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Selection Criteria of Optimal Conditions for Supersonic Tests in a Blowdown Wind Tunnel

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A natural desire of a wind tunnel test engineer is to plan and perform a test that will resemble the actual flight conditions as closely as possible. Geometric similarity and identical flight and wind tunnel Mach numbers are the primary requirements and they can be achieved without much problems, but the reduced size of the model and the limits of the operating envelope of the wind tunnel prevent the achievement of desired similarity with respect to the Reynolds number, which is generally much lower in a wind tunnel than in flight. Pressurized blowdown wind tunnels, like the T-38 in the Military Technical Institute (Vojnotehnički institut), Belgrade, were designed to reduce this discrepancy and achieve high Reynolds numbers by raising the stagnation pressure of the test-section flow. It is shown, however, that not the Reynolds number but instead the constraints related to model size, load range of available instrumentation, available run time, high aerodynamic loads, etc., are often decisive in the selection of the conditions for a high-speed wind tunnel test.

Key words: **wind tunnel, aerodynamic testing, supersonic flow, test plan.**

Nomenclature

M – Mach number
Re – Reynolds number
U – Freestream velocity, [m/s]
a – Speed of sound, [m/s]
ν – Cinematic viscosity, [m²/s]
P_{st} – Static pressure, [Pa, bar]
P_0 – Stagnation pressure, [Pa, bar]
P_{0start} – Stagnation pressure at flow start, [Pa, bar]
$P_{0\min}$ – Stagnation pressure at flow breakdown, [Pa, bar]
$P_{0\max}$ – Maximum stagnation pressure, [Pa, bar]
$P_{ststart}$ – Static pressure at flow start, [Pa, bar]
$P_{st\min}$ – Static pressure at flow breakdown, [Pa, bar]
$P_{st\max}$ – Maximum static pressure, [Pa, bar]
Patm – Atmospheric pressure, [Pa, bar]
Pt – Air-storage tank pressure, [Pa, bar]
q – Dynamic pressure, [Pa, bar]
$q_{\max}$ – Maximum dynamic pressure, [Pa, bar]
$q_{\min}$ – Dynamic pressure at flow breakdown, [Pa, bar]
T_0 – Stagnation temperature, [K]
T – Static temperature, [K]
D – Model diameter, [m]
H – Test section height, [m]
h – Altitude, [m]
L – Reference length, [m]
B – Wing span, [m]
A_{TS} – Test section area, [m²]
C_D – Drag coefficient
μ – Shock wave angle, [°]
α – Angle of attack, [°]
σ_x – Bending stress, [Pa]
S – Projected model contour area, [m²]
k – Transient pressure differential, [Pa]
F_T – Transient (starting load) force, [N]
M_T – Transient (starting load) moment, [Nm]

Introduction

SUPERSONIC wind tunnels are important tools of experimental aerodynamics. They are used to investigate high-speed-flow phenomena and determine such aerodynamic characteristics of flying vehicles that, with the current state of the art, cannot be determined computationally, or else, are too expensive to determine computationally. In flight, the air is stationary and the vehicle moves forward; in a wind tunnel, the air is moved past a fixed model of the flying vehicle, the model usually being built at a reduced scale. The two situations are "dynamically similar" for a steady flight, and the results from wind tunnel tests can be applied to the actual flight conditions. Obvious requirement for the relevance of the results from wind tunnel tests is the geometric similarity between the wind tunnel model and the actual object, i.e. the model has to be a scaled-down, as exact as possible, representation of the aerodynamic shape of the full-scale vehicle. Two other main similarity parameters that, ideally, should be identical in flight and in a wind tunnel test, are the Mach number (a non-dimensional ratio of the vehicle airspeed to the speed of sound) and the Reynolds number (a non-dimensional descriptor of the ratio of inertial forces to viscous

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forces). In the experiments related to heat transfer the Prandtl number becomes an important parameter as well [1], but its significance is not large in relation to the flow outside the boundary layers.

Matching the flight Mach number and the wind tunnel Mach number is usually easily accomplished in a supersonic wind tunnel: Mach number is set by a convergent-divergent nozzle, either of an adjustable type or of a fixed type with exchangeable blocks designed for certain predetermined Mach numbers. On the other hand, matching the flight and wind tunnel Reynolds numbers, while maintaining identical Mach numbers, presents a significant problem. The well-known relations defining the Mach and Reynolds numbers M and Re are:

$$M = U / a \tag{1}$$

$$Re = U \cdot L / \nu \tag{2}$$

where U is the velocity of the object relative to the undisturbed fluid, a is the speed of sound, L is a characteristic length of the object and ν is the cinematic viscosity of the fluid. In a wind tunnel test, the characteristic length L, related to the size of the object, will usually be much reduced to that of the actual object, so that the Reynolds number will be lower than in flight. On the other hand, the speed of sound is a function of the static temperature T, and the viscosity of the working fluid is a function of its composition, its temperature T and stagnation pressure P_0, all of which can be different in a wind tunnel, relative to those in flight. Therefore, the interdependencies between achievable values of M, Re, ν, T and P_0 can become complex in a wind tunnel environment. For example, if the working medium is air with the viscosity of 1.79×10^{-5} kg m^{-1}s^{-1} at 288 K and obeying the Sutherland's law [1], the relation Eq. (2) for the Reynolds number can be expanded to Eq. (3) referring to the static quantities of the air flow and Eq. (4) referring to the stagnation quantities (in SI units):

$$Re = 47874\,\mathrm{s^2kg^{-1}K}\,\frac{P_{st}\,M\left(110.3\,\mathrm{K}+T\right)L}{T^2} \tag{3}$$

$$Re = 47874\,\mathrm{s^2kg^{-1}K}\,\frac{P_0\,M\left(\left(1+0.2M^2\right)\cdot 110.3\,\mathrm{K}+T_0\right)L}{T_0^2\left(1+0.2M^2\right)^{2.5}} \tag{4}$$

It is seen from Eq. (3) and Eq. (4) that the Reynolds number in a wind tunnel with air as the working medium can be varied by changing the flow conditions, e.g. pressure or temperature. However, the choice of flow conditions in a particular wind tunnel is also restricted by a number of other constraints. Such constraints are analyzed in this paper for the case of supersonic tests in the 1.5 m × 1.5 m T-38 trisonic wind tunnel of VTI (Vojnotehnički institut- Military Technical Institute) in Belgrade. It is shown that, although the design of the facility permits a variation of the Reynolds number at any Mach number within the operating envelope by the means of changing the stagnation pressure and the model size, for any given model there is usually very little latitude to adjust the Reynolds number to flight conditions. Instead, test conditions are dictated by other considerations. The main ones are:

- Restrictions to model size relative to wind tunnel test section;
- Restrictions to dynamic pressure and, therefore, aerodynamic loads because of the structural safety of the model and the wind tunnel.

Achieving high Reynolds number in a supersonic wind-tunnel

There are several techniques by which high Reynolds number can be achieved in a wind tunnel. Depending on the design of a particular test facility, one or more of these techniques can be deployed:

Increasing the size of the model: a model built at the scale identical to the actual object would be ideal, as it could be tested close to the flight Reynolds number (except for the differences between wind tunnel and flight pressures and temperatures), and geometrical similarity would be total. However, it is obvious that for any but the smallest aircraft and missiles this would be a very expensive and impractical approach.

Increasing the pressure of fluid: It can be seen from Eq. (4) that the Reynolds number increases if stagnation pressure of the air flow is raised. To this end a number of pressurized wind tunnel facilities have been built. Unfortunately, increasing the stagnation pressure in a wind tunnel test section also means an increase in dynamic pressure and increase of model loads which may become unacceptable; besides, the entire wind tunnel must be sealed (except at the exhaust of a blowdown-type) in order to maintain the elevated pressure.

Changing the working fluid: Beside air, other gases, with viscosity different form that of air, can be used as the working fluid in a wind tunnel, so that the Reynolds number can be increased [2]. Same as for the change of pressure, the complete wind tunnel circuit must be sealed to prevent the escape of gas, which significantly complicates model changes. Besides, this approach is practical only for the continuous wind tunnels, not for the blowdown ones.

