Wind-tunnel scales for measuring aerodynamic forces on the hypersonic configuration ELAC I

by Armin Stromberg and Egbert Schmitz

In the Special Collaborative Research Center "Fundamentals of Design of Aerospace Planes" at Aachen University of Technology supported by the German Research Association (DFG) the requirements for the construction of reusable space aircraft were investigated. The development of this type of aircraft demands knowledge of the lift and drag, quantities which can be determined on scale models in a wind tunnel using a wind-tunnel balance based on strain-gage technology. In the tunnel used here, velocities of between Mach 0.3 and 3.6 can be simulated. The article explains the relevant parameters, describes the working principle of the balance and discusses an example of the results.

Introduction

The objective under the special research project "Principles for the design of space aircraft" set up at the RWTH Aachen is the development of possible methods for transporting pay loads into space. The take-off capability for a space transporter on a conventional runway demands that it is capable of flight at relatively low subsonic velocities, whereas the inflight velocity at the separation of the stages should be about eight times the speed of sound, i.e. Mach 8. The design configuration in this velocity range is being investigated under the project at Aachen.

The main concept under consideration is the ELAC I hypersonic design. **Figure 1** shows a view of the aircraft in three elevations. It shows a delta wing shape with a cross-section which is formed from two semi-ellipses. The largest thickness is situated at about 67% of the overall length. This shape enables the installation of a partly integrated balance. In the region of the pointed trailing edge two rudders are situated at the sides for stabilization and steering.

An significant part of experimental investigations into aerodynamically flying aircraft and space vehicles is the determination of forces and moments with the calculation of the lift and drag being of fundamental importance. Due to reasons of cost, wind-tunnel investigations are usually carried out in the development stage.

This article describes a wind-tunnel balance which is used in the 40 cm x 40 cm (16 x 16 in) wind tunnel at the Institute for Aerodynamics at the Rheinische Westfälische Technische Hochschule (RWTH) Aachen [1,2]. Mach numbers between 0.3 and 3.6 can be simulated with this tunnel. The wind tunnel operates on an intermittent basis, i.e. a reservoir system is evacuated and after a valve is opened, dried air is drawn through the measurement section from a supply balloon. The charging period for the tunnel is about eight to ten minutes whereas the experimental time available is only about three to five seconds.

The velocity range mentioned above represents the link between the subsonic velocity during the take-off and landing phases and the region of hypersonic velocities. With experiments at supersonic velocities compression shocks occur in the measurement chamber during the formation and decay of the flow. These shocks signify a high dynamic load on the model and its mounting.

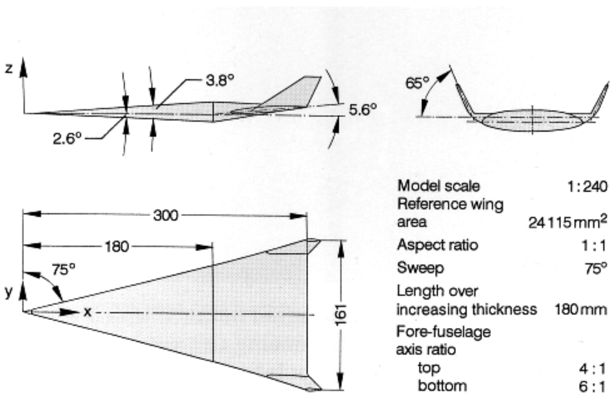

Fig. 1: Shape and dimensions of the model space transporter under test.

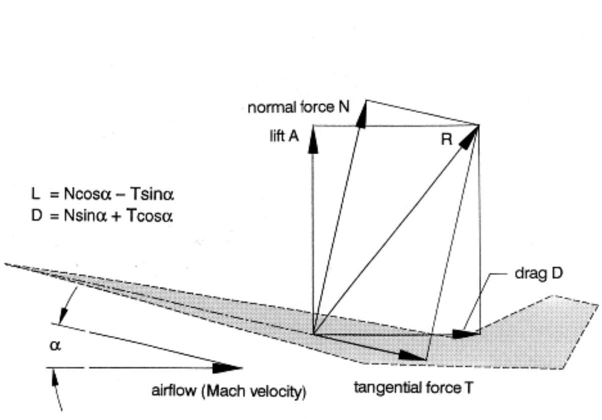

Fig. 2: Coordinate systems relative to the aircraft and relative to the airflow.

