Review of Potential Wind Tunnel Balance Technologies

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This manuscript reviews design, manufacture, materials, sensors, and data acquisition technologies that may benefit wind tunnel balances for the aerospace research community. Current state-of-the-art practices are used as the benchmark to consider advancements driven by researcher and facility needs. Additive manufacturing is highlighted as a promising alternative technology to conventional fabrication and has the potential to reduce both the cost and time required to manufacture force balances. Material alternatives to maraging steels are reviewed. Sensor technologies including piezoresistive, piezoelectric, surface acoustic wave, and fiber optic are compared to traditional foil based gages to highlight unique opportunities and shared challenges for implementation in wind tunnel environments. Finally, data acquisition systems that could be integrated into force balances are highlighted as a way to simplify the user experience and improve data quality. In summary, a rank ordering is provided to support strategic investment in exploring the technologies reviewed in this manuscript.

I. Introduction

The objective of this effort was to understand the future requirements of aeronautical researchers with respect to wind tunnel balances and then to identify promising technologies or techniques that may help achieve these requirements. Identifying the requirements proved more difficult than initially anticipated, because of the diversity of aeronautical testing conditions and the interdependency of the requirements.

As an example, we initially assumed that improved balance accuracy and precision would be a key expectation of researchers. In general this is true, but many researchers are subject to budget and time constraints and cannot afford to build a balance customized for their application. As a result, a balance engineer will attempt to match, as closely as possible, the available balance inventory to the researcher's requirements. In most cases, there is an existing balance which can satisfy the overall requirements, but it will not be tailored to the application. This means the researcher will likely take a hit on overall accuracy and resolution, because it is unlikely that all load components are optimized for their test. So, simply focusing attention on balance accuracy without considering cost and time of manufacture is shortsighted.

The objectives identified by balance users we interviewed were reduced balance cost, reduced balance lead and setup times, and increased balance factors of safety. More affordable balances will enable researchers to build balances customized for their applications. Shortening fabrication time will reduce overall lead time before experimental testing, and minimizing setup time will reduce tunnel time once in the facility. Ensuring balances have higher factors of safety minimizes the risk of damage to the balance and the wind tunnel.

In this review paper, we have identified technologies and processes that offer potential to address these objectives. Fatigue life will also be addressed as an area of interest due to recent concerns within the balance community.

II. Design and Manufacture

A wide variety of design approaches and manufacturing methods are used to develop balances. Regardless of the approach, balances tend to be expensive (average of $70,000 at 2004 rates [1]) and time consuming to manufacture (average of 410 day lead time [1]).

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Improvements in wind tunnel balance design and manufacture could significantly reduce development cost and time. Therefore, the primary focus of this section will be on impact to fabrication time and cost and not on absolute accuracy and resolution. It is important to consider that reduced cost and time of manufacture may result in more researchers customizing balances for their specific needs which may outweigh the benefits of overall accuracy.

Some design concepts may increase balance manufacturing cost and time, but could significantly reduce operational cost and time, so it is important to consider overall lifecycle benefits. For example, a variable stiffness balance would enable balance stiffness to be changed based on the expected loadings. This capability would eliminate the need for swapping balances based on the load requirements and save valuable tunnel time.

A. Additive Manufacturing

Additive manufacturing is a particularly attractive fabrication process for low volume complex parts like balances, because it can significantly reduce the cost and time required for manufacture. As an example, Atzeni et. al. [2] estimated the cost of a 1:5 model of an aircraft landing gear (7x7x21 cm) assembly using high pressure die casting and additive manufacturing. A single high pressure die cast part was predicted to cost $21,000 versus $525 for the additively manufactured part. This cost estimate includes materials, labor, and machine time.

Time savings can be just as significant. The five constant strain beams shown in Figure 1 were printed from 316L powder using a selective laser melting system in approximately 20 hours. More than 100 hours are needed to machine the five beams using traditional manufacturing methods. Balance fabrication time has the potential to be reduced from months to days. Moreover, the build envelope for commercial metallic selective laser melting systems is roughly a 30 cm cube, which should accommodate most balance designs.

