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The Development of Electron Beam Welded, Strain-Gaged Wind-Tunnel Balances

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For a long time multicomponent strain-gage balances have been machined from a solid piece of metal, thus achieving minimum internal friction and hysteresis. On the other hand, it is well known that built-up balances do have certain advantages. This paper reports on the design and manufacture of built-up balances whose components are welded by an electron beam process. In comparison, with existing types, good results promise both technical and commerical advantages. Design, material selection, and welding technique are discussed. Additional information is given on strain-gage application and on a novel technique for the application of calibration forces.

Introduction

THE development of strain-gage balances for multicomponent force measurements in wind tunnels had concentrated on two different types, a) one-piece balances, machined from a solid piece of metal and b) balances composed of a number of components. Normally the one-piece balance follows the double bending beam principle whereas the built-up balance represents the floating frame principle.

Compared with the double bending beam one-piece balance, the built-up floating frame balance allows much more freedom in the design and in the adaptation of the measurement ranges to the requirements. Low interference is easier to obtain than with the one-piece design. One the other hand the built-up balance suffers from major problems of creep, friction, and hysteresis produced by the screwed or wedged joints of the individual components. These problems are such that, to my knowledge, only two designs have earned a commercial reputation, these being the well-known Task balance and the Swiss EFW "Kastenwaage" shown in Fig. 1.[1,2]

The problem of the joints is completely avoided by the one-piece balance design, a typical example of a six-component one-piece balance being shown in Fig. 2. This is a double bending beam design with a parallelogram spring arrangement between the bending points for longitudinal force measurement. This system is widely used with good results in most wind tunnels. The main shortcoming of this standard design is the complicated design and the difficult machining necessary to generate the parallelogram spring design out of a single piece of metal. Even with a very sophisticated design, cuts are necessary which limit the stiffness and the strength of such a balance.

The "Welded Balance" Technology

VFW-Fokker have devoted considerable effort toward developing a balance which eliminates the friction and hysteresis problems of the built-up floating frame design as well as the low stiffness and the machining problems of the standard one-piece balance. The final result was a built-up balance whose components were electron beam welded, thus forming a one-piece balance without the machining restrictions of the standard design. Electron beam welding technology normally is used at VFW-Fokker for the fabrication of rocket fuel tanks and space satellite structures.

Floating Frame "Box"-Balance

Initially we tried to introduce the welding technique into the design of a floating frame balance of the EFW "Box" type. Figure 3 shows the complete balance (strain gages not yet applied). Much thought was given to the design of the welded connection of the bending beam and the flexible links. The final solution is shown in Figs. 4 and 5, which give close-up views on the welded seam.

This balance design met our aims of simplicity and easy fabrication, but the results of calibration and use in the VFW-Fokker Low Speed Wind Tunnel as a half-model balance were not so favorable. An unacceptable level of scatter and hysteresis was observed. The reason finally was found in the combination of an air-hardening austenitic steel with the circular welding seams. The air-hardening characteristics of this steel, which previously was used for strain-gaged balances with good results, generated very large radial stresses and microscopic shrinkage cracks in the circular welding seam. These cracks had no serious effect on the strength of the welded joints but produced internal friction and hysteresis. Another problem of this balance design was a high sensitivity to temperature gradients between base body and bending beam body.

Integrated Horizontal Tail Balance

The next attempt was a special design for the horizontal tail mounting of low-speed models. Figure 6 shows the complete balance. The balance is attached to the fuselage structure and the horizontal tail is mounted in the pivot of the balance. The balance incorporates a remotely controlled stabilizer setting and measures four components: lift, drag, pitching moment, and rolling moment.

