wind tunnel have concluded that the supersonic starting loads would not much exceed loads achievable at maximum dynamic pressures, and, therefore, model protection devices were not needed. That analysis, did not take into account the strength limits of available materials for the

balances and stings, and the reduced wind tunnel run times at high pressures, which limited very much the possibility of tests at such high dynamic pressures. Therefore, for a considerable time, most supersonic wind tunnel tests in the T-38 had to be performed near the lower limit of the wind tunnel operating envelope, at dynamic pressures of about 100 kPa. At such conditions, the load ranges of the balances selected on the basis of starting loads significantly exceeded the requirements of the test at steady flow conditions, leading to reduced accuracy of measurements.

However, with the increased capabilities for reliable FE simulations of balance and sting loads and stresses, the relaxation of the safety factors, and the introduction of the much stronger C-300 and C-350 maraging steels [6] as the materials for the production of the balances and stings of instead of the earlier-used PH13-8Mo steel, tests at higher dynamic pressures became feasible. Recent supersonic tests were performed at dynamic pressures of 150-180 kPa, reducing very much the gap between the balance load ranges required for the measurements and for withstanding the starting loads.

3.8 Monitoring of the loads by the data acquisition system

Normally, analog input signals from the wind tunnel balances are low-pass filtered in order to reduce electrical and mechanical noise and ‘smooth’ the data. This, unfortunately, tends to filter-out the dynamic starting loads, preventing realistic monitoring. To avoid this problem, whenever a high-Mach test is prepared for the T-38 wind tunnel, an arrangement is always made in the data acquisition system to monitor and record, in parallel with the filtered data, the unfiltered data from the wind tunnel balance components (Fig. 2). Also, the data acquisition system is always set to record the data taken during the starting and the stopping phases of the wind tunnel runs. The unfiltered recorded signals from the balance are checked against preset safety limits and the wind tunnel run is automatically stopped if transients exceeded permissible values. Besides, the unfiltered load

data are analyzed after each run to check the magnitude and character of recorded starting loads.

3.9 Visual monitoring

Supersonic runs in the T-38 wind tunnel are always visually monitored by observing real-time 3-colour schlieren visualizations of the flow in the test section (Fig. 1). Modifications [13] have been made to the somewhat cumbersome initial configuration of the schlieren system in the T-38, making it much easier to activate and use in all supersonic tests without much additional effort to adjust the optical components. A simple PC computer- controlled video system is used, synchronized with the wind tunnel data acquisition system, that produces video previews and recordings of relatively low resolution (VGA standard), but sufficient for monitoring purposes. A wind tunnel run can be aborted by the operator monitoring the schlieren image, e.g. in the case of the supersonic flow not starting or in the case of severe model oscillation or large sting deflections.

3.10 Rearrangement of test schedules

It was found convenient to sequence the supersonic wind tunnel runs in a test campaign so that Mach number is increased from run to run while the increase of the magnitude of starting loads is observed. From the observed trends, a prediction is made, during a test campaign, on the expected started loads at the next higher Mach number, and the test is stopped if they would become too large. If a particular test matrix does not contain a convenient series of increasing supersonic Mach numbers, additional wind tunnels runs are performed in the Mach 1.5 to Mach 2.5 range, so that the trend in the increase of the starting loads vs. Mach number can be estimated.

3.11 Establishment of starting loads database

A database is being accumulated of recorded supersonic starting loads from test campaigns of different model configurations. Empirical starting pressure differentials are derived from

these data, that can be used to predict the expected magnitude of starting loads on a particular model configuration to be tested.

3.12 Efficient balance calibration system

The hardware and software systems for calibration of internal wind tunnel balances in VTI, consisting of a calibration rig, several calibration bodies for the balances and a data reduction software was upgraded [14], to enable a full use of the composite-loadings method by a single force load (also known as the single-vector calibration method). The upgrade of the system enabled rotation of the balance, during a calibration, through the full 360° in pitch and roll, so that, by applying a single, vertically acting force, a number of combinations of component loads can now be realized (Fig. 9). The calibration matrix is calculated by the global regression least-squares procedure [15] from a complete dataset with a number of different load cases. Calibration matrices comprising the terms up to the third order, including, if considered necessary, absolute value terms and load-product terms, with up to 96 terms per component, can be calculated.



Fig. 9. Calibration of a 9 kN internal wind tunnel balance on the upgraded calibration rig in VTI; simultaneous application of axial force and pitching moment.

The upgrade has enormously improved the efficiency of balance calibration at the facility, making possible easy and quick recalibrations of high-capacity wind tunnel balances, selected on the basis of expected starting loads for some wind tunnel test, in the reduced load ranges appropriate for the actual measurement range in that test. Although loading is still done by manual application of weights (expected soon to be replaced by weight-stack lifting platforms), a typical calibration of a 5-10 kN balance, comprising about 60 loading sequences, can be performed in about five working days, and some have been finished in as little as three days.

3.13 Abandoned ideas

Some of the ideas initially thought of [2] as contributing to the reduction of the starting loads problem turned out to be impractical. Among them is the use of special balance-sting interfaces, other than the conventional male-female taper fits tightened with two or four screws. Taper fit was at first considered inadequate because the tightening screws often came loose or became damaged in supersonic tests. Tightening of a balance by a single nut having a thread and a counter-thread was proposed, similar to the designs described in [16] but was eventually discarded. A number of six-component balances have, over time, been acquired or produced having the de-facto-standard Able/Task interface tapers, and suitable stings were produced for them. It was felt that having two groups of mutually incompatible balance-sting fits would increase the costs and reduce the flexibility of operation. Besides, the problem of inadequate balance-tightening screws in the stings was solved by re-drilling and re-threading the holes on all stings for screws of a larger diameter.

Other abandoned ideas include positioning of the model at particular nonzero pitch and roll angles during the run start phases in order to better point the model into the unsteady airflow, which had a very limited effect, and the installation, proposed by the designers of the wind tunnel, of precursor shock generators on the sidewalls of the test section that were supposed to stabilize the flow and improve

supersonic diffusion, but proved completely ineffective [2] and, besides, prevented the use of sidewall windows.

4 Conclusions

By using the techniques presented above, the initially existing problems related to high supersonic starting loads were overcome to a large degree. Just two of the applied techniques, the second throat and the deliberate model-sting contact, reduced the starting loads by more than 50 %. Another most important improvement was the use of high-specific-loads monobloc wind tunnel balances instead of the initially purchased assembled balances. High-Mach tests are, in most cases, now successfully performed in the T-38 wind tunnel facility, with some limitations remaining for very slender models, where high bending moments during the starting phenomena may still present problems.

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