German-Dutch Wind Tunnels

Missile Testing

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Missiles and Aerodynamics

Tactical missiles and projectiles can be classified in eight different categories with each different Mach number requirements (see table inserted in diagram). In combination with the scale of the model to be tested this determines to a great deal the choice of wind tunnel. As flight speeds are predominantly transonic and supersonic, wind tunnels that qualify for these simulations need to cover Mach numbers ranging from high subsonic (Ma > 0.7) to hypersonic speeds (5 < Ma < 12). The high-speed wind tunnels available at DNW offer most of this potential in combination with supports that provide the right angle of incidence and roll for each Mach number range (see the Reynolds-Mach number diagram, Figure 1).

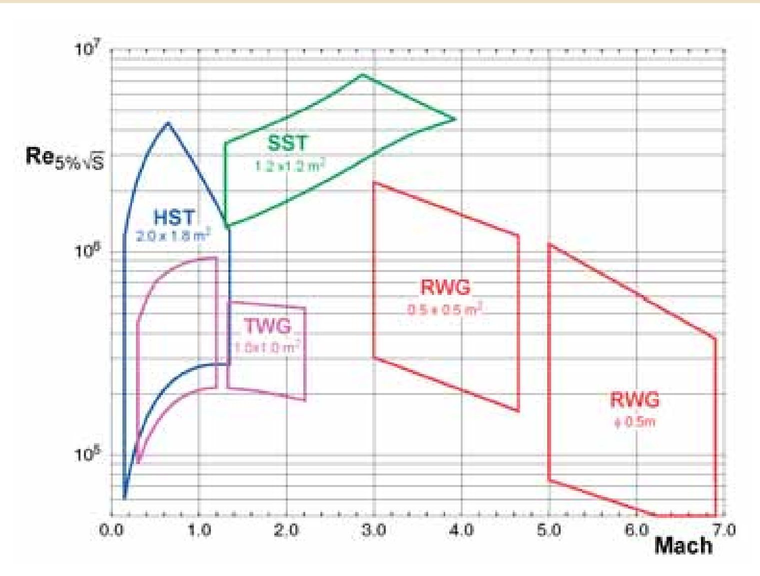
Test Objectives

Most missiles are characterized by extremely slender bodies with relatively small span wings and fins flying at relatively high angles of attack. The most appropriate solution for supporting missile models is a rear sting support. Like for most airborne vehicles, the classical aerodynamic test objectives comprise the determination of

- Integral forces and moments
- Stability derivatives
- Control surface effectiveness
- Hinge moments and loads
- Boat tail and nozzle drag
- (Unsteady) flow characteristics
- Deployable wings and/or fins
- Rolling and maneuver simulation
- Fluid structure interaction

To meet these objectives DNW, on a routine base, has a range of internal balances either of strain-gauge (Figure 2) or piezo type (Figure 3) and the pertaining data acquisition and processing software. In addition, electronically scanning pressure measurement equipment can be provided.

The introduction of new missiles and projectiles has generated new challenges to aerodynamicists. Modern missile designs are characterized by major trends in speed increase, higher agility and maneuverability. Moreover, new developments such as unconventional geometries (Figure 4), interference effects during launch from weapon bays or carrier vehicles, munitions deployment, stealth (radar cross section, RCS), jet and plasma control, smart materials, etc., are responsible for new trends in missile aerodynamics and consequently ask for sophisticat-



Type	Missile/ Projectile	Speed	Angle of Attack
A	Anti-tank (kinetic energy)	0.7 < Ma < 1.0 2.0 < Ma < 8.0	< |60|° < |15|°
B	Anti-ship	Ma > 2.0	< |30|°
C	Surface-to-air	0.7 < Ma < 1.5 1.5 < Ma < 4.0	< |60|° < |15|°
D	Air-to-air	1.0 < Ma < 2.0 1.5 < Ma < 4.0	< |45|° < |15|°
E	Air-to-ground (smart bombs)	0.7 < Ma < 1.0	< |30|°
F	Air-to-ground	1.0 < Ma < 5.0	< |15|°
G	Anti-ballistic	Ma > 5.0	< |15|°
H	Cruise	0.7 < Ma < 4.0	< |60|° < |15|°