Additive manufacturing comes with its own unique challenges. For instance, surface roughness is worse than would be desired for a manufactured part. 4-9 μm Ra can be expected (0.8 μm Ra typically specified for a balance). The dull appearance of the constant strain beams (Figure 1) is an indication of the surface roughness. Accuracy is generally about 0.1 mm (≈0.025 mm typically specified for a balance) with minimum wall thicknesses of 0.3-0.4 mm [3] [4]. As a result, secondary machining or finishing maybe necessary to achieve acceptable tolerances and surface finish.

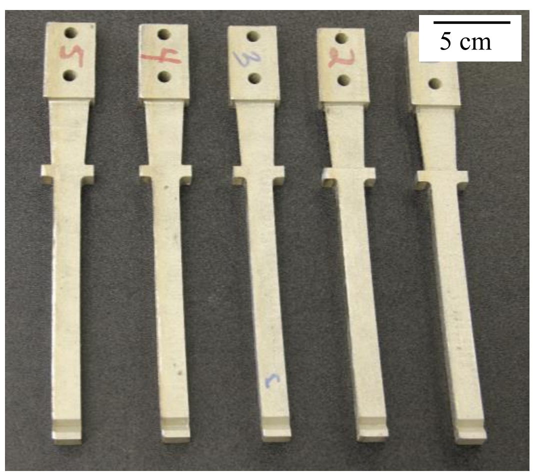

Figure 1. Cantilever beams fabricated using selective laser melting. The beams are made of 316L stainless steel.

Large residual stress distributions typically develop during manufacturing with laser sintering due to the high cooling rates [5]. As a result, a stress relief heat treatment may be necessary after the build to release stresses and ensure dimensional stability. Moreover, though parts are typically greater than 99.9% dense, some porosity is generally observed. To help improve the strength and fatigue life of the part, a hot isostatic press process is commonly performed prior to solutionizing and ageing of the part [6] [7].

The mechanical properties of additively manufactured parts deserve special attention due to the unique build process. For instance, greater anisotropy and greater yield strength variability can be expected compared to conventionally processed materials [8]. The microstructure of additively manufactured parts is also observed to vary from conventionally processed materials. This can require unique heat treatments to optimize mechanical properties [8] [9].

Bearing these challenges in mind, additive manufacturing offers new opportunities to explore unconventional design concepts because of the freedom offered to the designer and the lower cost and time expenditures required for manufacturing. Computational tools like topology optimization, which optimizes material placement within a design space, also work extremely well with additive manufacturing techniques and may offer new avenues for creative design [10]. However, no examples of force balances being fabricated using additive manufacturing were found in the literature.

B. Design Concepts

Beyond alternative manufacturing approaches, alternative balance design concepts may offer opportunities for reduced cost and time of manufacture in addition to other benefits to balance users.

For instance, Ringel et al. [11] designed and fabricated a non-integral, axial force measuring element. This single component force balance measures axial force independently and externally from another force balance that measured the remaining five components. The design showed low pitch and yaw interactions and good linearity even at high combined load ratios. They also mentioned the ability to accurately measure normal and axial force with ratios as high as 50 to 1.

This is intriguing from a cost and manufacturing perspective because the axial section is usually the most expensive to manufacture. If a set of external axial force elements were fabricated to cover the range of expected loads, more customers might be interested in fabricating the remaining five component balance tailored to their application.

III. Materials

Ultra-high strength steels like maraging steel C-300 are the most commonly used materials to manufacture balances. They are some of the strongest and stiffest materials in tension and compression. Moreover, these materials have a good combination of machinability, ductility, and fracture toughness. They also behave very well as spring materials. Continued ultra-high strength steel research is underway [12]. One development has been the AerMet 100 alloy, which was designed to replicate the strength of maraging steel 300, but with twice the fracture toughness [13].

Table 1 lists a few key mechanical properties for maraging steel C-250, maraging steel C-300, AerMet 100, and a few other traditional commercial alloys. These other alloys include iron based superalloy A-286 and nickel-cobalt based superalloy MP35N. AerMet 100 and MP35N have similar mechanical properties to maraging steel C-300. MP35N also has a higher modulus than C-300 and a very good combination of high temperature and cryogenic stability [14, 15]. Alloy A-286 does not offer the yield strength of the maraging steels, but does provide exceptional toughness [16] [17]. Moreover, alloy A-286 can be used at elevated temperatures [18].

In general, maraging steels continue to push the envelope in terms of overall strength and stiffness while still providing sufficient toughness. But recent concerns over fatigue life of balances, may justify surface hardening of maraging steels. Examples of nitriding and shot peening are presented below demonstrating benefits of a post fabrication surface treatment to enhance the fatigue life of maraging steels.