Definition of terms

In the mathematical description of aircraft there is, as shown in **Fig. 2**, a coordinate system relative to the aircraft and one relative to the airstream. In the former system the forces are resolved tangentially in the direction of the aircraft axis (tangential force *T*) and normally to it (normal force *N*). In the second system the drag *D* is defined parallel to the oncoming flow and the lift *L* normally to it. Normal and tangential forces are found from the measurement and converted by computation to the lift and drag using the angle of attack α. To be able to compare different aircraft, the flight performance is characterized, together with other quantities, by the following:

Lift coefficient $$c_l = \frac{L}{qS} = \frac{L}{\frac{1}{2}\rho_\infty v_\infty^2 S}$$

Drag coefficient $$c_d = \frac{D}{qS} = \frac{D}{\frac{1}{2}\rho_\infty v_\infty^2 S}$$

Pitch moment coefficient $$c_m = \frac{M}{ql_\mu} = \frac{M}{\frac{1}{2}\rho_\infty v_\infty^2 S l_\mu}$$

The dynamic pressure *q* depends on the velocity and density and is determined during the measurement in the wind tunnel. The lift and drag are produced as the resultant of the normal and tangential forces; the coefficients c_l and c_d are found by calculation from the quantities *L* and *D* together with the measured dynamic pressure. Pitch is the term used to describe the rotational motion of an aircraft about the transverse axis (in the direction of the wing span). The pitch moment coefficient c_m is normalized with a wing reference length l_μ.

The measurement task

The measurement task consisted of determining the lift, the pitch moment associated with the lift and the drag at various subsonic and supersonic Mach numbers and at attack angles between $-3° \le \alpha \le 10°$.

Apart from its magnitude the full description of the normal force also requires the point at which the force acts (center of pressure). Once both of these have been found, a moment can be calculated at any geometrical point. This moment is termed the pitch moment and enables conclusions to be drawn about the aircraft's maneuverability. The same applies to the tangential force which has its line of action in close approximation to the model's center of gravity.

One difficulty in the measurement of the normal and tangential forces is that they can differ in magnitude by a factor of up to a decade. For the measurement equipment this means that for the demanded sensitivity in one direction, the construction must be so rigid that a force ten times larger and acting perpendicular to it can be tolerated.

Measurement equipment

Principle of balance operation

A strain-gage balance, which was partially integrated into the model, was developed for the measurement [3]. The balance measures the deflections due to bending moments. The main components, made in a special steel, are the trapezoidal balance frame and the post which supports the model. The outer frame is cast in plastic together with the model in synthetic material (Araldite). The vicinity of the tangential-force bending beams lying transverse on the model support and the complete post are recessed to allow free deflection. **Figure 3a** shows the arrangement of the measuring points with their single strain gages of the type LY410.6/120. **Figure 3b** illustrates the model with the cover removed.

Due to the design of the tangential-force bending beams the small tangential forces are combined with large leverages. The position of these beams was selected based on knowledge obtained from previous investigations such that its center-line coincided as far as possible with the center of pressure. If the center of pressure deviates from this position, which is in fact the case depending on the Mach number and the angle of attack, a moment is produced that also twists the bending beam.