This balance follows in principle the design of the double bending beam balance and is similar to the one-piece balance shown in Fig. 2. It incorporates a parallelogram spring system for drag force measurement. We tried to find a simple fabrication method for a stiff drag force system using the welding process. After an attempt to weld the springs in place one by one, it was found best to fabricate both bending beam parts separately with a tapered outrigger beam. The parallelogram spring systems are fabricated by a simple milling process from plate stock material. Figure 7 shows the isolated balance body (strain gages not yet applied) and the four parts from which it was constructed. Front end, rear end, and the two parallelogram spring plates were fabricated

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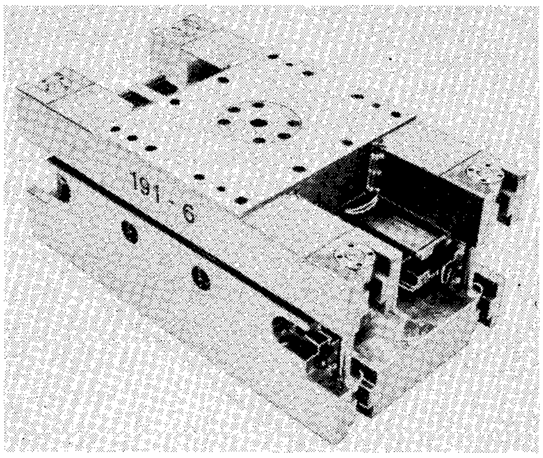

Fig. 1 Box-type balance ("Kastenwaage") (Eidgenössische Flugzeugwerke Emmen, Switzerland).

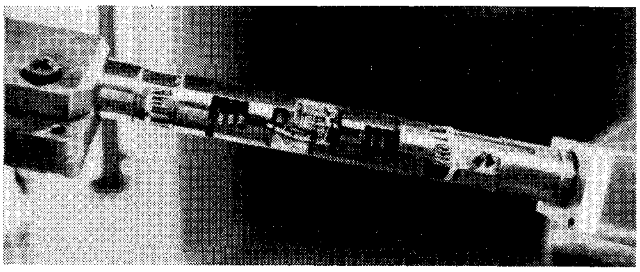

Fig. 2 Single-piece six-component balance double bending beam design (Aeronautical Research Association, U.K.).

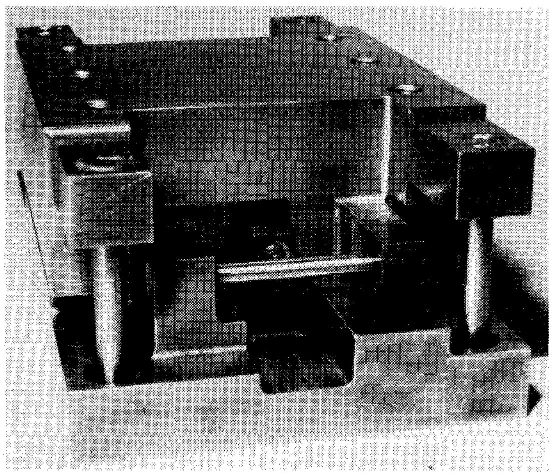

Fig. 3 Electron beam welded box-type balance.

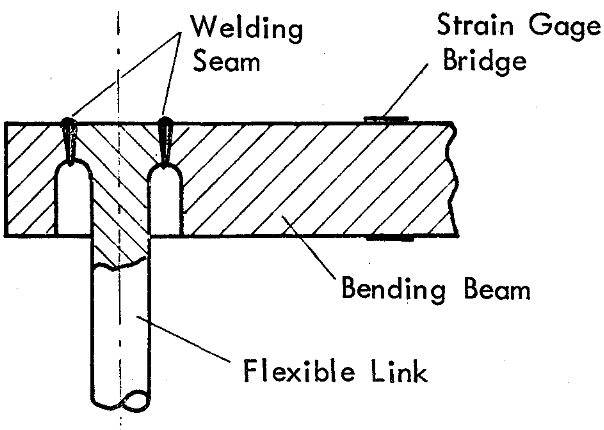

Fig. 4 Welded connection of bending beam and flexible link.

separately, which resulted in simple and inexpensive machining. The balance was integrated by four straight electron beam welding seams, two of which are clearly visible in the lower part of Fig. 7.

