Experimental Fluid Mechanics

Klaus Hufnagel

Wind Tunnel Balances

Springer

Experimental Fluid Mechanics

More information about this series at https://link.springer.com/bookseries/3837

Klaus Hufnagel

Wind Tunnel Balances

Springer

Klaus Hufnagel
Wind Tunnel
Technische Universität Darmstadt
Darmstadt, Germany

ISSN 1613-222X ISSN 2197-9510 (electronic)
Experimental Fluid Mechanics
ISBN 978-3-030-97765-8 ISBN 978-3-030-97766-5 (eBook)
https://doi.org/10.1007/978-3-030-97766-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

I would like to dedicate this book to Prof. Bernd Ewald, who was my teacher and doctoral advisor. From him, I acquired most of the knowledge in the field of wind tunnel balances. In the beginning of the 1980s, I was hired by him for a research project with the aim to develop internal balances for the emerging cryogenic wind tunnels. He was aware that the very promising aim of having the same Reynolds number in a wind tunnel test as on subsonic cruise flight could not be achieved without a force measuring technique that has the same accuracy as the systems built for conventional tunnels. The project was successfully brought to completion, but there was no interest in the industry to take over this knowledge of cryogenic balances for industrial production, and so, he decided to offer such balances directly from the university. He was an engineer that showed us how engineering creativity could solve totally new problems when it is coupled with solid engineering knowledge and art. He analyzed lot of problems by simple models and so delivered

the basis and the direction for the knowledge transfer to practical applications. His impact on the development on present status of wind tunnel balances is documented in numerous papers, the study of which is highly recommended if somebody wants to enter this field. Prof. Ewald passed away in June 2019.

Preface

The motivation to write this book came to me while sorting out material which the head of our institute, Prof. Bernd Ewald, had produced and collected on the subject of balances during his career. Following his retirement in 1998, he continued to work on balance design, and although he had intended on summarizing his life experience with balances in the form of a book, he became side-tracked—he dedicated his time to rebuilding a famous flying wing aircraft, the Horton IV. On every visit to the office, he therefore brought with him a trunk full of wind tunnel balance documents, rather than throwing them away. Together with the documentation I had collected at this time over my own 15 years of working with balances, I was therefore faced with deciding the fate of all this accumulated knowledge. The documentation comprised over six hundred articles related to wind tunnel balances and calibration machines and addressed such issues as operation over a wide temperature range or under large temperature gradients. Especially while reading through Prof. Ewald's notes, it became clear to me that we had overcome innumerable design problems in the past that represented important solutions and experience that others could benefit from.

It eventually became apparent that the only solution to preserving this knowledge for future reference was to write a book, condensing this combined experience obtained over a period of 36 years. Although I started this endeavor well in advance of my own retirement, this 14 year lead time was still not sufficient to finish the project. It was also never evident to me whether the book would be outdated before publication. The eventual role of computational fluid dynamics (CFD) was and is still not clear—to what extent wind tunnel testing would remain an important design tool for the aviation industry? In comparison with complicated and costly experiments employing contemporary techniques such as particle image velocimetry (PIV) or pressure/temperature sensitive paints (PSP/TSP), CFD appeared in many respects to be advantageous. However, in the end, both CFD and wind tunnel can be viewed as aerodynamic simulation tools that have their own specific uncertainties in the prediction of the airflow around an airplane. Since the development of cryogenic wind tunnels, which are able to close the Reynolds number gap between model testing and reality, wind tunnel testing now delivers extremely precise data for the performance of an airplane. So, time has revealed that wind tunnel balances remain

an important tool in the overall design of aircraft, and therefore, it is my hope that this book will be of use to present and future generations of engineers and technicians dealing with this measurement technology.

Darmstadt, Germany Klaus Hufnagel
April 2021

Acknowledgements Writing a book is a one part of the story, the other is to get it published. First, I have to thank my longtime colleague Matthias Quade for the first review of the text. For bringing the book to a scientific standard, I want to thank very much Prof. Dr.-Ing Cameron Tropea for the time he spent in proofreading and his support in the layout of the book. Finally, I would like to extend a word of thanks to numerous of my colleagues throughout the world, who have graciously sent me pictures of their balances and instruments and allowed me to use them in this book.