Arrangement and wiring of the strain gages

A full bridge was installed for the determination of the tangential force *T* as depicted in **Fig. 3a**. The strain gages were wired such that with the loading of this measurement point by a tangential force the magnitudes of the strains on the individual strain gages are added. A second full bridge M and two half bridges N_V

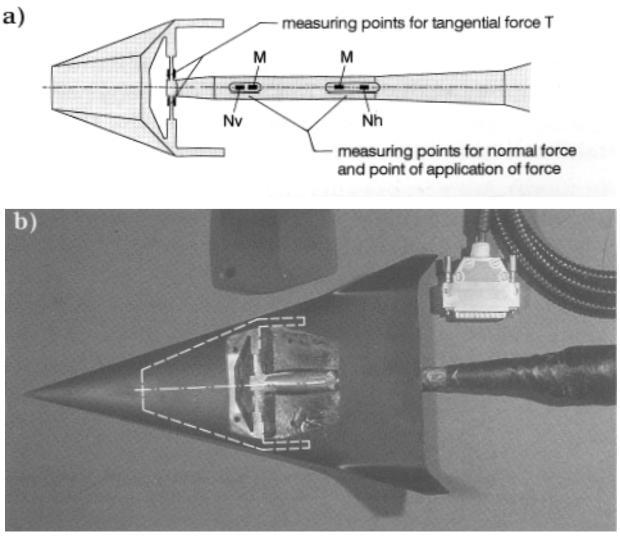

Fig. 3: Design of the wind-tunnel balance which was integrated into the model, showing the arrangement of the strain-gage measuring points.

a) Sketch of the design.
b) Photograph of the model with the cover removed.

and N_h, were fitted as shown in **Fig. 3a** to measure the strains on the upper and undersides of the model support which were produced by the bending moment.

With increasing leverage the expected normal force produces a linear rise in the bending moment. Only two measuring points are needed to determine the slope of the bending moment curve and its zero crossover. The third measuring point was applied for reasons of redundancy and as a control on the other measurements.

Calibration curves and interference

The calibration of the separate measurement configurations on the balance took place outside the wind tunnel in a device made for this purpose. Here, defined forces and moments were applied with the aid of weights acting through rope and pulleys and the relevant measurements were recorded.

In contrast to the wind-tunnel test, "artificial errors" occurred during the calibration due to the application of mechanical force. This is explained below using the calibration of the normal force as an example.

It cannot be ascertained without substantial effort whether the forces are transferred exactly perpendicular to the model axis. Also, the deflection of the balance causes a skewing of the calibration arrangement. Whereas the effects of the relatively small resulting angular error on the normal force are themselves only slight, the influence on the more sensitive tangential-force measuring point cannot be neglected.

The error at the measuring point *T* due to the stated skew position increases linearly with the force and trigonometrically with the skew angle. Therefore, both effects can be quite easily found separately by computation and compensated. The causes of this type of interference do not occur during the wind-tunnel test, but must be considered during calibration. **Figure 4a** shows the signals from the four measuring points during loading by a normal force with a line of action through the middle of the measuring point *T* (eccentricity $e = 0$). The trace of the tangential-force signal is in this case *(e*= 0 mm) only determined by the skew. If e is not equal to zero, the normal force also produces a torsion moment which is transferred by crosstalk to the measuring point *T* and must be considered during the calibration and the test itself. The same applies to the application of a pure pitch moment.

The application of tangential forces has an effect as shown in **Fig. 4b** only on the measuring point *T* provided for it. The application of side forces has no influence on any of the measuring points.

The changes in the angle of attack $\Delta\alpha$ occurring during the calibrations and due to the deflection of the complete system was measured with the aid of dial gages. Here, the magnitude and the point of action for the normal force were systematically varied. The overall deformation was composed of the deflection of the model support with a corresponding change in the angle together with the twisting of the model about the bending (torsion) beam at the measuring point *T*.

After taking into account all the errors and interference effects it transpired that the calibration curves could be substituted mathematically with good correlation by regression lines (r > 99.99%). Due to this linear behavior of the balance, the computational treatment was substantially simplified. The reactions at the individual measuring points and the angular changes could be described by a linear system of equations with the parameters *N,* the point of action of force e and the tangential force *T*.

