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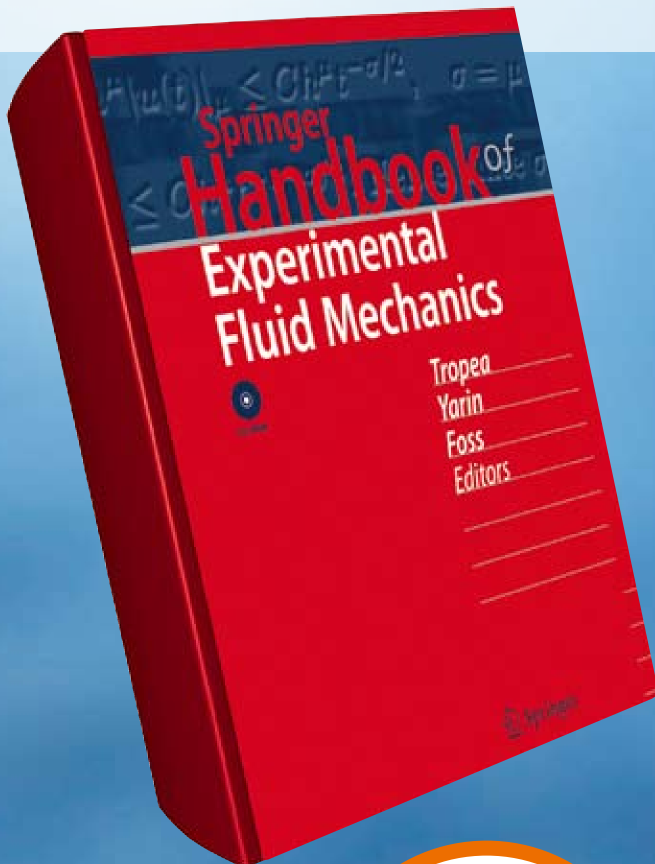

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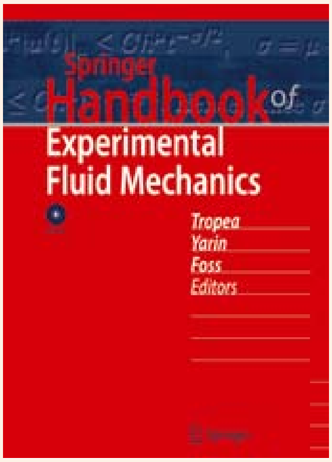

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Springer Handbook of Experimental Fluid Mechanics

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This Handbook consolidates authoritative and state-of-the-art information from the large number of disciplines used in Experimental Fluid Mechanics into a readable desk reference book. It comprises four parts: Experiments in Fluid Mechanics, Measurement of Primary Quantities, Specific Experimental Approaches, and Analyses and Post-Processing of Data. It has been prepared for physicists and engineers in research and development in laboratories in universities, in industry and in government research institutions or national laboratories. Both experimental methodology and techniques are covered fundamentally and also for a wide range of application fields. A generous use of citations directs the reader to additional material on each subject.

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- ► The boundary-value problem
- ► Measurement of primary quantities
- ► Specific experimental approaches
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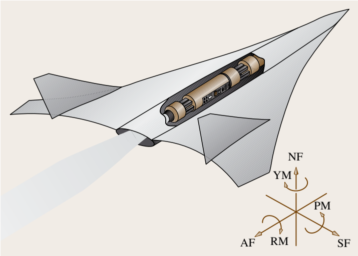

Fig. 8.6 Definition of wind axis system in the USA

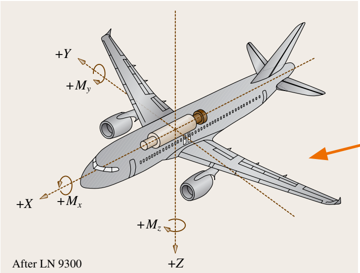

Fig. 8.7 Definition of model-fixed axis system in Europe

flow direction. The lift force is generally defined as the force on the model acting vertical to the main flow direction whereas the drag is defined as the force acting in the main flow direction. This definition is common all over the world. However, the definition of the positive direction of the forces is not universal. Whereas lift (normal force) and drag (axial force) are defined positive in the USA (Fig. 8.6), in Europe (Fig. 8.7) weight and thrust are defined as positive in the wind axis system.

To form a right-hand axis system, the side force in the USA has to be positive in the starboard direction. The definitions of the positive moments do not follow the sign rules of the right-hand system. The pitching moment is defined as positive turning right around the y-axis, but yawing and rolling moments are defined positive turning left around their corresponding axes. This makes this system inconsistent in a mathematical sense.