Contents

List of Figures

List of Tables

Chapter 1
Historical Review

1.1 Introduction

Before embarking on a detailed description of wind tunnel balance design, it is instructive to first review the evolution of force measurements using such balances. The justification for such a review in an engineering handbook is quite simple and comes from years of experience.

Despite having access to innumerable articles written on a subject, the chronological sequence of these articles can be particularly revealing about why and when certain inventions were made. Circumstance often lies behind the saying that 'necessity is the mother of invention'. This is very well exemplified by the parallel development of two sectors eventually merging to yield what we now know as strain gauge based wind tunnel balances. On the one hand very basic physical laws and effects of elasticity and electricity were being developed, eventually culminating in the fundamentals of measuring strain with a strain gauge. On the other hand, the need for aerodynamic force measurements was rising rapidly with the advent of wind tunnel testing. It is this sequence of events and steps of progress which is summarized in the following sections.

1.2 From Fundamental Physics to the First Force Transducers

The basic research to build a force transducer with a metal spring and a wire strain gauge was conducted by *Robert Hooke* (1635–1703), *Georg Simon Ohm* (1789–1854), *Charles Wheatstone* (1802–1875) and *William Thomson, 1st Baron Kelvin of Largs* (1824–1907).

Robert Hooke was a famous physicist and an architect. Among other things he formulated in 1678 the basic theory of elasticity [9] and this is also the reason why the elastic relationship between stress and strain is known as *Hooke's Law.*

K. Hufnagel, *Wind Tunnel Balances*, Experimental Fluid Mechanics,
https://doi.org/10.1007/978-3-030-97766-5_1

Georg Simon Ohm was professor for physics at the universities of Cologne, Nuremberg and Munich. In 1827 he published his work on the correlation between voltage, current and electrical resistance. His relation between voltage current and resistance became the basic principle for an electrical circuit and the measurement of electrical resistance [16]. Using his name as the unit for the electrical resistance honored this work.

Charles Wheatstone contributed work on the electrical telegraph and published work on the "*Wheatstone Bridge*" circuit in 1843 [22]. Although he never claimed to have invented the special electric circuit to determine small electrical resistances that was named after him. The first description of the bridge circuit was given by *Samuel Hunter Christie* (1784–1865), from the Royal Military Academy, who published it in 1833 [4].

William Thomson was knighted in 1866 and became *1st Baron Kelvin of Largs* in 1892. His most famous works were his contributions that made the first transatlantic telegraph cable a success, but he also published numerous articles on physics, among these in 1856 an article on the relationship between mechanical stress and electrical resistance of metals [21], which had been already mentioned by *Wheatstone*.

This small excursion to early developments shows, that the basics for metal strain gauges resulted from the work of several scientists working sequential to one another with only minimal temporal overlap. For instance, after *Thomson's* contribution, another 61 years went by until the first use of the effect was reported for a sensor application. The first person who actually used the effect of the change of electrical resistance under mechanical stress for measurements was *Walther Nernst* (1864–1941), who built a pressure gauge in 1917 to measure the pressure fluctuations inside a piston engine. This application, and the resulting pressure diagram were published in 1928 [12, 13].

Edward. E. Simmons (1911–2004) was an assistant at the *California Institute of Technology* when he invented a material testing apparatus for measuring the percussive force in 1936. At that time *Simmons* and others he worked with probably did not realize the importance of their invention and that is one reason that it was patented only several years later [19, 20]. The patent for this apparatus [17] was granted in 1942 (Fig. 1.1). This is the first application where a wire strain gauge was used to measure a force.

At nearly the same time on the east coast at *Massachusetts Institute of Technology*, *Arthur Claude Ruge* (1905–2000) used a meandering wire on a piece of paper to measure the strain on the surface of a containment vessel model to predict the stresses in the real vessel (Fig. 1.2). This was the first use of a resistance strain gauge in experimental stress analysis.