Measurement results

During supersonic flow very strong instabilities in the form of compression shocks and expansions occur. These are linked to high dynamic loads. **Figure 5** shows the typical signal traces from all measuring points for an oncoming flow with a velocity of Mach 2. After opening the quick-acting valve in the wind tunnel, a compression shock wave passes through the measurement chamber. This can be seen from substantial over-

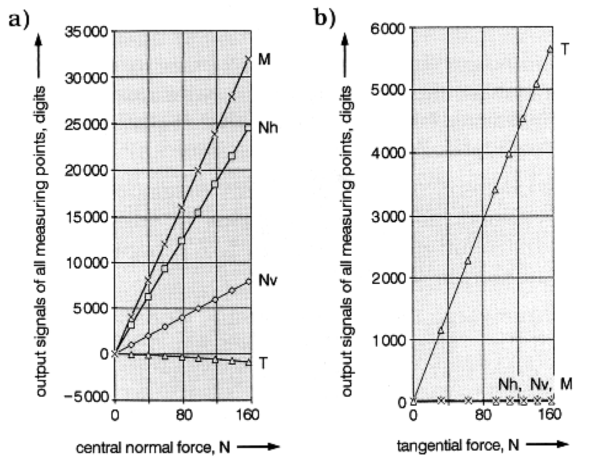

Fig. 4: Calibration curves for the measurement configurations:

a) under the action of a central normal force,
b) under the action of a tangential force.

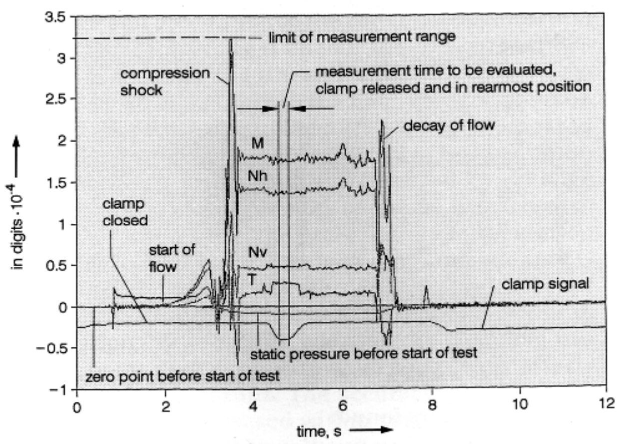

Fig. 5: Typical signal traces from the measuring points with an airflow velocity of Mach 2.

shoots on the signals. Due to the averaging of the signals over time, the actual peak that occurs cannot be read. In the example shown even the limit of the measurement range has been reached. In preliminary tests this strong dynamic load caused the trailing edge of the model to impinge on the support post and threatened to destroy the model. Therefore, a damping device in the form of a clamp was necessary which held the model firm while the flow built up and decayed. The position of the clamp was measured by a displacement transducer and shown on the measurement plot. Then the time interval for the evaluation can be defined by positioning the opened clamp at the point remotest from the model on the downstream side. The evaluation is based on the measurements for this time interval.

During the wind-tunnel tests the indicated values from the measuring points were recorded and then from these an average found for the measurement period per signal. From these signal quantities and with the aid of the system of equations, *N*, *T* and e are found and the angle of attack later corrected by computation.

As an example, the results for the tests at Mach 0.6 are shown. **Figures 6 and 7** illustrate the processed measurement results in graph form. Figure 6a shows the lift coefficient in relation to the angle of attack. At low angles the linear relationship can be recognized. At angles from about 6 to 8 degrees a non-linear section takes over which is linked to the formation of a vortex system and the ensuing low pressures. The zero-lift angle, i.e. the angle at which no lift is produced, is about α = 2.5 degrees. **Figure 6b** shows the relationship between the lift coefficient and the drag coefficient.