Figure 1: Reynolds-Mach number diagram of the DNW wind tunnels used for missile testing

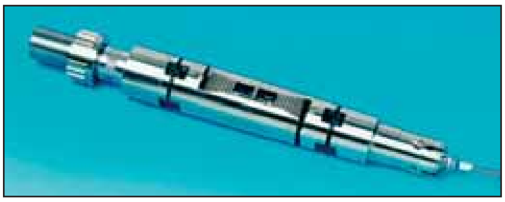


Figure 2: Internal strain gauge balance

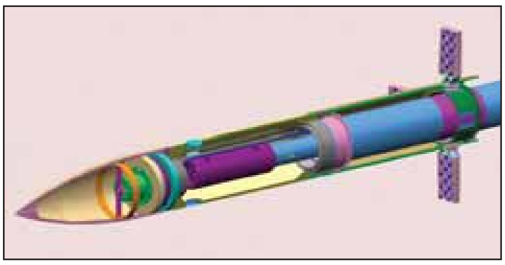


Figure 3: Free-to-roll DLR missile model mounted on a six-component piezo balance used in TWG

ed design methods and experimental verification. The list of test requirements includes:

- Integration of air intakes and coolers
- Thrust-drag bookkeeping
- High angle of attack aerodynamics
- Flow field surveys
- Effectiveness of lateral control jets
- Non-circular body aerodynamics
- Optimization of RCS contours
- Effect of pyrotechnical controls, etc.

DNW has worked out a number of new test techniques to cope with these new requirements in a practical and client oriented way. DNW is registered to the ISO 9001:2000 Quality Management System Standards and employs a strict client confidentiality policy.

Simulation Aspects

Beside the Mach number an important parameter for selection of the most appropriate wind tunnel is the Reynolds number, for missiles, typically based on the fuselage diameter. Circular body missiles are susceptible to cross-flow separation induced vortex flow and this affects not only acting forces, moments and rudder effectiveness but also determines the dynamic behavior, in particular the coning motion. Moreover, for missiles with air breathing propulsion systems, the vortex flow is of major influence on the air intake conditions. Although a generalized figure for all configurations is hard to give, it is customary to maintain for wind tunnel tests a minimum Reynolds number of not less than 3×10^5. This affects the scale and thus the minimum size of test model.

For most wind tunnel tests of missiles under high angle of attack it is customary to limit the maximum model diameter to 5% of the square root of the test section cross area to avoid blockage of the flow ($Ma < 1$) or shock reflections from the walls ($Ma > 1$) if the model becomes too long. This limits the maximum attainable Reynolds number of DNW's wind tunnels as shown in the Reynolds-Mach diagram in Figure 1.

Hence, apart from the Mach number and angle of attack range, selection of size and scale of the model are of importance in the choice of the most appropriate wind tunnel. Taking account of the relative sizes of the various vehicles, this leads to a classification as shown in the table of Figure 1.

The actual selection of the wind tunnel, however, is often a trade-off between client requirements, technical capabilities, program objectives and costs.

Figure 4: DLR missile model in the TWG

Testing Techniques

All missiles have in common that they are not recoverable but the initial flight principle of "fire and forget" is making place for "fire and control" to optimize the effect of the firing action and to avoid, if possible, collateral damage. As result of that all missiles today know some form of active control either by aerodynamic stabilizers or cross-flow jets or a combination of both. The latter is currently relevant for anti-tank (A) and surface-to-air (C) missiles, which due to their relatively short flying time require optimum control efficiency to quickly react to control inputs from sensors and rudders. For the determination of performance and stability characteristics at very large angles of attack (62°) and yaw (17°) of this size of models, the Transonic Wind Tunnel Göttingen (TWG) provides the ideal conditions up to Mach 2 (Figure 5).