Table 8.1 Definition of positive axis direction

Balance Axis System	Name of Component	European	USA
		Positive direction	Positive direction
X	Axial force	In flight	In wind
Y	Side force	To starboard	To starboard
Z	Normal force	Down	Up
M_x	Rolling moment	Roll to starboard	Roll to starboard
M_y	Pitching moment	Turn up	Turn up
M_z	Yawing moment	Turn to starboard	Turn to starboard

The European axis system is a consistent with the right-hand system and the definition is based on a standard given by DIN-EN 9300 or ISO 1151. A balance which always stays fixed in the tunnel, and relative to the wind axis system, always gives the pure aerodynamic loads on the model.

In the case of the model-fixed axis system, the balance does not measure the aerodynamic loads directly. The loads acting on the model are given by the balance and the pure aerodynamic loads must then be calculated from these components by using the correct yaw and pitch angles. The difference between American and European definitions of the positive direction remains the same in this case.

Specification of Balance Load Ranges

Before a balance can be designed, the specifications of the load ranges and the available space for the balance are required. This is a challenging step prior to the design of a balance since cost and accuracy considerations must be made long before the first tests are performed.

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sting is attached through the after body of the fuselage. In some cases the vertical fin (Fig. 8.12) is also used to support the model.

For tests which require the free flow around the after body two sting setups (Fig. 8.14) can be used. In such cases one balance is needed inside each sting. To determine the influence of the tail sting two measurements are performed, one with a dummy tail sting and one without the dummy tail sting in place.

Today the support of the model by wires is seldom used anymore (Fig. 8.15). In such cases the balance must be an overhead external balance and the model hangs from the balance through wires. To keep the model stabile in the tunnel, the system must be preloaded by weights (Sp), which are usually dampened in a water basin under the test section. The advantage of such a model support is the very low interference on the flow around the model.

In Fig. 0-96 the model hangs upside down in the tunnel minimizing the preload. This is beneficial since the balance cannot measure loads smaller than the preload. Sometimes modern wind tunnels test the model upside-down position in order to preload the balance in the lift direction. This way the lift generated by the model contributes to the preload such that the balance signal does not pass through zero as in a normal setup. In such a way the additional nonlinearities associated with the zero-load regime can be avoided.

Mounting Interference

The aerodynamic loads on the model itself are always affected by the presence of the model mounts. The mounting loads themselves are subtracted from the model loads by performing tests without the model in place. The second effect to be considered is the influence of the mounts on the flow field around the model and the influence of the model on the flow field around the mounts. A complete separation of the effects is not possible. Therefore it is not possible to eliminate the influence of the model-mount interference completely. Several methods for the compensation of model-mount inference are described in [8.6].

8.1.4 Strain Gauge

Strain Gauge Fundamentals

The basic technique to measure forces with any kind of wind-tunnel balance is the measurement of the strain on an elastic spring which is deformed by the aerodynamic loads acting on the wind-tunnel model. In this chapter the fundamentals of strain measurement and strain sensors are described. For wind tunnel balances two major types of strain sensors are used. The most commonly used is the wire strain gauge sensor. Also of importance is the semi-conductor strain gauge.

The wire strain gauge is based on an electromechanical effect developed by *W. Thomson (Lord Kelvin)* in 1856. Thomson measured the electrical resistance of a metal wire and found that it could be correlated to the strain in the wire while stressed.

This effect was subsequently used by *E. Simmons (Caltech)* and *A.C. Ruge (MIT)* in 1938 in the development of the wire strain gauge. Simmons was the first to build a force transducer based on the wire strain gauge technique while Ruge used his wire strain gauges to perform experimental stress analyses. Ruge's strain gauge was very successful since it was cheap and easy to handle. Industry needed many of them such that in 1952 a technique was patented to produce the foil strain gauge in great numbers. No longer was a wire glued on a carrier foil. Rather a thin metal foil was glued on the carrier and the contour of the wire was etched out of the metal foil by a photo chemical process. This technique is still used today to produce the foil strain gauge sensors, as it produces very precise sensors with high resolution at a low price.

The physical principle of a wire strain gauge is that a change in electrical resistance is produced when a strain is applied to the gauge. The electrical resistance of a wire can be written as:

$$R = \frac{\rho l}{A}\,, \tag{8.1}$$

where R is the resistance of wire, l the length of the gauge grid, A the cross section of the wire and ρ the specific electric resistance.