Changing the temperature of working fluid: Lowering the temperature of the working fluid in a wind tunnel causes its viscosity to change, e.g. Eq. (3). Cryogenic wind tunnel facilities are built to utilize this fact. This approach is very expensive as a wholly new range of materials, transducers and measuring techniques must be used that can operate at low temperatures. Model changes are difficult and require time-consuming procedures involving heating and re-cooling of the model area. Still, the cryogenic wind tunnel testing technique has become mature and several such facilities [2,3] are successfully operated.

The T-38 Wind Tunnel

The T-38 wind tunnel at VTI (Fig.1) is a 1.5m×1.5m pressurized, blow-down-type facility for tests in the Mach number range from 0.2 to 4. For subsonic and supersonic tests, the test section is with solid walls, while for transonic tests, a section with porous walls is inserted in the tunnel configuration.

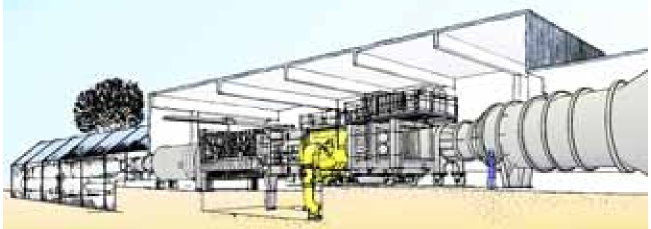

Figure 1. The T-38 wind tunnel in VTI (artist's impression)

In the supersonic configuration, Mach number is set by a convergent-divergent nozzle formed by flexible plates that can be bent in order to create the desired nozzle contour. In the transonic configuration, Mach number is set by sidewall flaps and the flexible nozzle, but also actively regulated by a blow-off system. In the subsonic configuration, Mach number is set by the sidewall flaps downstream of the test section of the wind tunnel. Mach number can be set and regulated to within 0.5% of the nominal value.

Stagnation pressure in the test section can be maintained between 110 kPa (1.1 bar) and 1.5 MPa (15 bar), depending on the Mach number and regulated to 0.3% of nominal value. Run times range from 6 s to 60 s, depending on the Mach number and stagnation pressure. Models are normally supported in the test section by a tail sting mounted on a pitch-and-roll mechanism by which the desired aerodynamic angles can be set. The facility supports both step-by-step and continuous (pitch-sweep) movement of the model during measurements.

Design operating envelope for the 3D test sections of the T-38 wind tunnel is shown in Fig.2 in terms of stagnation pressure and run times vs. Mach number and in Fig.3 in terms of Reynolds number and stagnation pressure vs. Mach number. The designed supersonic operating envelope of the T-38 wind tunnel is limited from the lower side by the minimum pressures needed to start and maintain a supersonic flow created by the air flowing out from the storage tanks into the atmosphere (the pressure needed to start the supersonic flow being higher than the pressure needed to maintain the flow), and on the upper side by the structural safety limits. On the lower side, Mach number is limited to 0.2 by structural safety limits and the mechanical design of the choke flaps. On the upper side, it is limited by the mechanical design on the flexible nozzle and the need to avoid the liquefaction of air that may occur above Mach 4.

Numerical values of the flow parameters at the upper and lower limits of the operating envelope of the T-38 wind tunnel in the supersonic speed range are presented in Table 1.

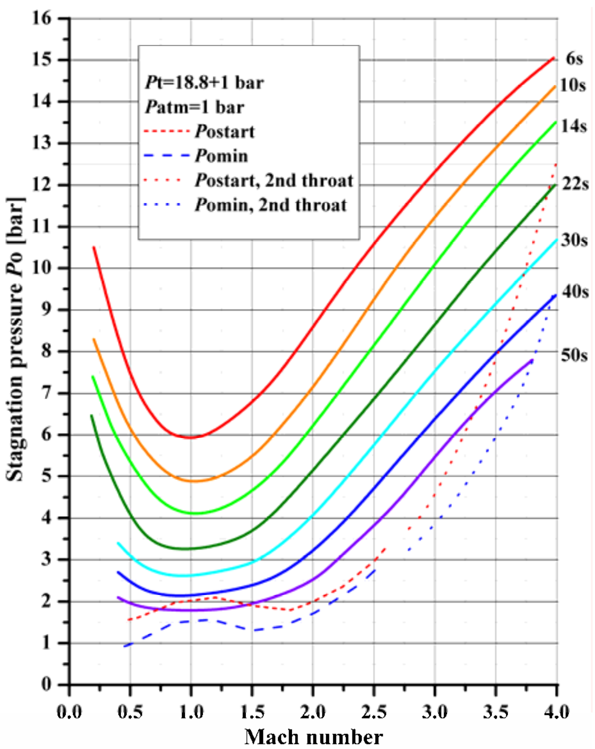

Figure 2. Operating envelope of the T-38 wind tunnel–stagnation pressure vs. Mach number and run time

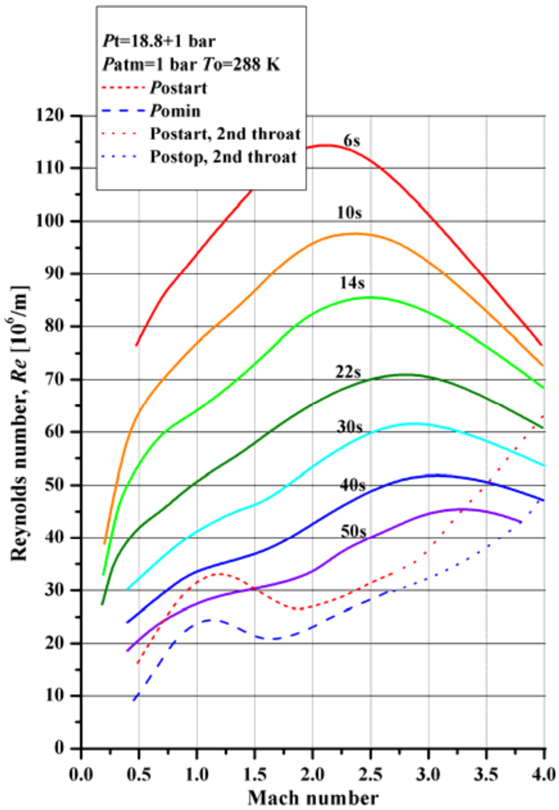

Figure 3. Operating envelope of the T-38 wind tunnel–Reynolds number vs. Mach number and run time

Table 1. Pressures on the supersonic envelope of the T-38 wind tunnel

Pressure, kPa	Mach number					
	1.5	2.0	2.5	3.0	3.5	4.0
Minimum stagnation, $P_{0\min}$	180	200	270	400	600	950
Stagnation at start, P_{0start}	230	200	300	530	980	1430
Maximum stagnation, $P_{0\max}$	680	870	1070	1250	1390	1500
Minimum static, $P_{st\min}$	49	26	16	11	8	6
Static at start, P_{tstart}	63	26	18	14	13	9
Maximum static, $P_{st\max}$	185	111	63	34	18	10
Minimum dynamic, $q_{\min}$	77	72	69	69	67	70
Maximum dynamic, $q_{\max}$	292	311	274	214	156	111

While the complete operating envelope can generally be utilized, the practical envelope for some types of measurements may be somewhat restricted, e.g. for the force measurements it is customary to select test conditions at least 50 kPa above the minimum start pressure in order to ensure the safety of the instrumentation. Also, a pitch-sweep run of at least 10° requires, including flow-settling-time, a runtime of at least 10 s.

The wind tunnel was designed for very high Reynolds numbers, relative to the majority of other facilities of the time (about the year 1980, Fig.4) and is still a facility among the ones with the highest Reynolds-number capability in the world. The design intent was to achieve such performance by operating at high stagnation pressures. It can be seen from

Fig.3 that the maximum achievable Reynolds number in the T-38 is above 115×10^6 per metre at Mach 2.25 and that the Reynolds number in the supersonic speed range can be varied, by changing the stagnation pressure, approximately in the maximum-to-minimum ratio of more than 4:1 at Mach 2.25 and about 1.6:1 at Mach 4.