Due to the straight arrangement of the welding seams the shrinkage crack problem did not occur and the balance gave excellent results. It can also be seen in Fig. 7 that undercuts, which reduce stiffness and strength of the drag force system are not necessary. Technical data and accuracy are given in Table 1.

Six-Component Balance

The present state-of-the-art in electron beam welded balance design is shown in Fig. 8. This balance was designed for use in a wind-tunnel test rig for roll and spin tests. This rig was designed and built as part of a joint program of the

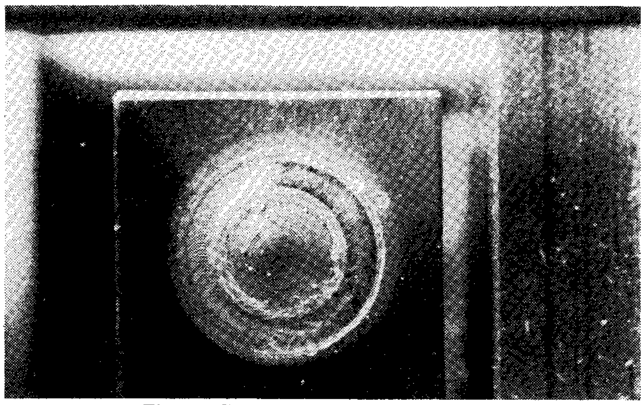

Fig. 5 Close-up view of welding seam.

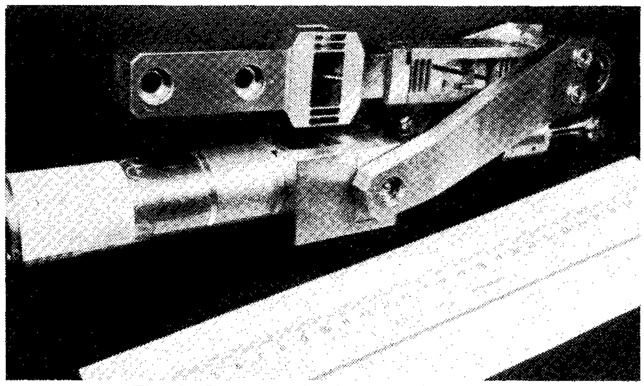

Fig. 6 Integrated horizontal tail balance.

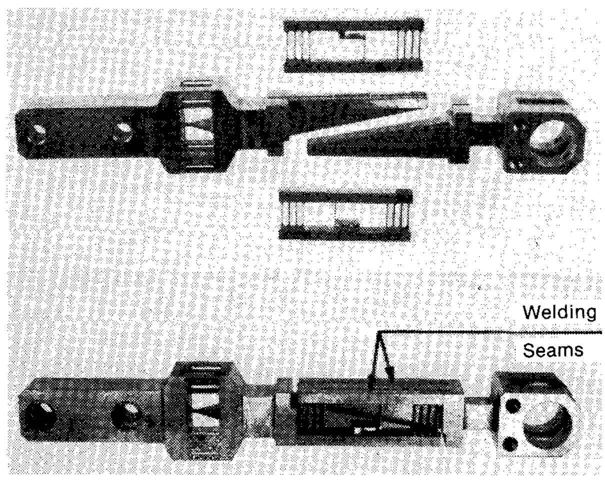

Fig. 7 Electron beam welded horizontal tail balance; parts and ready welded balance body.

Table 1 Technical data and accuracy for horizontal tail balance

		Lift	Drag	Pitching moment	Rolling moment
Maximum,	N	350	150		
Range,	Nm			40	50
Full-scale signal (supply voltage 5 V)	mV	6.8	7.9	2.6	8.5
Accuracy maximum error in % of full scale		0.2	0.5	0.3	0.3

German Aerospace Industry and the DFVLR for the development of dynamic wind-tunnel test methods.

The proposed use of the balance called for maximum stiffness combined with high sensitivity. Most well-known balance designers were requested to submit tenders and the subsequent evaluation showed clear advantages in price and performance for the welded design.