It can be seen that the zero-lift angle coincides with the lowest drag. This is because to produce lift from the flow (as with a sailplane) or from the engine (as with a motorized airplane) power must be extracted, which is equivalent to a so-called induced drag. The value of the minimum drag coefficient combines pressure and friction drags which are, among other factors, dependent on the body shape and surface texture. For larger angles of attack the drag increases.

The curve of the lift coefficient versus the pitch moment coefficient is reproduced in **Fig. 7a**. The quality

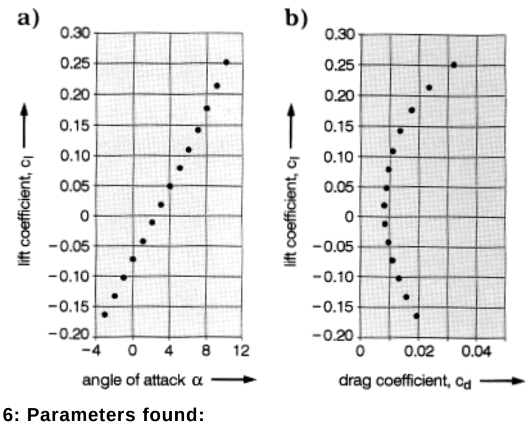

Fig. 6: Parameters found:

a) lift coefficient as a function of the angle of attack,
b) relationship between the lift and drag coefficients (measure of aerodynamic quality).

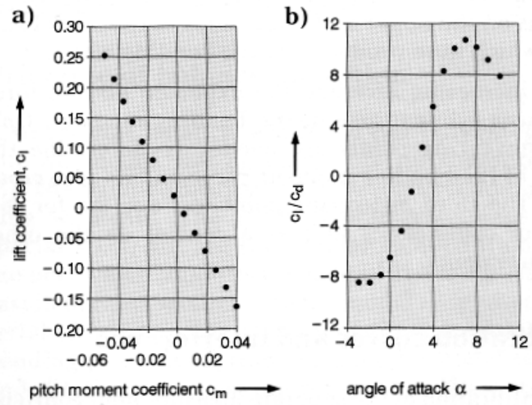

Fig. 7: Other evaluation results:

a) Graph of the lift coefficient against the pitch moment coefficient (measure of inflight stability)
b) Ratio of the lift and drag coefficients against the angle of attack (maximum for most efficient cruising).

of the stability in flight can be taken from this graph. An aircraft flies in a stable manner when changes to the angle of attack in the fully trimmed condition due to disturbances (e.g. gusts) are compensated by a restoring moment. A moment that increases the angle of attack (tail heavy moment) is defined positively. In the case shown here, the negative slope of the curve indicates stability. If the angle of attack and therefore the lift coefficient increased due to a disturbance, a negative pitch moment restores the situation, i.e. the nose drops. For a more detailed aerodynamic assessment, knowledge about the position of the center of gravity is also required, but not considered here. A different type of conclusion can be drawn from **Fig. 7b**. Here, the ratio of the lift to drag is plotted against the angle of attack. As can be seen, this ratio is particularly favorable at an angle of attack of 8 degrees and this can be used as the design point for an aircraft (e.g. efficient cruising).

References

[1] Limberg, W, Stromberg, A.: Pressure measurements at supersonic speeds on the research configuration ELAC I; Z. Flugwiss. Weltraumforsch. Vol. 17, No. 2 (1993).

[2] Stromberg, A.,Limberg, W: Measurements of pressures, forces and moments at subsonic and supersonic speeds on ELAC I; Z. Flugwiss. Weltraumforsch. 20 (1996).

[3] Stromberg, A.: Experimentelle Untersuchungen an der Hyperschallkonfiguration ELAC I bei Unter- und Überschallanströmung; Dissertation RWTH Aachen (1994).

Dr.-Ing. Armin Stromberg, formerly with the Aerodynamisches Institut, RWTH Aachen, is now with WPC Consult, Munich and **Dipl.-Ing. Egbert Schmitz** is a member of the Aerodynamisches Institut (Director: Prof. E. Krause, Ph.D.)