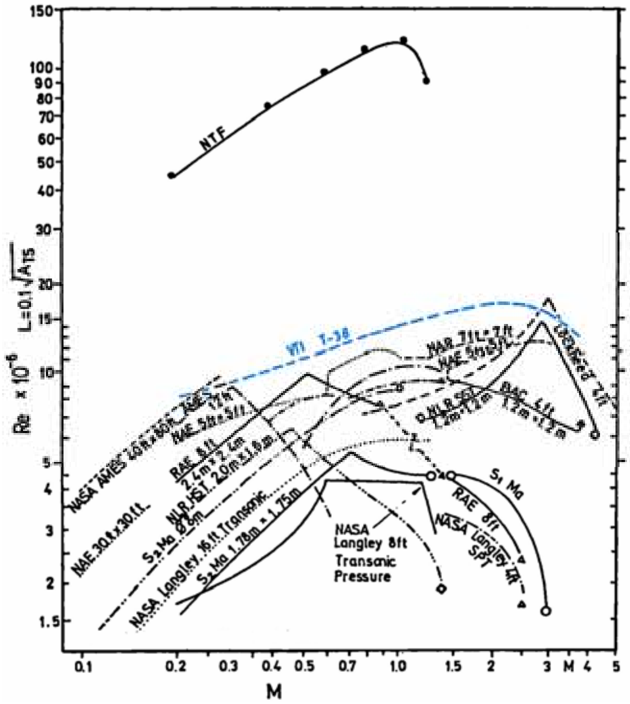

Figure 4. Comparison of the Reynolds numbers achievable in the T-38 wind tunnel and other experimental facilities at T-38 design time; graph from the T-38 design documentation

Differences between test conditions in the T-38 and flight conditions

Certain differences between atmospheric flight conditions and wind tunnel test conditions, as applicable to the T-38 blow-down wind tunnel, should be pointed to:

- In the atmospheric flight, static pressure is equal to ambient (atmospheric) pressure at flight altitude. Dynamic pressure and stagnation pressure increase as the flight velocity and Mach number increase.
- In the T-38 wind tunnel, stagnation pressure is selected at will within the operating envelope (Fig.2) having in mind the available run time. Dynamic pressure is determined by the stagnation pressure and the Mach number. Static pressure is related to the stagnation pressure through isentropic equations and drops significantly below the atmospheric pressure at higher Mach numbers, to a minimum of about 6 kPa at Mach 4.
- In the atmospheric flight, static temperature is equal to ambient temperature at flight altitude. Stagnation temperature increases as the Mach number increases.
- In the T-38 wind tunnel, stagnation temperature is near to ambient temperature and drops by about 7 K during a run because of the adiabatic expansion of air in the storage tanks. Static temperature is related to the stagnation temperature through isentropic equations and drops significantly below the ambient temperature to a minimum of about 75 K at Mach 4. Besides, same as the stagnation temperature, static temperature drops slightly during a run.
- In the atmospheric flight at a given altitude, air velocity is directly proportional to the Mach number.
- In the T-38 wind tunnel, air velocity in the test section depends both on the Mach number and the static temperature of the flow. As the static temperature drops in a nonlinear way with the increase of the Mach number, the velocity does not change proportionally to the Mach number, being about 526 m/s at Mach 2 but only about 690 m/s at Mach 4 in the wind tunnel vs. 680 m/s and 1360 m/s at Mach 2 and Mach 4, respectively, in the atmospheric flight at low altitude.

Capability of the T-38 wind tunnel to reproduce flight Reynolds number

The capability of the T-38 wind tunnel to reproduce the flight Reynolds numbers of the test articles is illustrated by the examples of a model of a fighter aircraft at 1:18 scale and a model of a surface-to-air missile at 1:4 scale (scales of both models are typical for the tests in the T-38 wind tunnel). Table 2 and 3 show the relevant flow parameters for the two models, including Reynolds numbers, at the test conditions on the lower and upper limits of the operating envelope of the T-38 wind tunnel, and for the full-scale objects in the standard atmosphere at altitudes of 0 m and 9000 m. An arbitrary reference length of 1 m was selected for both full-scale vehicles, and scaled down for the wind tunnel models.

Table 2. Flow parameters relevant for the test of a 1:18-scale fighter-airplane model at Mach 2

Variable	T-38, min P_0	T-38, max. P_0	Flight, h=0 m	Flight, h=9000 m
Reference length, L[m]	0.056	0.056	1	1
Mach number, M	2	2	2	2
Reynolds number, $Re\times10^6$	1.3	5.7	47	19
Air velocity, U[m/s]	526	526	681	608
Stagnation pressure, P_0 [kPa]	200	870	793	241
Static pressure, P_{st} [kPa]	25	111	101	31
Stagnation temperature, T_0 [K]	310	310	519	414
Static temperature, T [K]	172	172	288	230

Table 3. Flow parameters relevant for the test of a 1:4-scale missile model at Mach 3

Variable	T-38, min P_0	T-38, max P_0	Flight, h=0 m	Flight, h=9000 m
Reference length, L [m]	0.25	0.25	1	1
Mach number, M	3	3	3	3
Reynolds number, $Re\times10^6$	7.1	22	70	29
Air velocity, U [m/s]	633	633	1021	912
Stagnation pressure, P_0 [kPa]	400	1250	3722	1131
Static pressure, P_{st} [kPa]	11	34	101	31
Stagnation temperature, T_0 [K]	310	310	807	643
Static temperature, T [K]	111	111	288	230

It can be seen from Table 2 that, same as in most wind tunnels, the flight Reynolds numbers of the high-speed airplanes cannot be reproduced in the T-38. Even at the maximum operating pressure and with the run time of only 6 s, the wind tunnel can only come close to the order of magnitude of the high-altitude-flight Reynolds number (5.9×10^6 in the wind tunnel vs. 19×10^6 in flight at an altitude of 9000 m). Wind tunnel capabilities are better regarding the tests of high-speed missiles: Reynolds numbers close to high-altitude flight values being achievable in the test (Table 3) and adjustable to a certain degree by variation of the model size. It may be noted (Fig.4) that many other wind tunnel facilities in the world fare much worse than the T-38 in this regard, flight Reynolds numbers being achievable only in several large-scale cryogenic facilities [3].

Fortunately, analyses and experiments, e.g. [4-6], have shown that, while some supersonic wind tunnel tests are affected by Reynolds number, in a number of test types the Reynolds number similarity is not an indispensable requirement, because it affects the viscous drag but only very slightly the pressure drag which is usually dominant in supersonic flight. A near-independence of the results from Reynolds number was confirmed, e.g. in the tests [7] investigating the stability and control characteristics of a clipped-delta-wing spaceplane, tests of the aerodynamic characteristics of a decelerator atmospheric-reentry body [8], etc. Numerous tests have shown that, if the wind tunnel Reynolds number is sufficiently high to induce transition to turbulent boundary layer on the model body and not downstream of the model base, both base drag and total drag will be only slightly affected by the Reynolds number [5,6], as illustrated in Fig.5 for several cone-cylinder models at Mach 2.41 [6]. Furthermore, the tests [6,9] have shown that, in a supersonic flow, transition to turbulent boundary layer occurs at Reynolds number (based on transition length) of about 2×10^6 to 8×10^6, depending on the Mach number, turbulence level in the wind tunnel, etc. This condition is easily met in the T-38 where the -minimum- Reynolds number for a typical model length of 1 m is of the order of 20×10^6 and the maximum one can be more than 100×10^6 (Fig.3). Therefore, base pressure and base drag in the supersonic tests in the T-38 are not likely to be sensitive to the dissimilarity between the test and the flight Reynolds number.