As models become more voluminous due to internal instrumentation and remotely operated controls, the size of the test section might form a constraint. In that case DNW can offer the larger High-Speed Tunnel/Super Sonic Tunnel (HST/SST) in Amsterdam (Figure 6). This may become relevant for high Reynolds number tests of relatively large models of anti-ship missiles (B), air-to-air missiles (D), air-to-ground missiles (E) or cruise missiles (H) flying at speeds below Mach 4. For kinetic energy (A), ramjet (F) and hypervelocity missiles (G, H) DNW rec-

Figure 5: Mounting of an (air-to-air) missile model on a 25° cranked roll adapter in the TWG test section

ommends the Rohr-Windkanal Göttingen (RWG), which can attain speeds up to Mach 7.

Loads and Moments

A significant aspect of most wind tunnel tests is formed by the determination of loads and moments on the model and individual model parts such as wings, fins and control surfaces. The latter are required for design and construction of components, selection of materials, fabrication processes, definition of structure tests and powering of controls. Despite the extremely thin model parts the solution to determine these loads is found in the use of small two- or three-component strain-gauge balances, often integrated into the connecting structure. Design and construction of these balances is done in close consultation with DNW. Another novel technique is the determination by integration of pressure distributions on upper and lower surface from Pressure Sensitive Paint (PSP) data.

Integral force and moment coefficients are typically provided in the vehicle flight axes or stability axes system, while hinge load and moment coefficients are given in the local balance axes system.

Propulsion Integration

In general, two types of propulsion may be distinguished, rocket boosters and air breathing engines. As for the first it is customary to separate the nozzle from the metric part to get the pure aerodynamic interference effects and add these to the clean drag and propulsion forces. The second is more complicated and for a correct thrust-drag bookkeeping requires an assessment of the intake interference contribution. The internal flow is either free or driven by an ejector located between the intake and the missile base. The flow rate is adjusted by a throttling cone (Figure 7) and the mass flow and loss of momentum are determined from measurement data of internal calibrated pressure and temperature rakes.

For calibration the air intake duct may be connected to a vacuum tank or mounted in the model Engine Calibration Facility (ECF). The ECF consists of a tank, which is vacuumed by means of suction pumps, and has a balance for determination of internal thrust forces. All facilities have available compressed air for blowing or suction.

Optical Techniques

Flow visualization is indispensable for a better understanding of the vehicle's behavior and the measured physical quantities. Moreover, the rapid progress in Computational Fluid Dynamics has created new requirements for improving physical flow