The specific electric resistance is given as:

$$\rho = \frac{2 m v_0 A l}{N_0 e^2 \lambda}\,, \tag{8.2}$$

where m is the mass of an electron, v_0 the velocity of the electrons, N_0 the number of free electrons, e the charge of an electron and λ the free wave length of the electrons. With the above equation for the specific electric resistance, the resistance of a wire can be formulated as:

$$R = \frac{2 m v_0 l^2}{N_0 e^2 \lambda}\,. \tag{8.3}$$

8. Force and Moment Measurement

Measurement of steady and fluctuating forces acting on a body in a flow is one of the main tasks in windtunnel experiments. In aerodynamic testing, strain gauge balances will usually be applied for this task as, particularly in the past, the main focus was directed on the measurement of steady forces. In many applications, however, balances based on piezoelectric multicomponent force transducers are a recommended alternative solution. Contrary to conventional strain gauge balances, a piezo balance features high rigidity and low interferences between the individual force components. High rigidity leads to very high natural frequencies of the balance itself, which is a prerequisite for applications in unsteady aerodynamics, particularly in aeroelasticity. Moreover for measurement of extremely small fluctuations, the possibility exists to exploit the full resolution independently from the preload.

Concerning the measurement of small, steady forces, the application of piezo balances is restricted due to a drift of the signal at constant load. However, this problem is not as critical as generally believed since simple corrections are possible.

The aim of this chapter is to give an impression of the possibilities, advantages and limitations offered by the use of piezoelectric balances. Several types of external balances are discussed for wall mounted models, which can be suspended one-sided or twin-sided. Additionally an internal sting balance is described, which is usually applied inside the model. Reports are given on selected measurements performed in very different windtunnels, ranging from low-speed to transonic, from short- to continuous running time and encompassing cryogenic and high pressure principles. The latter indicates that special versions of our piezo balances were applied down to temperatures of −150 °C and at pressures of up to 100 bar.

The projects span from a wing/engine combination in a low-speed wind tunnel to flutter tests with a swept-wing performed in a Transonic Wind

Each chapter comes with a summary and its own index for fast cross-referencing to sections

Section title heading

output proportional to lift/pitch and side force/yaw. The signals which are proportional to each of these loads must be then calculated by summing or subtracting the signal from one another, before being fed into the data reduction process. The advantage is that the associated concentrated wiring on each section is much less sensitive to temperature effects.

Force Balances. This type of balance uses two measurement sections placed in both the forward and the aft section of the balance. In these measurement sections a forward and aft force is measured most often through tension and compression transducers. These forward and aft force components are used to calculate the resulting force in the plane as well as a moment around the axis (perpendicular to the measurement plane). An example of a typical force balance is shown in Fig. 8.32.

Moment-Type Balances. Moment-type balances have a bending moment measuring section in the front as well as in the aft regions of the balance (S_1 and S_2 in Fig. 8.33).

The measurement of the two bending moments (S_1 and S_2) is used to obtain a signal which is proportional to the force in the measurement plane and a second one which is proportional to the moment around the axis (perpendicular to the measurement plane). The stress distribution shows that the moment M_y (M_z) is proportional to the sum of S_1 and S_2. However, the force F_y (F_z) is proportional to the difference in the signals S_1 and S_2.

To measure the rolling moment (M_x) one bending section must be applied with shear stress gauges to detect the shear stress τ. The most complicated part of the balance is the axial force section which consists of flexures and a bending beam to detect axial force. These flexures enable axial movement whilst carrying the other loads.

Direct-Read Balances. A direct-read balance can be categorized as either a force-balance type or as a moment-balance type. Instead of measuring a force or a bending moment at each section separately, half bridges on every section are directly wired to a moment bridge while the other set of half bridges are directly wired to a force bridge. Thus the difference between direct-read balances and the other types is only in the wiring of the bridges. The disadvantage of such a wiring is the length of the wires from the front to the aft ends. Temperature changes inside these wires cause errors in the output signals.

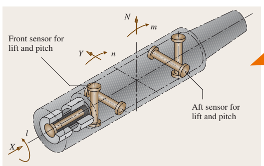

Fig. 8.32 Force balance with tension transducers in forward- and aft-sections (courtesy of Able Corp.)

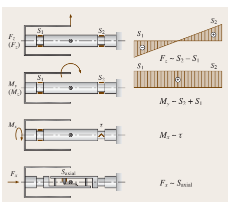

Fig. 8.33 Workings of a moment-type balance

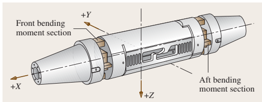

Fig. 8.34 Moment-type balance

Box Balances

The main difference between box balances and sting balances are the model and sting attachment area (Fig. 8.35). The load transfer in such balances is from

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Prof. Tropea studied and worked in Toronto, Karlsruhe and Erlangen before taking the Chair of Fluid Mechanics and Aerodynamics at the Technical University of Darmstadt in 1997. His background is in experimental fluid mechanics and he has authored numerous book sections and journal publications on this subject. He is currently Editor of Experiments in Fluids from Springer-Verlag.

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