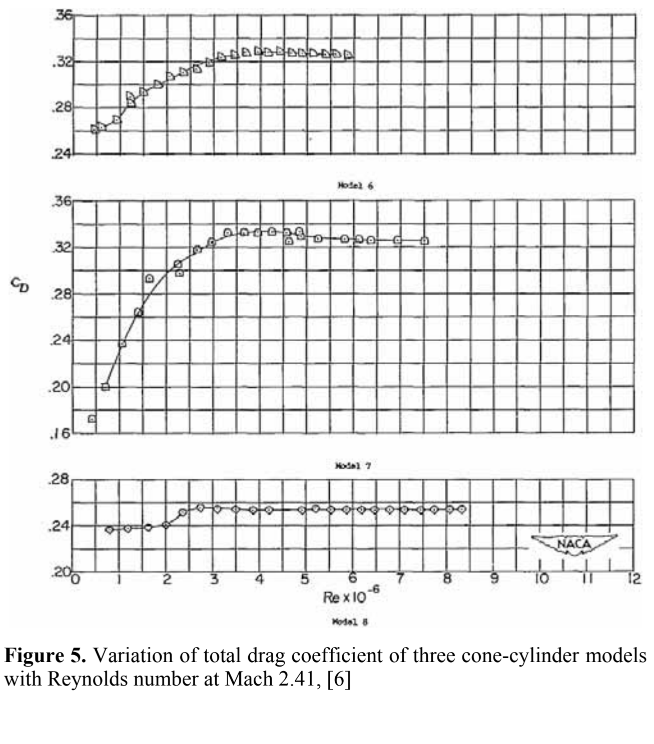

Figure 5. Variation of total drag coefficient of three cone-cylinder models with Reynolds number at Mach 2.41, [6]

Constraints to model size

A wind tunnel test engineer is inclined to perform a test with a model as large as possible, because many model-shape details are easier to produce at larger scale and also because the aerodynamic loads on the model will increase with the model size and may be easier to measure accurately with available instrumentation. Besides, an increase in the model size means an increase in the Reynolds number, however slight it may be, and a better simulation of the flight conditions. There are constraints, however, that limit the practical size of a model in any wind tunnel, including the T-38. They are related mostly to aerodynamic blockage, model support geometry and the shock-wave patterns in the supersonic test section.

Transonic blockage

Wind tunnel tests in the transonic speed range are very sensitive to interference from the wind tunnel walls, which restrict the curvature of the streamlines around the model, cause a reduction of the effective angle of attack, cause an increase in the effective Mach number, may cause longitudinal gradients of Mach number in the test section and, in a particularly badly-designed test, may cause local shock waves around the model, non-existing in free flight. Empirical, "rule-of-thumb", recommendations have long-since been developed [9-11] for limiting the size of the model in order to limit the interference to the acceptable levels. Those recommendations are relevant primarily for the tests in the transonic wind tunnels with porous or slotted test-section walls, and can be somewhat relaxed [12] for purely supersonic tests. However, it is an almost universal practice to test a wind tunnel model both in the transonic and supersonic speed range, so the size of a model for a supersonic test is likely to be determined on the basis of considerations related to the transonic tests. Suffice it to say that, according to the recommendations, the model size should be selected so that the frontal blockage of the model, i.e. the projection of the model contour along the line of free-stream velocity at zero angle of attack, should not exceed 0.5% to 1% of the cross-section area of the wind tunnel test section. Likewise, the model length should not exceed the height of the test section and the model wing span should not exceed 50% to 60% of the test section width. Significantly smaller values than these are often deployed if reliably interference-free test results are desired.

Model-support geometry

A model placed in the test section of a supersonic wind tunnel is usually mounted on a cylindrical sting-like support attached to an articulated mechanism that is placed downstream of the test section (Fig.6). The sting enters the model through a model base. It is well known that such an arrangement produces aerodynamic interference and modifies the flow about the base of the model [5]. In order to minimize this interference the diameter of the sting should be as small as possible while respecting structural safety. Also, the length of the cylindrical part of the sting, upstream of the conical fairing between it and the model support, should be as large as possible. It has been established that there exists "critical" maximum diameter and minimum length of the sting beyond which the interference becomes acceptably small and independent of the test conditions [9]. This critical sting length is about 2-5 model base diameter depending on the Reynolds number and Mach number, the length of three base diameters usually being a good choice if the model wake is turbulent [13]. Likewise, sting diameter of no more than 0.3 base diameters is recommended, but may be unacceptable because of the stresses induced in it by the aerodynamic loads acting on the model.

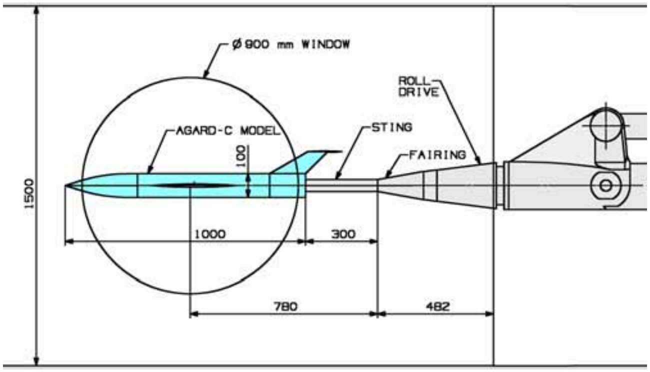

Figure 6. AGARD-C model [14] with a diameter D=0.1 m on the standard model support in the T-38 wind tunnel.

In the particular case of the T-38 wind tunnel, its pitch-and-roll model support is located so that the conical fairing of the roll drive [15] with sting-mounting flange protrudes into the supersonic test section (Fig.6) by about 0.48 m and is located, with small variations due to various sting designs, less than 0.8 m downstream of the centre of the test section (indicated in Fig.6 by the circular contour of the sidewall windows). If it is desired to place a model in the middle of the test section but also to obtain the recommended sting length of three base diameters, the length of a typical model with a slenderness ratio of 10:1 such as the AGARD-C [14] is limited to about 1 m. Failure to comply to this restriction results either in the nose of the model being placed too far upstream in the nozzle, where the flow is not uniform, or else in the base of the model being placed too close to the model support, resulting in an interference with the base pressure.

Yet another restriction on the model size for the T-38 wind tunnel exists if it is desired to perform a visualization of the flow around the entire model using the schlieren method [16], in which the case model length should be reduced to about 0.8 m so that it is completely visible in the 0.9 m-dia. circular sidewall window.

Wall-interference from the reflected shock waves

Wall interference in the supersonic speed range manifests itself in the form of the reflection of the shock waves, generated by the model, back from the test section walls towards the model.

For the tests in the supersonic speed range, model wing span and length must be limited to such value that the shock wave(s) generated by the model nose and reflected from the test section walls back towards the centerline, do not strike the wing tips or the rear part of the model, but pass behind its base (Figures.7 and 8). A distance of about 1.5 model diameters between the rear model parts and the shock wave is considered to be sufficient [9] to limit the effect of the reflected wave to model wake only.

Application of an exact computational procedure for determining the position of reflected shock waves relative to the model is usually impractical. Moreover, the problem becomes more complicated when the model is at a nonzero angle of attack or displaced vertically from the centre of the test section. In such cases, the behaviour of the bow shock wave cannot be readily determined before the test except by resorting to CFD methods which can be costly and time-consuming (although it may not remain so in the near future, with the rapid increase in availability of powerful computational resources).