A. Nitriding of Maraging Steels

Karlinski [24] conducted a study looking at a variety of nitriding treatments on maraging steels. He confirmed through statistical analysis that at high cycles to failure (lower applied stress) there is a significant difference between specimens that were only aged and specimens that received an additional nitriding treatment. The bending fatigue limit for 2x10^6 cycles was 870+/-20 MPa for nitrided steel and 600+/- 30MPa for aged specimens. Thus, the increase in fatigue strength was about 45%. It is recommended to perform nitriding of maraging steels in the solution annealed condition [19]. Consideration must be given to potential distortion and dimensional changes of the part after nitriding.

Table 1. Mechanical properties for C-250 and C-300 maraging steels as well as a few other commercial alloys.

Material	**Young's Modulus Msi (GPa)**	**Yield Stength ksi (GPa)**	**Ultimate Strength ksi (GPa)**	**% elongation**	**Charpy Impact Room temp./ cryo temp. ft-lb. (J)**	**Rockwell Hardness**
C-250 [17, 19]	27 (186.2)	248 (1.71)	253 (1.74)	10.7	20/10 (27/14)	RC 50
C-300 [17, 19]	27.5 (189.6)	287 (1.98)	294 (2.03)	10.3	19/10 (26/14)	RC 55
A286 [20, 17]	29.1 (200.6)	112 (0.77)	159 (1.10)	26	55/50 (75/68)	RC 36
MP35N [14, 17, 21, 22]	33.8 (233.1)	285 (1.97)	295 (2.03)	9.4	17/16 (23/22)	RC 55
AerMet 100 [13, 23]	28.2 (194.4)	246 (1.70)	285 (1.97)	14	35/19 (47/26)	RC 55

B. Shot Peening

Two studies ([25] and [26]) have shown the benefits of shot peening maraging steel. Shot peening was performed after machining, polishing, and ageing the samples. In both cases, a maximum compressive residual stress of approximately 900 MPa was generated at the sample surface. Fatigue strength, particularly in the case of high applied stress, increased substantially. This was supported by evidence that fracture initiated at the surface on un-peened specimens and internally for the peened specimens. Peening of an entire balance maybe impractical given the number of recessed surfaces, but could prove beneficial in specific areas prone to fatigue cracks.

IV. Sensors

The sensors covered in this section consist of transducers measuring a variety of different phenomena including resistance change and resonant frequency shift among others. We recognize that all of these sensors are analog in nature and thus have effectively infinite resolution. In an effort to compare resolution across sensor classes, we report resolutions stated in the literature that reflect typical resolution limitations introduced by the data acquisition systems, system noise, etc.

Resistive foil strain gages remain the state-of-the-art transducer for balances. They offer a compelling combination of resolution (less than 1 microstrain [27]), long term stability, and temperature stability [27].

While strain gage technology is very mature, other sensor technologies offer alternatives that are worth exploring to assess the unique benefits they may offer to address researcher needs. For instance, technologies with better strain resolution and accuracy would enable balances to be designed with higher factors of safety and hence longer fatigue lifetimes without sacrificing force resolution and accuracy. Improved sensors may also be able to reduce time and cost of manufacture by simplifying balance design. In this section, we review alternative strain sensing technologies that could replace or complement existing resistive foil strain gages.

A. Semiconductor Piezoresistive

A semiconductor gage's change in resistance is related to the strain experienced by the gage, similar to a foil-resistive gage. However, a semiconductor gages change in resistance is affected by the average number of charge carriers and the average carrier mobility of the semiconductor [28]. Similar to resistive strain gages, they are often placed into a bridge configuration to compensate for temperature effects [29]. Careful attention must be paid to thermal matching of the piezoresistive gages and other bridge thermal compensation techniques because piezoresitive gages are more sensitive to temperature than foil gages [29] [30].

Unlike a foil strain gage, whose change in resistance is primarily linked to geometrical changes, semiconductor gages exhibit greater sensitivity (gage factor >100) [29]. Strain resolution less than 0.1 microstrain can be expected [27]. While semiconductor based gages are inherently brittle, manufacturers typically guarantee their gages to 3500 microstrain in tension [30]. Semiconductor gages also have larger bandwidths and shorter response time compared to foil gages [30], which makes them well suited for dynamic measurements [31] [32].