The design principle is shown in Fig. 9. Front end and rear end, each machined from one piece of metal, are already aligned with fitting bolts. The parallelogram spring plates are machined simply from stock plate material. For maximum stiffness combined with high sensitivity the bending beams are resolved in 5-bar cages.

The balance just after the welding process, fitting bolts not yet removed, is shown in Fig. 10. The welding seam is clearly visible in this picture. The close-up view (Fig. 11) after mudblast treatment demonstrates the real one-piece appearance of the balance.

Technical data of this balance are given in Table 2. A complete range of this type of balance in different sizes and load ranges is now designed and built by VFW-Fokker.

Material Problems

Normally in selecting a balance material one looks only for ideal elasticity up to high stress levels and acceptable machinability. Both criteria were satisfied by an air-hardening austenitic steel (Deutsche Edelstahlwerke DCNR, main alloying constituents are 1.3% chromium, 0.4% molybdenum and 4% nickel) which has been used successfully in balances at VFW-Fokker for a long time.

In the case of the welded balance, weldability is a further criterion which led to the disappointment with our first welded balance. In general, we found that austenitic air-hardening steels develop large internal stresses in the welding seams. Even if these stresses are removed by heat treatment, they may have caused internal cracks. These cracks give rise to scatter and hysteresis due to internal friction.

A major search for suitable materials for welded balances led to the use of a high-alloyed martensite age-hardening steel. Main alloying constituents are molybdenum (5%), nickel (18%), cobalt (12%), and titanium (0.9%). This special steel has been developed for extremely high-stressed parts in the aerospace field. This material gives excellent machinability in soft annealed condition. The heat treatment for ultimate tensile strength gives only very small heat treatment distortion and restores full strength in the welding seams. The material allows balance designs for stress levels up to 395 MPa.

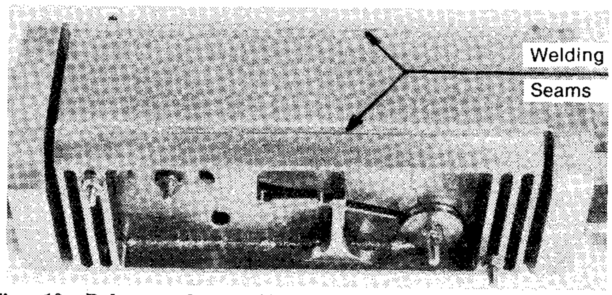

Fig. 10 Balance after welding process (fixture bolts not yet removed).

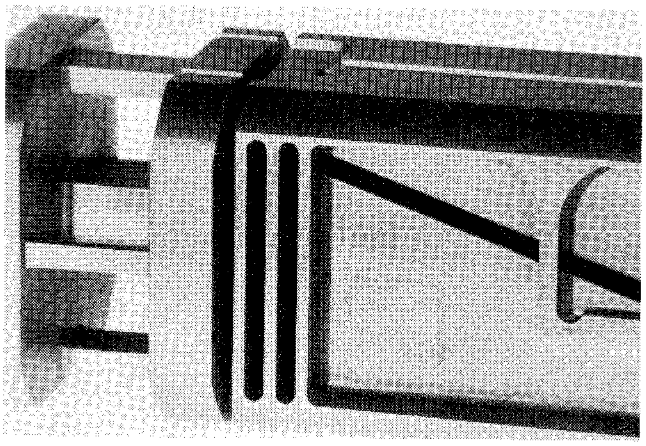

Fig. 11 Close-up view of finished balance, 5-bar cage, and parallelogram system.

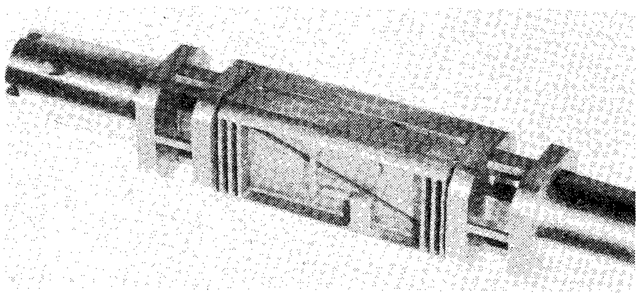

Fig. 8 Welded six-component balance.