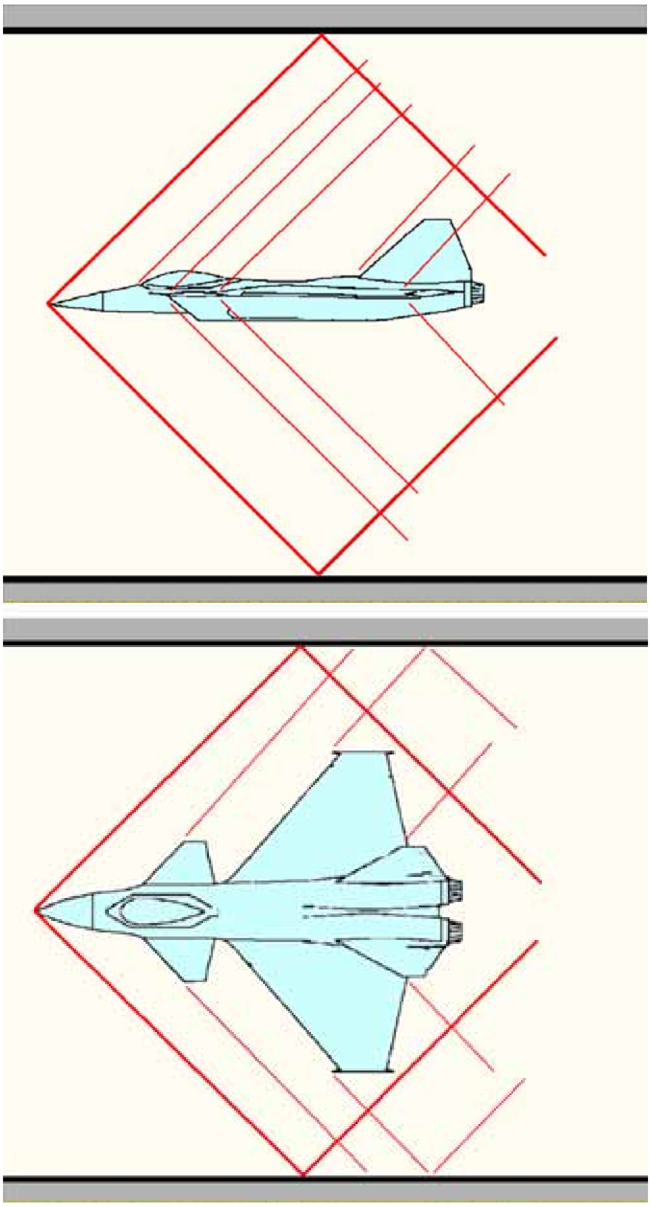

Figure 7. Shock waves generated by the airplane-model parts and reflected by the wind tunnel walls

However, by making few approximations, reasonable estimations of the allowed model length can be made. The bow shock waves are assumed to be reflected from a plane located at a distance equal to the boundary layer displacement thickness inside the wind tunnel walls. Also, it is assumed that the angle of the shock wave reflected from the wall is identical to that of the incoming shock wave, though this is not strictly true. The assumption that this angle is similar to the shock wave angle on a cone at zero angle of attack is reasonable, particularly at moderate angles of attack. A sufficiently accurate estimate of the maximum permissible model size can thereafter be obtained from the graphs such as in Fig. 8 or from the graphs showing positions and angles of the bow shock waves relative to the model noses of various shapes at various Mach numbers, such as in [17].

Wall interference from reflected shock waves results in the existence of a minimum supersonic Mach number at which a particular model can be tested, e.g. for a blunt-nosed 1 m-long missile model with a fin span of 0.2 m in the T-38 wind tunnel, and with a detached bow shock, the minimum Mach number for interference-free test is 1.5. For tests of long models at supersonic Mach numbers below 1.5 it is advisable to use the transonic test section with perforated walls which have a property of cancelling the reflected shock waves.

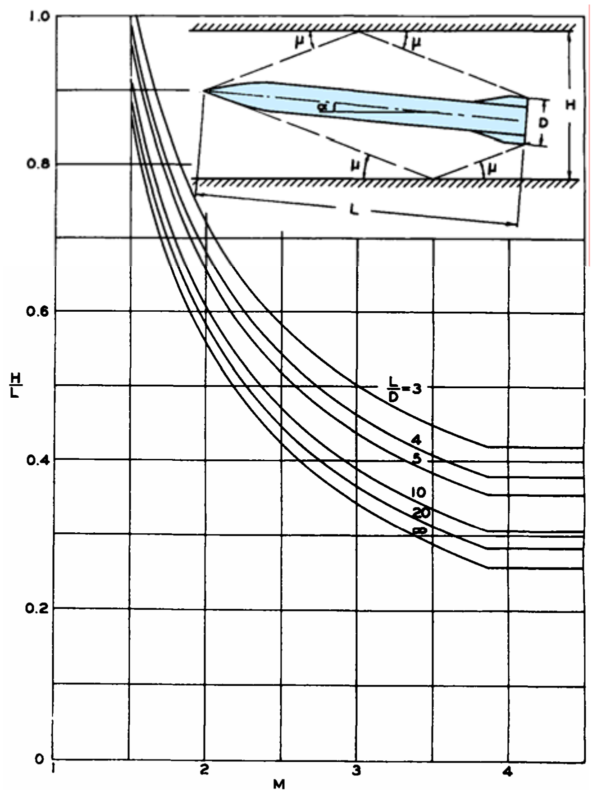

Figure 8. Limitations to missile-model length because of reflected shock waves, [18]

Summary effects of the model-size constraints

The summary effects of constraints on the model size in the T-38 wind tunnel are that the length of any model is limited on the upper side to approximately 1 m, which can sometimes be increased to about 1.2 m but with compromises. On the lower side, the minimum practical diameter of the model is usually about 0.04-0.05 m, determined by the finite size of the internal balances, model-to-balance- and balance-to-sting fasteners.

Wind tunnel flow conditions in relation to structural stresses

For geometrically and structurally similar models at identical flow conditions, structural stresses in the model components are almost independent of the model size. Aerodynamic forces on the model increase in proportion to the area of the model aerodynamic surfaces, i.e. proportionally to the square of model size. On the other hand, for a given aerodynamic force, tensional/compressive stress in a mechanical component of the model is inversely proportional to the cross-section of the component, which increases with the square of the model size, i.e. at the same rate as the aerodynamic forces. In a similar way, aerodynamic moments on a model increase with the size of the model surfaces and moment arms, i.e. with the cube of model size. For a given moment, bending stress in a component is then inversely proportional to the section modulus of the component, which is proportional to the cube of the component size, i.e. it changes with the model size at the same rate as the bending moments. Therefore, neither the tensional/compressive nor the bending stresses in structural components of the model will change when its size is changed. By a similar reasoning it can be shown that, for geometrically similar models and model support stings, the angle of deflection under aerodynamic loads does not depend on the model size. It should be remarked, however, that this is only approximately true because models geometrically similar on the outside but built in different sizes will usually have different interior mechanical designs. Besides, any wind tunnel facility has only a finite repository of the model support stings or internal balances so that, if a model dimensions are changed, the size, relative to the model, of the optimum available sting or force balance may change, as well as the stresses in those components.

While only weakly dependent on the model size, stresses due to steady aerodynamic loads on the model at a given Mach number are proportional to the dynamic pressure, which, in turn, is proportional to the stagnation pressure of the wind tunnel flow. There is also the issue of supersonic starting loads that are proportional to the minimum stagnation pressure required for starting the supersonic flow at a given Mach number. Both the steady and the transient loads can be a decisive constraint in selecting the flow conditions for a wind tunnel test.

Steady aerodynamic loads

The design concept of the blowdown wind tunnels calls for tests at high stagnation pressures (and, therefore, at high dynamic pressures) in order to increase the Reynolds number of the test according to Eq. (4). However, this capacity is limited by the increase of the stresses in the model, model support and in-model instrumentation caused by aerodynamic loads. This can be illustrated by the example [19] of the standard hypervelocity ballistic wind tunnel model known as HB-2 (Fig.9). The model is a cylindrical body of revolution with a blunted conical nose and a conical tail flare. The diameter of the standard sting for this model is 0.3 times the model forebody diameter, while the length of the sting is three forebody diameters. Although the model does not have aerodynamic lifting surfaces, the aerodynamic loads at high dynamic pressure in a wind tunnel test can exceed the safety limit of the sting. As shown in Fig. 10, normal bending stress in the root of the sting support at a constant angle of attack is proportional to the dynamic pressure. The slope of the normal-force curve of this model does not change much with the Mach number [20], so the analysis is valid at any supersonic Mach number. If the safety factor of at least ν=2 relative to the yield strength of the sting material is desired, and the tests are to be performed at high angles of attack up to 30°, the dynamic pressure in a test is limited to the values below 0.12 to 0.15 MPa (1 to 1.5 bar). If the angle of attack is limited to 15°, the dynamic pressure is limited to about 0.3 MPa (3 bar). All these pressures can be achieved at supersonic Mach numbers in the T-38 wind tunnel, and, therefore, stresses due to aerodynamic loads are a realistic constraint, even more so because, for winged models, they would be higher than those for the HB-2 model.