The aerospace industry was developing an urgent need for simple and inexpensive strain measurement sensors at that time and so the first industrially produced foil strain gauge, ***SR4***, immediately became a success. The sensor was named ***SR4*** because *Simmons* and *Ruge* together with four people (*de Forest, Tatnall, Clark and Hathaway*) negotiated the terms of the corporate patent of *Simmons* and *Ruge* for the wire strain gauge.

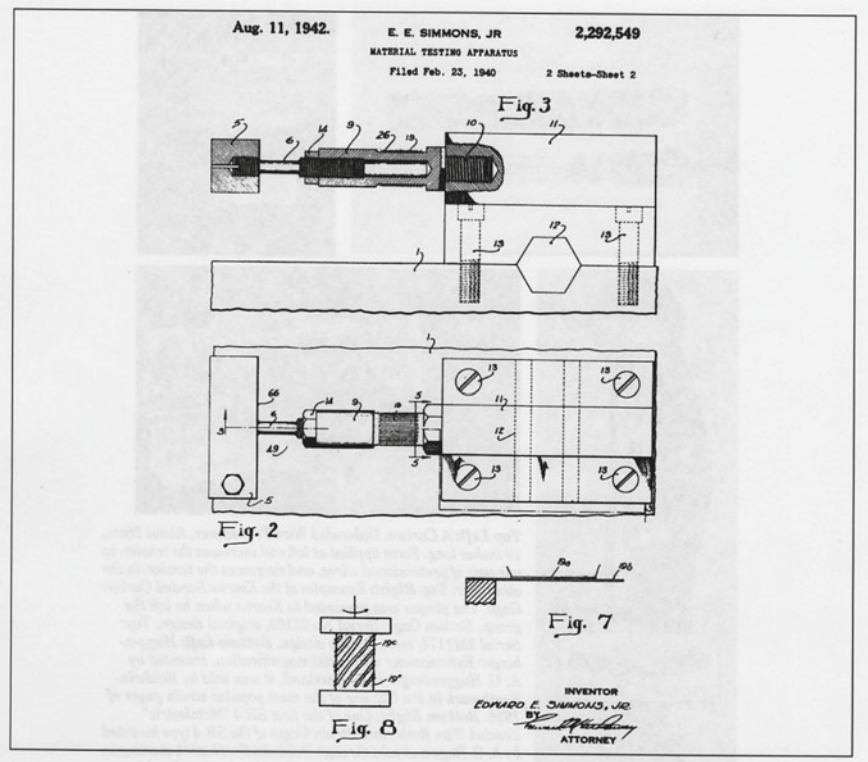

Fig. 1.1 Extract from Simmons' material testing apparatus patent document (HBM Hofmann)

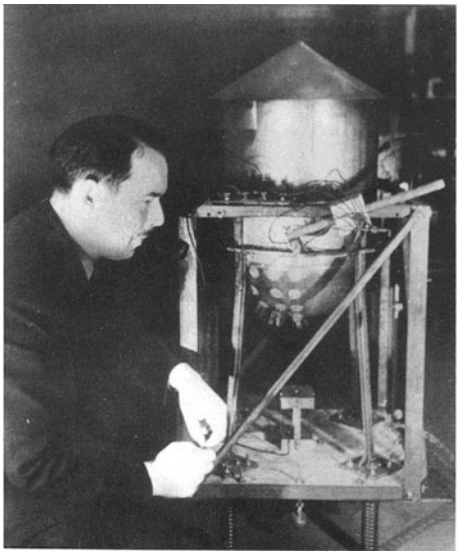

Fig. 1.2 Prof. Ruge with a model of a containment vessel (HBM Hofmann)

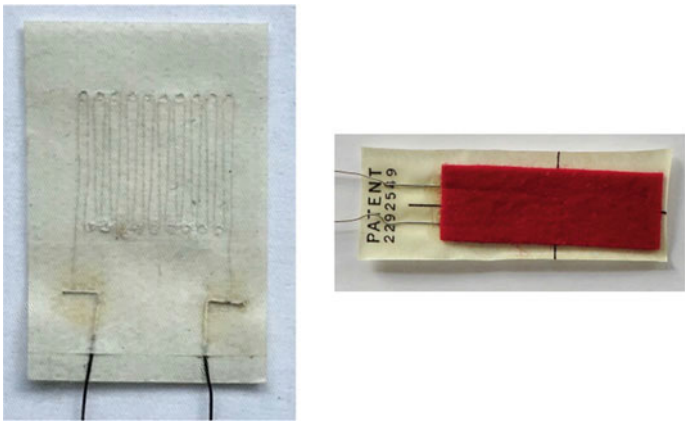

Fig. 1.3 Photographs of early wire gauge and the patented strain gauge SR4 (with permission by Dr. Stockmann)