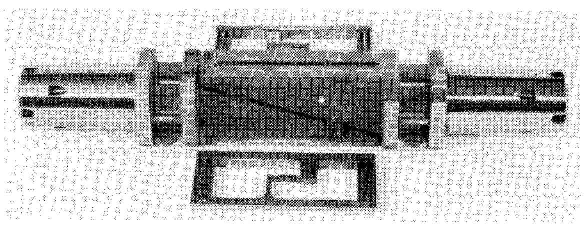

Fig. 9 Balance prepared for welding process.

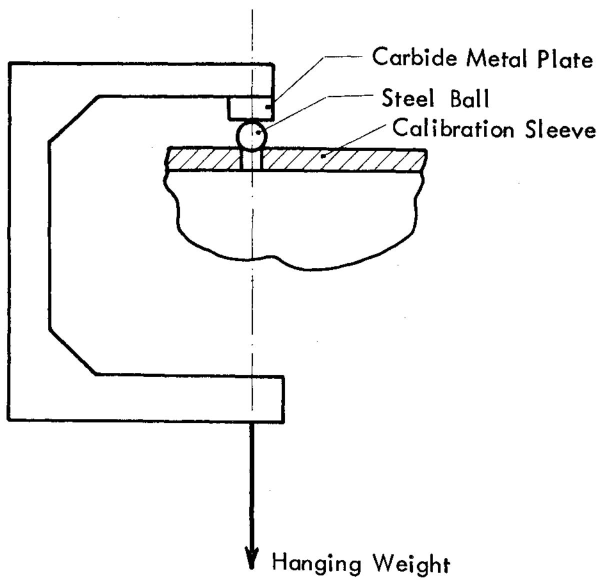

Fig. 12 Load application system.

Table 2 Technical data and accuracy for six-component balance.

		Lift	Drag	Side force	Pitching moment	Rolling moment	Yawing moment
Maximum,	N	1500	200	325			
Range,	Nm				150	80	100
Full-scale signal, (supply voltage 5V)	mV	2.15	6.06	1.79	3.59	5.96	8.34
Accuracy							
Maximum error in % of full scale		0.08	0.18	0.13	0.16	0.09	0.11

Another material, which combines excellent weldability with ideal elasticity up to high stress levels, is copper-beryllium alloy. The modulus of elasticity of copper beryllium is much lower than that of steel which may be advantageous in the case of very small balances.

Strain-Gage Application and Calibration Procedure

Strain gages with temperature compensation especially adapted to the balance material are used. The strain gages were applied with normal techniques recommended by the strain-gage manufacturers. Since we found that thermally caused changes in the adhesive structure had a large effect on the balance stability, a multiple thermal aging process was successfully developed.

A multicomponent strain-gage balance is never interference free, and so any balance can be only as good as its calibration. In the interest of optimum overall economy a simple balance design with larger interference may be the better compromise if the interferences are determined by a sophisticated calibration process. The standard calibration method used at VFW-Fokker allows for both linear and second-order interferences. Calibration loads are only applied by free hanging weights, thus eliminating all friction of guide wheels or similar devices. Calibration data are recorded by process computer-controlled equipment. This equipment allows on-line evaluation of the calibration results and immediate computation of the second-order calibration matrix. The constant monitoring of the calibration results allowed by this system gives excellent accuracy and repeatability.

A constant source of scatter of the calibration results was discovered in the force application on the calibration sleeve. The normal cone and dimple force application produces considerable friction and applies uncontrollable moments onto the balance. Finally, we used the force application system shown in FIg. 12. The loading holes in the calibration sleeve are machined on a precision jig drill. The force transmission between the steel ball and the carbide metal surface is self-aligning through the center of the hole and absolutely free of moment transmission. With this load application system, scatter of the results was much reduced compared with the normal cone and dimple system.

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