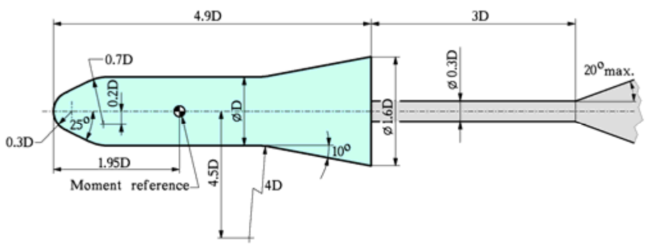

Figure 9. HB-2 standard wind tunnel model and sting support

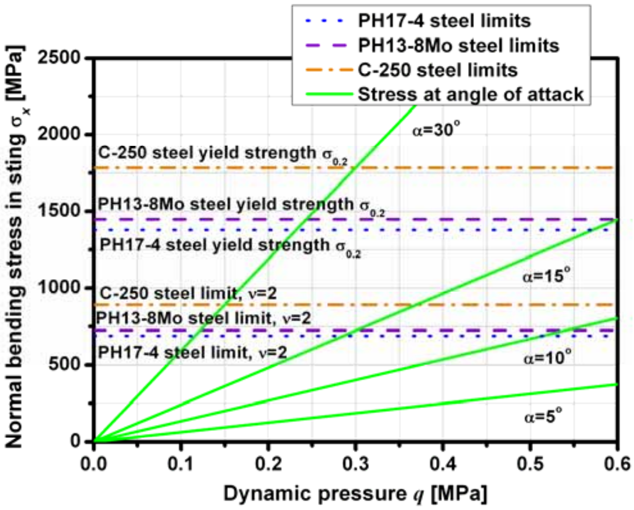

Figure 10. Stresses in the standard sting of the HB-2 reference model vs. strength limits of three high-quality steels

Supersonic starting loads

The operation of many supersonic wind tunnels, including the T-38, is characterized by transient phenomena occurring at the time of the establishing and stopping of the supersonic flow in the test section, when stochastic systems of strong normal and oblique shock waves pass through the test section (Fig.11). This can lead to a large local variation in the pressure and flow direction in the test section, subjecting the tested model to high aerodynamic loads that can exceed the magnitude of loads expected in a steady supersonic flow several times. Starting loads can cause unacceptably high stresses in the model and the measuring devices such as force balances (Fig.12).

Figure 11. Transient shock waves in the test section of the T-38 wind tunnel during the starting of the flow at Mach 2.5 in a test [21] of kinetic-energy projectile; 3-colour schlieren visualization

The magnitude of starting loads is mostly dependent on the Mach number and the stagnation pressure at the time of establishing or breakdown of the supersonic flow. It is of particular importance in the blowdown wind tunnels in which the supersonic flow starts at high values of stagnation pressures, thus inducing high starting loads. Among such wind tunnels is the T-38 wind tunnel. When it became operational, it became evident that minimum operating pressures were higher than anticipated, and resulted in higher than anticipated starting loads. An investigation of starting loads [22] was, therefore, performed during the commissioning of the wind tunnel and a number of subsequent supersonic tests in the facility. The investigation showed that the supersonic starting loads, when properly scaled according to the normal-shock theories [9,23], were of a similar magnitude as in other wind tunnels, and their large absolute magnitude was due to high minimum starting pressure of the wind tunnel. An empirical method for estimating the starting loads was established [24], based on the Boeing method [25]. Expected maximums of starting loads for the missile-like models in the T-38 wind tunnel (transient 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}) are estimated using the relations:

$$\begin{aligned} F_{TX} &= k_X S_X \\ F_{TY} &= k_Y S_Y \\ F_{TZ} &= k_Z S_Z \\ M_{TX} &= k_L S_Z B \\ M_{TY} &= k_M S_Z L \\ M_{TZ} &= k_N S_Y L \end{aligned} \tag{5}$$

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, $k_Y \dots k_N$ are empirically derived, Mach number dependent, "starting-loads pressure differentials" as in Fig.13. 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.

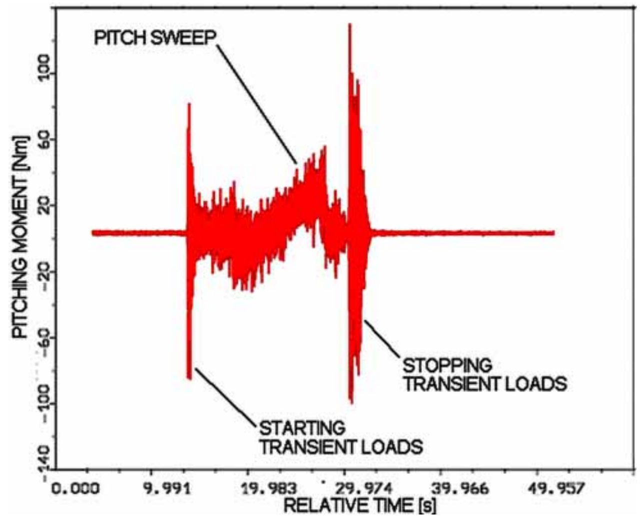

Figure 12. Plot of a typical unfiltered output from the pitching-moment component of an internal wind tunnel balance in a Mach 2.5 supersonic wind tunnel run

The supersonic starting loads are dangerous phenomena and their duration in a wind tunnel test should be minimized. This is achieved by selecting test conditions sufficiently above the minimum operating pressure of the wind tunnel, so that there is no danger of some disturbance eventually causing the wind tunnel to "misfire", remaining stuck in the startup phase of a run, or to repeatedly revert to subsonic flow during a run. As the nominal minimum operating pressures, as shown in Fig.2, are actually pressure -ratios- relative to 100 kPa atmospheric pressure, small changes of the atmospheric pressure can significantly affect the actual minimum start pressure, especially at Mach numbers 3 to 4. Therefore, a selection of stagnation pressures at least 50 kPa (0.5 bar) above the minimum start pressure is recommended for supersonic tests. Accidentally, such flow conditions correspond to test dynamic pressure of about 100 kPa (1 bar).

Supersonic starting loads also affect the selection of the flow parameters indirectly, through the load range of the in-model instrumentation such as the internal wind tunnel balances. As the starting loads are usually higher than the aerodynamic loads at steady supersonic-flow conditions, they are relevant for selecting an appropriate size and load range of the model support sting and internal balance. The balance selected on that basis is then very likely to be oversized relative to the steady aerodynamic loads, and the accuracy of measurements may suffer. This unwelcome effect can be minimized by selecting, for a wind tunnel test, the flow conditions at which the dynamic pressure will be as high as possible, so that the steady-flow loads will be closer to starting loads and the balance load range will be better utilized. In such case the dynamic pressure is limited by the structural safety of the model and the available run time of the wind tunnel, which decreases as the dynamic pressure is increased. This is illustrated in Fig.14 where a recommended [26] selection of stagnation pressures for a test of the HB-2 standard model at Mach numbers 1.5 to 4 is shown by the "diamond" symbols, relative to the operating envelope of the T-38 wind tunnel. The dynamic pressure is about 200 kPa except where further limited by the 20 seconds runtime required for a pitch-sweep run at angles of attack up to 15º.