In 2015 [32], they were installed in a balance designed specifically for high drag models requiring large starting and stopping loads. These tests were tens of seconds in duration and produced a small temperature change of approximately 1°C. The researchers concluded the balance worked well for this application, but they speculated that it would not be ideal for general use. Semiconductor gages have also been incorporated into numerous commercial products including pressure transducers and multi-axis force and torque transducers.

B. Piezoelectric Strain Gage

The measurement of strain with piezoelectric strain gages is fundamentally different than resistance based gages. With these devices, charge is generated as a result of straining a piezoelectric material. The amount of charge generated is measured and related to the strain experienced by the gage. Piezoelectric based strain gages have been used successfully in dynamic wind tunnel balances [33] [34]. Applications have mainly been dynamic in nature because at low frequencies large drift in the signal amplitude is present [29]. In fact, it is not possible to determine the true static condition because of leakage current through the piezoelectric material [35].

In contrast, the high frequency noise is very low [29] and the strain resolution can be less than 0.01 microstrain for the best piezoelectric quartz gages [27]. The enhanced resolution has enabled balance designers to increase balance stiffness and therefore to lower gage stresses. These lower stresses are needed because of the brittleness of most piezoelectric materials. Moreover, nonlinearities and material property changes begin to occur above 150 microstrain [35].

C. Surface Acoustic Wave Sensors

Surface acoustic wave (SAW) devices incorporate a piezoelectric material that generates a surface acoustic wave within a substrate material. With these devices, the resonant frequency of the surface acoustic wave changes with applied strain to the substrate [36]. The sensitivity of these devices is measured in terms of a shift in resonant frequency per amount of strain. A commercial SAW strain sensor [37] provides a 408 Hz shift in resonant frequency per 1 microstrain with a resonant frequency of 433.97 MHz. Temperature sensitivity has been reported between 450 Hz/°C and 926 Hz/°C [36]. A reference sensor is often used for temperature compensation [38].

One key advantage to SAW devices include their ability to operate wirelessly through the use of radio frequency pulses. Radio frequency antennas are required for operation but, the sensing system requires no power to operate. If the SAW devices are physically connected, they can be daisy chained as long as their resonant frequencies are sufficiently spaced such that their signals do not interfere. SAW devices currently have limited commercial availability and have not been used in any balance applications.

D. Fiber Optic Strain Sensors

Fiber optic strain sensors comprise a diverse range of optical technologies, but they can generally be divided into three classes: interferometric, distributed, and gratings based [39]. Within these classes are several subclasses. Given the scope of this review, we will focus on Fabry-Perot based interferometric and fiber Bragg grating sensors because their current strain resolution and commercial availability make these sensors best suited for wind tunnel balances.

Typical strain resolution for a Fabry-Perot sensor is approximately 0.15 microstrain [39]. Newer fiber Bragg grating sensors report a strain resolution of 0.4 microstrain [40]. Fabry-Perot sensors have greater strain resolution, but they generally have limited multiplexing ability – with a single sensor per fiber. Fiber Bragg grating based sensors can have hundreds of gratings on a single fiber [39], but higher accuracy grating fibers typically have less than ten. Both Fabry-Perot and Bragg grating sensors measure strain at discrete points. The bend radius is limited to approximately 17 mm [41] and care must be taken to pre-tension the fibers in order to accurately measure compressive strains.

Temperature compensation of strain measurements using fiber optic technologies is necessary. Optical fibers, just like all strain sensors, will measure thermally induced strains due to the coefficient of thermal expansion of the fiber optic and its base material. In addition, the refractive index of the fiber optic exhibits a temperature dependence which can create apparent strain. [42] [43] [44]. For fiber Bragg gratings, a 1°C temperature change can generate the equivalent of 8 microstrain [42]. Numerous temperature compensation schemes have been proposed [42] [43].

Several researchers have reported designing and fabricating wind tunnel balances using fiber optic technology. Pieterse and Bidgood [45] demonstrated a 4 component optical fiber balance designed around what they refer to as a two groove concept. With this concept, they measure the displacement between two grooves cut into the balance rather than measuring strain of the material at some point on the balance. This idea takes advantage of mechanical amplification in that the deformation increases as distance from the center of the balance increases. In a subsequent concept paper [46], they propose taking advantage of a lever to further improve accuracy in the axial section using a displacement concept.