The success story of the metal strain gauge was described by *Tatnall* [8]. He was a salesman of the *Baldwin-Southwark Company* and promoted the distribution of the paper strain gauges produced by the *Ruge/de Forest Company*, so that the planned production for the first year (1941) of 50,000 gauges (Fig. 1.3) was sold out within two months. The Second World War and the associated rapidly expanding aircraft industry created great demand for these strain gauges for material testing and testing of aircraft structures. The paper strain gauge dominated the area of experimental stress analysis very rapidly. The strain gauge production company of *Ruge* and *de Forest* was sold to *Baldwin Lima Hamilton (BLH)* in 1955, a company which today still produces gauges designated ***SR4***.

In the field of force measurement some developments can be traced back to the beginning of the 20th century using electro dynamometers as force transducers. In the USA *Burton McCollum* and *O.S. Peters* published an article about a "new electrical telemeter" in 1924 [15]. They used a stack of carbon plates as a strain sensitive element and so, were the first to use a semiconductor gauge for strain measurement. Another example was a piezoelectric dynamometer that was used in a test by *Max Kramer* at the *Aachen University of Technology* in 1932 to determine the dynamic lift force of a two-dimensional wing generated by a quick change of angle of attack [14]. In 1932 *Fred Scoville Eastman* from the *University of Washington* reported on a weigh beam for an external balance using an electromagnetic dynamometer [6].

All of these applications were used or proposed for use in a wind tunnel, but eventually metal strain gauge sensors dominated this application for wind tunnel strain gauge balances. One main reason for this was the next significant step in the development of the strain gauges made by *P. Jackson* in Great Britain with the invention of the foil strain gauge, where the grid was no longer a wire [10]. The production of the gauge was performed using a photo-chemical etc.hing process, similar to that of the printed circuit technology by the *Technograph Inc. Company*

under the license of the *Saunders-Roe Company (UK)* in 1952, where *P. Jackson* worked as a test engineer.

This process resulted in the mass production of the gauges, which made high quality gauges much less expensive and more reliable. In 1954 the *Baldwin Company* bought the license for the production of foil strain gauges from *Technograph Inc.* (UK) and the *SR-4 foil strain gauge* was produced.

In the 1950s several companies emerged to produce strain gauges in large numbers and in increasingly varied shapes. *Hottinger Messtechnik* started production of foil strain gauges in Darmstadt in 1955 [11] and in 1963 this company merged with *Baldwin Lima Hamilton Corp.* and formed *Hottinger Baldwin Messtechnik (HBM)*. *HBM* still exists today, but is now owned by other companies. Since 2001 *BLH* is part of the *Vishay Company*, which was founded at the beginning 1960s and is now the largest strain gauge manufacturer worldwide. Numerous other strain gauge manufacturers were established over the years, but none of these play a role in the market comparable to *BLH*, *HBM* and *Vishay Micro Measurements*.

Up to now in this historical review the story of the semiconductor strain gauges was not mentioned. One reason for this is that semiconductor strain gauges do not play a major role in the production of wind tunnel balances. This is because of their nonlinear characteristic and their strong temperature sensitivity. However, for some applications they are applicable, where a quick response to a sudden or dynamic change in load must be measured. Then their high sensitivity and the likely higher stiffness of the balance body are decisive. Semiconductor strain gauges use the piezoresistive effect, the change of the electrical resistance caused by the change of density in the crystal structure of a semiconductor under stress. *P.W. Bridgman* conducted comprehensive experiments on the electrical resistance of metals and crystals and in 1932 he published an article on the effect of homogeneous mechanical stress on the electrical resistance of a crystal [3]. He tested the change of resistance on crystals by the influence of static pressure. Under his supervision *Mildred Allen* performed first experiments on the effect of tension on crystals in 1932 [1]. She tested the change of electrical resistance on Bismuth crystals under tension, related to different crystal orientations. However, her measurements did not directly lead to the development of a strain sensor.