Figure 6: A model of an air-to-ground smart bomb in the HST

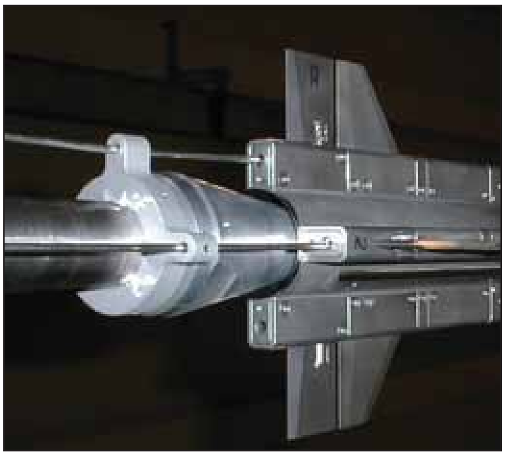


Figure 7: Throttling cone for adjustment of internal flow

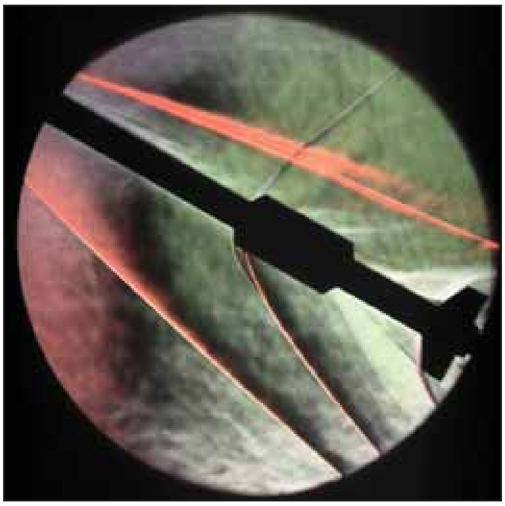


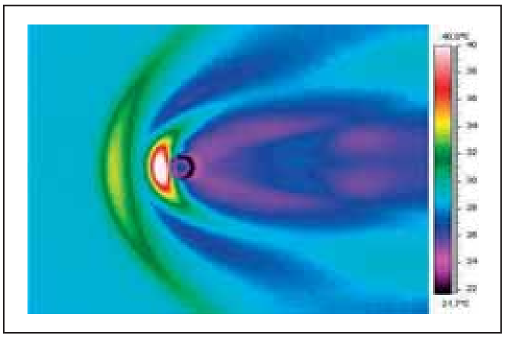
Figure 8: Schlieren picture of a missile in the TWG

models to aid in the (semi-)empirical design process and for validating the calculated flow properties. Both objectives have led to the advent of new measuring and visualization techniques in addition to already existing methods as schlieren (Figure 8), shadowgraph interferometry of shock and expansion waves and oil flow visualization of surface streamlines.

Infrared Imaging (IRI)

Lateral jets used for improving the controllability and thereby the agility of missiles, cause complex interactions with the external flow. Understanding of the flow mechanisms is crucial to avoid that such applications result in loss of lateral propulsive forces and disturb the pitch and rolling moments. Figure 9

Figure 9: Infrared image for heat transfer determination around a lateral jet at Mach 5 in the RWG



shows a top view of an infrared image of heat transfer on a model with a lateral jet at Mach 5 (flow coming from the left). The study aimed at analyzing the effects of various upstream devices on the flow characteristics.

Pressure Sensitive Paint (PSP)

Apart from a better understanding of flow mechanisms, the application of PSP has the benefit of offering a rapid determination of loads. By conducting a full 180° roll of the model, the test section cameras are able to make a full registration of the paint emitted light. Processing of the data gives the local surface pressure. The method can be applied to rolling models as well at both transonic and supersonic speeds.

Particle Image Velocimetry (PIV)

This technique is routinely available at Mach numbers < 1 to visualize and quantify complex flow fields around a test object. The technique is particularly useful for studying interference effects due to vortex shedding from missile components such as fuselages, canards, strakes, wings and control mechanisms and helps to understand hysteresis effects by pitching and rolling of models in opposite directions.

Beside the highlighted techniques IRI, PSP and PIV, on a routine base DNW can offer laser light sheet pictures, schlieren pictures, oil flow visualization and five-hole probes to visualize and quantify flow phenomena.

Maneuver Simulation

Dynamic simulation of rolling and yawing characteristics is often required to determine unsteady loads and to obtain better insight into hysteresis effects on performance and stability. It puts high demands on wind tunnel rigs if the roll and yaw rates of the vehicle are high and the scale factor requires an inversely proportional roll or yaw speed to realize equal conditions for the external flow. Special instrumentation such as accelerometers is necessary to separate inertia forces from integral aerodynamic forces. For these tests TWG can be equipped with a rig capable of dynamic simulation of roll rates up to 20°/s with specially designed light weight rolling models mounted to either strain-gauge or piezoelectric balances. By flanging the rig to the sting angles of attack are realized up to 32°. The rolling motion can be either free (only aerodynamically driven) or forced by a motor (constant, oscillatory, or transient). By comparison to steady models it is possible to predict the roll damping. The free roll mode makes it possible to find stable roll frequencies and to collect input data for dynamic calculations.

Scope of Services

- Consultancy with respect to simulation, scaling and sizing of missile models and adaptation of air intakes
- Provision of modern measuring techniques and instrumentation like PSP, infrared imaging and flow visualization (PIV)
- Provision of balances (internal and external)
- Measurement quality control by on-line data acquisition and processing and display of test data during the test
- Off-line data processing, formatting and secure data transmission to users all over the globe
- Post test evaluation by expert team and data analysis and interpretation (at request)

Wind Tunnels Operated by DNW

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