Edwards [47] noted better accuracy (0.8%) and resolution (0.002%) of a Fabry-Perot sensor directly compared to a foil strain gage sensor. He further demonstrated the use of a Fabry-Perot sensor on a force balance with mixed results.

E. Sensor Fusion

Generally, only a single type of strain sensor is applied to a wind tunnel balance. Recent studies in the nanopositioning field have demonstrated the benefits of using two complementary strain sensors [48] [49] [50]. Since every strain sensor has its limitations, the idea is to develop an algorithm that incorporates strain measurements from two or more strain sensors measuring the same apparent strain and to convert the two measurements into a single measurement with improved characteristics.

This may offer a way to extend the capabilities of existing balances with modest investments. For example, an application may require increasing the sensitivity of a single component on an existing balance. Rather than designing an entirely new balance to accommodate the sensitivity requirement, a complementary sensor could be added to provide the increased sensitivity.

V. Data Acquisition

Acquisition of data from wind tunnel balances is application and facility specific. However, it is common for a high precision DC power supply to provide a specified amount of voltage to the numerous Wheatstone bridge circuits on the wind tunnel balance. Differential voltage across the bridges is then typically measured with a high precision multimeter placed outside of the wind tunnel. This is a highly accurate and stable measurement because of proper shielding of the lead wires and because of the high input impedance from the multimeter, which minimizes current flow through the bridge lead wires (which can extend several meters in length).

While the current approach works well, it presents logistical challenges, since each balance typically has unique quantities of input and output signal cables. This requires the balance user to dedicate time to proper wiring and integration of the balance into the wind tunnel's data acquisition system. Integrating parts of the data acquisition system into the balance could make use of balances more streamlined. For instance, several commercial load cell manufacturers sell load cells with built in electronics. The on-board electronics convert the analog signals to digital signals internally to the load cell or within the lead wire bundle so that the load cells can be directly plugged into a computer. This approach eliminates the need for costly external power supplies, multiplexers, and multimeters. Moreover, built in electronics may enable simpler tracking of a balances loading history since there could be an on-board data logger.

There are few examples of integrated circuits (IC) being incorporated into wind tunnel balances in the literature. For example, Bidgood [51] reported using an IC in a refurbished side wall balance to provide the bridge excitation, amplify the balance signal, and add a thermal offset to compensate for thermal drift.

Starting in 2008, engineers at NASA Glenn have developed onboard electronics and wireless telemetry systems (Figure 2) to facilitate data acquisition from rotating balances used in fan models. The onboard electronics can accommodate up to 12 balance bridges, 4 bridge-based pressure transducers, 24 strain gages, 10 temperatures, and 7 health monitoring voltages. The system utilizes 24-bit analog to digital converters for data acquisition. The analog to digital converters utilized for balance bridges, strain gages, and pressure transducers are simultaneously sampled and synchronized amongst ICs. The remaining signals are sequentially sampled by a single analog to digital converter. Onboard logic is provided by field-programmable gate arrays.

The digitized data is transferred out of the rotating model via one of two methods: a set of two magnetically coupled coils providing uni-directional serial links or a fiber-optic slipring providing gigabit Ethernet. A field programmable gate array based receiver card is at the other end of either link and is responsible for further data transmission and processing.

Figure 2. Image of a telemetry system installed on a dummy rotating balance. (Courtesy of Jonathon Ponder at NASA Glenn Research Center)

VI. Summary

In this review we have focused on manufacturing, design, materials, sensors, and data acquisition technologies that could be applied to wind tunnel balances to reduce manufacturing cost, manufacturing time, setup time, and increase the factor of safety.

Based on our cursory review, we believe additive manufacturing is the most likely technology to make an immediate and significant impact on force balance design, cost, and manufacturing time. Alternatives to foil based strain gages represent another promising research area and we plan to continue to investigate new sensor technologies so we can make informed decisions regarding implementation in future balances. Finally, we plan to further research incorporating digital electronics into balances to simplify the user experience and to enable the wireless transmission of data.

All of the technologies discussed here offer potential benefits, however selection and further development should be driven by aeronautical researcher needs. Moreover, decisions regarding implementation require a force measurement systems view given the interdependency between requirements.

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