About 20 years later *Charles S. Smith* at the *Bell Laboratories* discovered the strain sensitivity of Germanium and Silicon. This research was used to develop the semiconductor strain gauge [18]. In 1958 *Honeywell* offered the first commercially produced semiconductor strain gauge [18]. In the coming years numerous developments arose using semiconductor strain gauges for pressure transducers (*Kulite, Honeywell*). Since 1962 *Baldwin Lima Hamilton (BLH)* has offered bondable semiconductor strain gauges, similar in use to the metal strain gauges they produce. However productions of these strain gauges was terminated some years ago. The use of bonded semiconductor strain gauges was described in detail by *James Dorsey* from *BLH* in his *Semiconductor Strain Gage Handbook* [5] in 1964 and *BLH* offered semiconductor strain gauges until 2004. Nowadays, semiconductor strain gauges are available from *Kulite, Kyowa and Micron Instruments*.

1.3 Force Measurement in Wind Tunnels

Apart from the development of strain gauges, there was also the development of force transducers and wind tunnel balances. With the acceleration of aerodynamic research and the use of wind tunnels in the early 20th century, the measurement of aerodynamic forces on test specimens was of paramount importance.

Benjamin Robins (1707–1751) and later on in 1804 *Sir George Cayley* were the first to perform experiments with a whirling arm to determine lift on plate segments [2]. Also *Otto Lilienthal*, around 1888, used a whirling arm apparatus to obtain lift and drag for different profiles (Fig. 1.4). Lift was measured by the weights, which balanced the thrust of the "propeller" and the drag was proportional to the time which the weights needed to reach the ground. The disadvantages of such a system are obvious. There are only short or no moments with steady state conditions during the experiment. This is likely one of the reasons why *Frank H. Wenham* (1824–1908) built a wind tunnel in 1871, which used a steam engine to drive a fan upstream of the model to generate a constant airflow through a wooden box of 3.7 m length and a cross section of 45 cm × 45 cm. This wind tunnel is the first documented wind tunnel and it was built for the Royal Aeronautical Society. It is reported that *Wenham* used a device to measure the forces on profiles by compensating the forces with weights outside the tunnel section. This device looked like a balance which was usually used to measure weight, and so the designation "Wind Tunnel Balance" may be traced back to this force measuring instrument. Later on the *Wright Brothers* employed a small wind tunnel with an external balance for their experiments with airfoils.

One of the first larger wind tunnels in which experiments with models of airplanes were conducted was built by *Gustave Eiffel* in 1910 [7]. His principle of a flow-through wind tunnel, sucking air through a nozzle, test section, collector and a diffuser with a fan drive at the end of the diffuser, is still in use today and tunnels built according to this design are called *Eiffel* type wind tunnels (Fig. 1.5). He also used an external wind tunnel balance according to the compensation principle (Fig. 1.6). So the use of external balances, working according to the compensation principle, prevailed as the wind tunnel force measurement system.