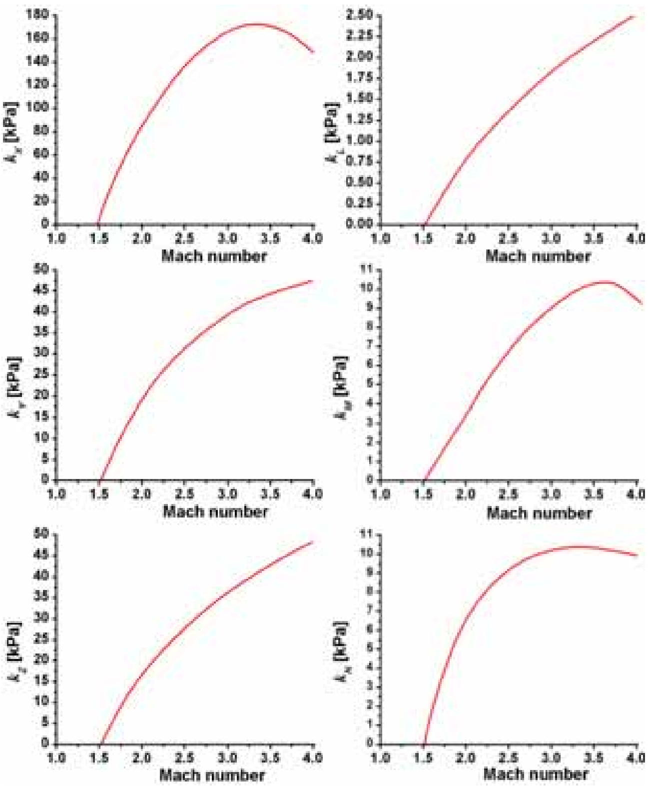

Figure 13. Pressure differentials for an approximate calculation of supersonic starting loads in the T-38 wind tunnel, [24]

On the other hand, if a wind tunnel test campaign comprises high-angle-of-attack polars, normal force and pitching moment at the maximum angles of attack (e.g. at 30º or more) and high dynamic pressure can exceed the starting loads. Therefore, in the high-angle-of-attack tests, lower dynamic pressure, closer to the lower operating limit of the wind tunnel, should be selected. In Fig.14 this is illustrated by the blue "dot" symbols for the test at 100 kPa (1 bar) dynamic pressure.

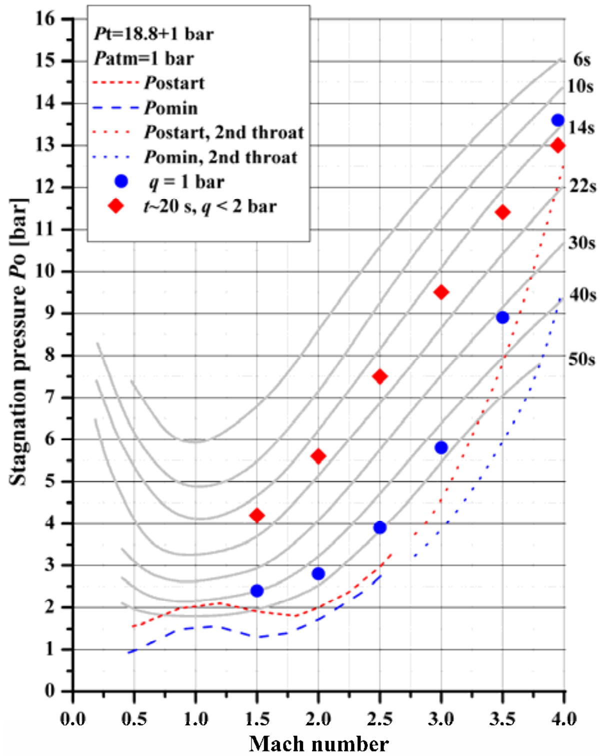

Figure 14. Operating envelope of the T-38 with supersonic test points at dynamic pressure of 100 kPa (1 bar) and at preferred elevated dynamic pressure with run time of cca. 20 s; [26]

Conclusions

It has been shown that the choices of the test conditions (model size, Mach number and stagnation or dynamic pressure) for supersonic tests in the T-38 blowdown wind tunnel are limited by several constraints.

Mach number in the supersonic test section is limited to the range from 1.4 to 4 by the mechanical design of the wind tunnel, though some further limitations, imposed by the starting loads, the safety of the model and instrumentation, and the interference from the wall-reflected shock waves may exist for very slender models and models having large aerodynamic lift and control surfaces, for which the use of the transonic test section with perforated walls may be needed at Mach numbers below 1.5.

The dynamic pressure is limited on the lower side by the minimum operating pressure of the wind tunnel, while on the upper side it is limited both by the structural safety of the model at high dynamic pressures and by the run time required to perform the desired test. In order to achieve better measurement accuracy with the robust instrumentation dictated by the staring loads, a high dynamic pressure may be selected so that the stationary loads come closer to the high starting loads, which are dependent on the minimum operating pressure. However, if the wind tunnel tests comprise high-angle-of-attack polars, steady aerodynamic loads at the maximum angles of attack may exceed the starting loads, in which case the test dynamic pressure should be limited to the lower values.

Additional constraints are exerted on the model size, which can be limited by the transonic blockage and wall interference considerations and the geometry of the test section and the model support.

The operating envelope of the wind tunnel and the size of the model limit the achievable Reynolds number in the missile tests to that of a high altitude flight, while it is by at least an order of magnitude too low in tests of airplane models. However, this is still considerably better than what is achievable in many other supersonic wind tunnels.

The summary results of the analysed overlapping constraints is that a choice of model size and flow conditions made for a particular supersonic test in the T-38 wind tunnel may not be just optimum; often it may be the only possible one at which the test may be executed. The achievable Reynolds number must then be accepted as it is. However, it has been shown that the results of a number of the high-Mach wind tunnel test types are practically independent of the Reynolds number, provided that it is sufficiently high for the boundary-layer transition to occur on the model body. Because of the high Reynolds number capability of the T-38, this condition is practically always met in tests of missile-like models, so such tests can be successfully performed. Also, there is not much point in extending the schedules for tests in the T-38 to include the investigation of the Reynolds number effects because such variations are not likely to be noticeable within the operating envelope of this wind tunnel.

References

[1] SHAPIRO,A.H.: *The Dynamics and Thermodynamics of Compressible Fluid Flow*, The Ronald Press Company, New York, 1953.

[2] PARYZ,R.,W.: *Recent Developments at the NASA Langley Research Center National Transonic Facility*, AIAA-2011-877, 49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 4-7 January 2011, Orlando, Florida, AIAA, Reston, US.

[3] HEFER,G.: *ETW – A Facility for High Reynolds Number Testing, IUTAM Symposium Transsonicum IV, Göttingen, Germany,* 2-6 September 2002, DOI 10.1007/978-94-010-0017-8, Springer Science and Business Media, B.V. 2002, pp. 157-164.

[4] KULFAN,B.M: *Reynolds Number Considerations for Supersonic Flight*, AIAA-2002-2839, 32nd AIAA Fluid Dynamics Conference and Exhibit, 2002, St. Louis, Missouri, US.

[5] KURN,A.G.: *Drag Measurements on a Series of Afterbodies at Transonic Speeds Showing the Effect of Sting Interf*erence, Aeronautical Research Council C.P., 1968, No.184.

[6] GRIGSBY,C.E., OGBURN,E.L.: *Investigation of Reynolds Number Effects for a Series of Cone-Cylinder Bodies at Mach Numbers of 1.62*, 1.93 and 2.41, RM-L53H21, Langley Aeronautical Laboratory, NACA, 1953

[7] BLAIR,A.B.Jr.: *Effect of Reynolds Number on the Aerodynamic Stability and Control Characteristics of a 55° Clipped-Delta-Wing Orbiter Configuration at Supersonic Mach Numbers*, NASA Technical Memorandum TM-X-3376, Langley Research Center, 1976.

[8] TRESCOT,C.D. JR., BROWN,C.A. JR. HOWELL,D.T.: *Effects of Reynolds Number and Model Support on the Supersonic Aerodynamic Characteristics of a 140°-Included-Angle Cone*, NASA Technical Memorandum TM-X-3019, 1974.

[9] POPE,A., GOIN,K.L.: *High-Speed Wind Tunnel Testing*, John Willey and Sons, 1965.

[10] GOETHERT,B.H.: *Transonic Wind Tunnel Testing,* AGARDograph 49, Pergamon Press, 1961.

[11] DAUGHERTY,J.C.: *NASA Ames Unitary Plan Wind Tunnel Blockage Recommendations*, NASA Ames, 1984.

