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# Springer Handbook of Experimental Fluid Mechanics

Edited by C. Tropea, A. L. Yarin, J. F. Foss

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## Springer Handbook of Experimental Fluid Mechanics

**C. Tropea**, Technische Universität, Darmstadt, Germany; **A. L. Yarin**, University of Illinois at Chicago, IL, USA; **J. F. Foss**, Michigan State University, East Lansing, MI, USA (Eds.)

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

### **Key Topics**

- Experiments in fluid mechanics
- ► The boundary-value problem
- Measurement of primary quantities
- Specific experimental approaches
- Fundamentals of data acquisition, processing, and analysis
- Measurement systems for temperature, concentration, heat flux, pressure, flow, shear stress; forces and moments
- Applications: fans, blowers and pumps, hydraulics, aerodynamics, microfluidmechanics, flow visualization, mixing, aeroacoustics, biological fluids, atmospheric and oceanographic measurements, magnetohydrodynamic systems, nonisothermal and multiphase flows, combustion diagnostics

### **Features**

- ► Contains over 900 two-color illustrations.
- Includes over 100 comprehensive tables summarizing experimental techniques and properties of materials.
- Emphasizes physical concepts over extensive mathematical derivations.
- Parts and chapters with summaries, detailed index and fully searchable CD-ROM guarantee quick access to data and links to other sources.
- Delivers a wealth of up-to-date references and further reading.

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### Introduction

**Part A Experiments in Fluid Mechanics** 

 The Experiment as a Boundary-Value
 Problem 
 Nondimensional Representation of the Boundary-Value Problem
 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.

### Part B Measurement of Primary Quantities

- Material Properties: Measurement and Data
- Pressure Measurement Systems
- Velocity, Vorticity and Mach Number
- ► Temperature, Concentration and Heat Flux
- ► Forces and Moments

### Part C Specific Experimental Approaches

- ► Non-Newtonian Flows ► Measurement of Turbulent Flows ► Flow Visualization
- Measurement of Wall Shear Stress
- ► Topological Considerations ► Measurements in Boundary Layers ► Volume Flow Rate

► Internal Incompressible Viscous Flow ► Fans,
 Blowers and Pumps ► Hydraulics ► Aerody namics ► Measurements in Compressible Flows
 Applied Topics ► Atmospheric Measurements
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- Measurements in Nonisothermal Flows
- ► Combustion Diagnostics ► Measurements in Multiphase Flows ► Electrohydrodynamic Systems

### Part D Analyses and Post-Processing of Data

▶ Review of Some Fundamentals ▶ Fundamentals of Data Processing ▶ Data Acquisition
 ▶ Data Analyses

About the Authors

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### 4 Part B | Measurement of Primary Quantities



### 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.

Part B 8.1

### Table 8.1 Definition of positive axis direction

Balance Axis System	Name of Component	European	USA
		Positive	Positive 🦊
		direction	direction
X	Axial force	In flight	In wind
Y	Side force	To starboard	To starboard
Ζ	Normal force	Down	Up
$M_{\chi}$	Rolling	Roll to	Roll to
	moment	starboard	starboard
$M_y$	Pitching	Turn up	Turn up
	moment		
$M_z$	Yawing	Turn to	Turn to
	moment	starboard	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 tannel, 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.

### 10 Part B Measurement of Primary Quantities

Autorhan regime can be avoued. Mounting interference The aerodynamic loads on the model itself are al-ways 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 influ-ence of the mounts on the flow field around the model and the influence of the model on the flow field around the model. Second property expansion of the effects is not influence of the model-mount interference completely. Several methods for the compression of model-mount influence are escribed in [8,6].

### 8.1.4 Strain Gauge

8.1

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 spiring which is deformed by the aerodynamic loads acting on the wind-tunnel model. In this chapter the fundamentals of strain measurement and strain sensors

<text><text><text><text><text><text>

(8.1)

(8.3)

### $R = \frac{\rho l}{A}$

 $R = \frac{2mv_0l^2}{N_0c^2\lambda}$ 

there R is the resistance of wire, l the length of the uge grid, A the cross section of the wire and  $\rho$  the cific electric resistance. The specific electric resistance is given as:

### $\rho = \frac{2mv_0 Al}{N_0 c^2 \lambda}$ (8.2) -

where *m* is the mass of an electron, to the selecity of the electrons, *N*<sub>0</sub> the number of free electrons, *c* file dange of an electron and  $\lambda$  the free wave length of the elect trons. With the above equation for the specific electric resistance, the resistance of a wire can be formulated as:

### **Includes** over

100 comprehensive tables summarizing experimental techniques and properties of materials.

### **Easy to understand** figures throughout the entire handbook.

### Part title for easy navigation

Clearly displayed math

### 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 tem-

### Steady and Ouasi-Steady Measurement ... 81 2 Basics 8.1.1 8.1.2 Basic Terms of Balance Metrology... 6 8.1.3 Mounting Variations 8.1.4 Strain Gauge..... 8.1.5 Wiring of Wheatstone Bridges...... 10 11 8.1.6 Compensation of Thermal Effects.... 13 8.1.7 Compensation of Sensitivity Shift ... 14 8.1.8 Strain Gauge Selection ..... 16 **Each chapter** 8.1.9 Strain Gauge Application ..... 16 8.1.10 Materials..... 17 8.1.11 Single-Force Load Cells ..... 8.1.12 Multi-Component Load 18 Measurement ..... 20 8 1 13 Internal Balances 8.1.14 External Balances 74 sections 8.1.15 Calibration .... 28 Force and Moment Measurements 8.2 in Aerodynamics and Aeroelasticity Using Plezoelectric Transducers..... 32 8.2.1 Basic Aspects of the Piezoelectric Force Measuring Technique ..... 34 39 8.2.2 Typical Properties 8.2.3 Examples of Application..... 43 8.2.4 Conclusions ..... 51 Section title References 51 eratures 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 Force and Mome 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 associ-ated concentrated wiring on each section is much less sensitive to temperature effects. Force Bolance: This type of balance uses two mea-surement sections placed in both the forward and the aft section of the balance. In these measurement sections a forward and aff force is measured most often through tension and compression transducers. These forward and aff 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). As example of a typical force balance is shown at Fig. 8.22. Fig. 8.32 F of Able Corp.) 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<sub>1</sub> and S<sub>2</sub> in Fig. 8.33). IIIIIII $F_{2} \sim S_{2} - S_{1}$ Fig. 8.33). Example 1 for the second $M_s \sim S_2 + S$ and $S_2$ . To measure the rolling moment ( $M_d$ ) one bending section must be applied with shear stress gauges to de-tect the shear stress r. The most complicated part of the balance is the axial force section which consists of hexures and a bending beam to detect axial force. These learners can be axial movement whilst carrying the other the stress can be axial movement whilst carrying the other **Thumb indices** identify the part Direct-feed Balances: A direct-read balance can be categorized as either a force-balance type or as a noment-balance type. Instead of measuring a force-trading moment at each section separately, half bridges on every section are directly wired to a noment-bridge while the other set of half bridges are directly wired to a force tridge. Thus the difference between direct-read balances and the other types is only in the wiring of the bridges. The disadvander of such are directly using of the bridges. The disadvandance 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. and chapter section Fig. 8.30 The main difference b palances are the mod Fig. 8.35). The load tr etween box balance del and sting attacl ransfer in such balan

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### **About the editors:**

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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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