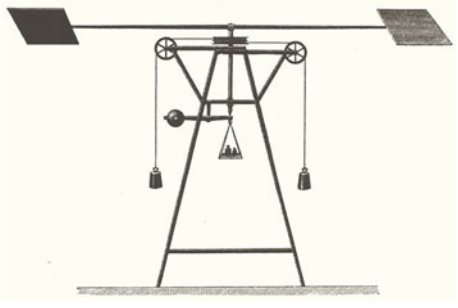

Fig. 1.4 Test rig of Lilienthal for airfoil testing

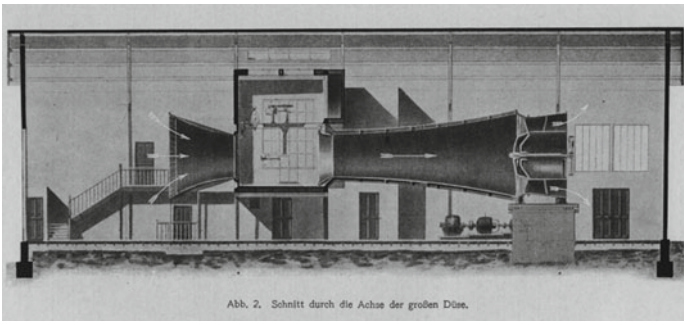

Fig. 1.5 Schematic picture of Eiffel's wind tunnel in Auteuil

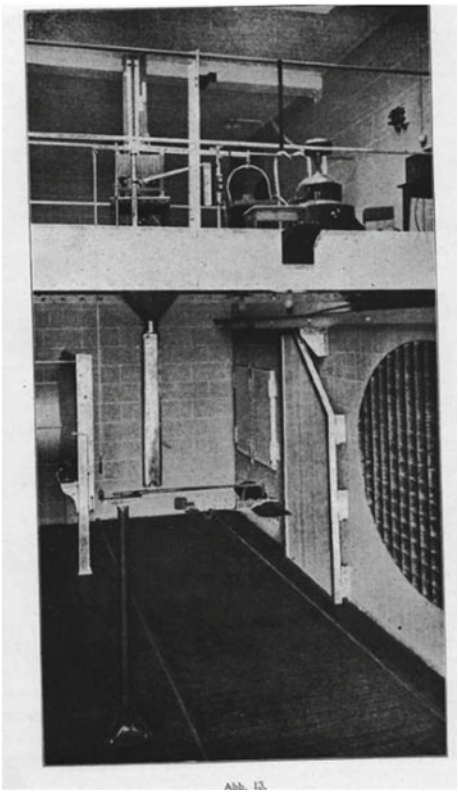

Fig. 1.6 Eiffel's wind tunnel balance with model

As remarked above, some key developments took place in the early 1930s and in the mid 1940s, when electrical sensor based force transducers were used to measure dynamic forces in a wind tunnel, or in the first pressure transducer of *Nernst*. However the real breakthrough for transducer based force measurements in a wind tunnel was the invention of the strain gauge. It is understandable that scientists and the engineers immediately adopted this inexpensive and precise sensor for the development of force transducers. The high sensitivity of the strain gauge allowed the development of force transducers with a very high stiffness and precision.

In all countries with an aircraft industry, numerous wind tunnels were being built. These tunnels required precise, multi-component force measurements. Following the Second World War a large number of high *Mach* number tunnels were also built. To achieve high *Reynolds* numbers at supersonic speed these tunnels were pressurized and the model loads increased, caused by the higher density of the gas. This circumstance, and the relatively low interaction afforded using a back sting support, made the development of the compact sting balance necessary and the development of the internal sting balance was only possible by using strain gauges.

The first report of such an internal sting balance is the report of Wingham [23] from 1945. *Wingham* used strain gauges to measure lift and pitch on a model in a high-speed wind tunnel. This balance was a sting balance with two bending sections (Fig. 1.7).

In this report a reference to an earlier report from 1944 by members of *Vickers-Armstrong Ltd.* was mentioned, but this report was not published. Thus, although it is not absolutely clear who and when the first sting strain gauge balance was built, it is clear that shortly after the strain gauge was commercially available, wind tunnel engineers started to design and build wind tunnel balances using strain gauges as sensors. In the early 1950s numerous developments in the area of sting balances and external balances with force transducers are reported. Along with the construction of new wind tunnels, the development of new balances was necessary to achieve precise and reliable results for the aerodynamic force measurement.

After a long period of development, the emergence of cryogenic wind tunnels (around 1980) set new requirements for the temperature stability of internal wind tunnel balances. The balances for these tunnels were required to measure with the precision of balances at ambient temperature, but over a much larger temperature range. Without this precision, the advantage of the high *Reynolds* number achieved using the cryogenic temperatures was useless. The challenges generated by the cryogenic wind tunnels were responsible for the latest developments of strain gauge based wind tunnel balances.

Optical strain gauges with higher sensitivity than the metal foil gauges did not have a major impact on the development of the wind tunnel balances. Their capabilities can only be fully exploited when new balance materials with a much higher *Young's modulus* than that of steel are available.