[12] *High Speed Wind Tunnel and Test Systems Design Handbook*, Publication number AER-EIR-13552-E, Lockheed Martin Missile and Fire Control, 2002.

[13] HASTINGS,R.C.: *A Note on the Interpretation of Base Pressure Measurements in Supersonic Flows*, C.P. No.409, Royal Aeronautical Establishment, Bedford, 1958.

[14] *Wind Tunnel Calibration Models*, AGARD Specification 2, AGARD, 1958.

[15] VUKOVIĆ,Đ., ILIĆ,B., MILOSAVLJEVIĆ,M.: *Upgrade of the Roll-Angle-Setting Mechanism on the Model Support System in the T-38 Wind Tunnel in VTI*, OTEH 2011 4th International Conference on Defensive Technologies, 2011.

[16] RISTIĆ,S.: *Flow visualisation techniques in wind tunnels - optical methods* (Part II) Scientific Technical Review, ISSN 1820-0206, 2007, Vol.57, No.2, pp. 38-49

[17] VITIĆ,A., DAMLJANOVIĆ,D., VUKOVIĆ,Đ.: *Analysis of Bow Shock Waves from a Hemisphere-Cone Nose at Mach Numbers from 1.5 to 4 in the T-38 Wind Tunnel of VTI*, Scientific Technical Review, ISSN 1820-0206, 2013, Vol.63 No.4, pp. 40-45

[18] FERRI,A., BOGDONOFF,S.M.: *Design and Operation of Intermittent Supersonic Wind Tunnels*, AGARDograph AG-1, NATO Advisory Group for Aeronautic Research and Development, 1954.

[19] DAMLJANOVIĆ,D., RAŠUO,B., MANDIĆ,S., VUKOVIĆ,DJ., ISAKOVIĆ,J.: *Usability of Comparative Experimental - Numerical Test Cases With the HB Reference Model*, ICAS2014-0162, 29th Congress of the International Council of the Aeronautical Sciences (ICAS 2014), St. Petersburg, Russia, 7-12 September 2014, ISBN: 978-1-63439-411-6

[20] GRAY,J.D., LINDSAY,E.E.: *Force Tests of Standard Hypervelocity Ballistic Models HB-1 and HB-2 at Mach 1.5 to 10*, AEDC-TDR-63-137, Arnold Engineering Development Center, 1963.

[21] DAMLJANOVIĆ,D., MANDIĆ,S., VUKOVIĆ,Đ.: Computational fluid dynamics and wind tunnel determination of the aerodynamic characteristics of an axi-symmetric projectile with a conical tail flare. Scientific Technical Review, ISSN 1820-0206, 2011, Vol.61, No.3-4, pp. 49-55

[22] VUKOVIĆ,DJ.: *Investigation of Supersonic Starting Loads in the T-38 1.5m ×1.5m Trisonic Wind Tunnel at Žarkovo*, 19th Congress of the International Council of the Aeronautical Sciences, Anaheim, 1994, Vol.1, paper ICAS-94-5.1.4, pp. 162-171.

[23] MAYDEW,R.C.: *Compilation and Correlation of Starting Loads from Several Supersonic Wind Tunnels*, Report SC-4691 (RR), Sandia Corporation, 1962

[24] VUKOVIĆ,DJ., ĆURČIĆ,D., MARINKOVSKI,D., SAMARDŽIĆ,M., VITIĆ,A.: *Living With Supersonic Starting Loads in the T-38 Wind Tunnel*, ICAS2014-0138, 29th Congress of the International Council of the Aeronautical Sciences (ICAS 2014), St. Petersburg, Russia, 7-12 September 2014, ISBN: 978-1-63439-411-6

[25] SOHREIBER,R.E., PETERSON,L.D., RUSSEL,J.H.: *Test Planning Manual – Boeing Supersonic Wind Tunnel*, D2-22871, The Boeing Company, 1989.

[26] DAMLJANOVIĆ,D.: *Measurement Accuracy of Flow Field Parameters in Supersonic Wind Tunnels*, (in Serbian, Tačnost merenja parametara strujnog polja u supersoničnim aerotunelima) Ph.D. Dissertation, Faculty of Mechanical Engineering, University of Belgrade, 2013.

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Kriterijumi za izbor optimalnih uslova za nadzvučna ispitivanja u aerotunelu sa nadpritiskom

Prirodna želja aerotunelskog test inženjera je da planira i izvede ispitivanje koje će što je bolje moguće reprodukovati uslove u stvarnom letu. Geometrijska sličnost i jednakost Mahovih brojeva u letu i u aerotunelu su glavni zahtevi koji se postižu bez većih problema, ali smanjena veličina modela i granice operativne anvelope aerotunela sprečavaju postizanje željene sličnosti u pogledu Rejnoldsovog broja koji je uglavnom mnogo niži u aerotunelu nego u letu. Aerotuneli prekidnog dejstva sa nadpritiskom, kao što je T-38 u Vojnotehničkom institutu u Beogradu, su projektovani da postignu velike Rejnoldsove

brojeve povećanjem zaustavnog pritiska strujanja u radnom delu. Pokazuje se, međutim, da često nije Rejnoldsov broj odlučujući u izboru uslova ispitivanja na velikim brzinama, već su to druga ograničenja, vezana za veličinu modela, radni opseg raspoložive instrumentacije, raspoloživo vreme rada aerotunela, visoka aerodinamička opterećenja, itd.

Ključne reči: **aerodinamički tunel, aerodinamičko ispitivanje, supersonično strujanje, planiranje ispitivanja.**

Критерии выбора оптимальных условий для испытаний в сверхзвуковой аэродинамической трубе с избыточным давлением

Всегда существуют естественные желания инженеров-испытателей проводить испытания в аэродинамической трубе, чтобы планировать и проводить тестирование, и по возможности воспроизвести условия для полёта в реальном времени. Геометрические сходства и равенства чисел Маха в полёте и в аэродинамической трубе основные требования, которые достигаются без каких-либо серьёзных проблем, но уменьшенные размер модели и границы оперативной огибающей аэродинамической трубы препятствуют достижению желаемых сходств с точки зрения числа Рейнольдса, который, как правило, в аэродинамической трубе намного ниже, чем в полёте. Аэродинамические трубы прерывистого эффекта с избыточным давлением, такие как Т-38 в Военно-техническом институте в Белграде, предназначены для достижения больших чисел Рейнольдса с возрастанием давления торможения потока в испытательной секции. Оказывается, однако, что число Рейнольдса часто не является решающим в выборе условий испытаний на высокой скорости, но и другие ограничения, связанные с размером модели, с рабочим диапазоном доступных приборов, с доступным временем выполнения в аэродинамических трубах, с высокими аэродинамическими нагрузками и т.д.

Ключевые слова: **аэродинамическая труба, аэродинамические испытания, сверхзвуковой поток, планирования испытаний.**

Les critères pour le choix des conditions optimales pour les tests supersoniques dans la soufflerie aérodynamique à rafale

Le désir naturel d'un ingénieur travaillant dans la soufflerie aérodynamique est de projeter et de réaliser le test qui reproduira le mieux possible les conditions existantes au cours d'un vol réel . La similitude géométrique et l'égalités des nombres de Mach en vol et dans la soufflerie sont les exigences principales réalisables sans problèmes mais la taille réduite du modèle et les limites d'enveloppe opérationnelle empêchent la similitude voulue à l'égard du nombre de Reynolds généralement plus petit dans la soufflerie qu'en vol. Les souffleries aérodynamiques pressurisées à rafales, tel que T-38 à l'Institut militaire technique à Belgrade, ont été conçues pour atteindre les grands nombres de Reynolds en augmentant la pression totale du flux dans la veine d'essais. On a constaté cependant que le nombre de Reynolds n'était pas décisif pour le choix des conditions du test à grandes vitesses mais c'étaient des autres contraintes liées à la taille du modèle, la portée des instruments disponibles, le temps disponible de travail de la soufflerie, la haute charge aérodynamique, etc.

Mots clés: **soufflerie aérodynamique, examen aérodynamique, flux supersonique, conception de test.**