Summary Report of the First International Symposium on Strain Gauge Balances and Workshop on AoA/Model Deformation Measurement Techniques

John S. Tripp[*], Ping Tcheng[*],
Alpheus W. Burner[#], and Tom D. Finley[#]
Mail Stop 238
NASA Langley Research Center
Hampton, Virginia 23681
USA

1. SUMMARY

The first International Symposium on Strain Gauge Balances was sponsored under the auspices of the NASA Langley Research Center (LaRC), Hampton, Virginia during October 22-25, 1996. Held at the LaRC Reid Conference Center, the Symposium provided an open international forum for presentation, discussion, and exchange of technical information among wind tunnel test technique specialists and strain gauge balance designers. The Symposium also served to initiate organized professional activities among the participating and relevant international technical communities.

The program included a panel discussion, technical paper sessions, tours of local facilities, and vendor exhibits. Over 130 delegates were in attendance from 15 countries. A steering committee was formed to plan a second international balance symposium tentatively scheduled to be hosted in the United Kingdom in 1998 or 1999.

The Balance Symposium was followed by the half-day Workshop on Angle of Attack and Model Deformation on the afternoon of October 25. The thrust of the Workshop was to assess the state of the art in angle of attack (AoA) and model deformation measurement techniques and to discuss future developments.

2. INTRODUCTION

The concept of an international strain gauge balance symposium was advocated in a technology assessment entitled "A White Paper on Internal Strain Gauge Balances." This internal document, published by LaRC staff members in March 1995, was based on an international survey of internal strain gauge balances conducted under contract in 1994-1995 (ref. 1). The conclusions of the white paper were presented to a peer review panel on wind tunnel testing technology, composed of selected leaders from major commercial and government aeronautical facilities, held in July 1995 at LaRC. The panel strongly endorsed the proposed international strain gauge balance symposium, which is the first of its kind.

Over 130 delegates from 15 countries were in attendance, including Australia, Canada, China, Finland, France, Germany, India, Indonesia, Israel, the Netherlands, Russia, South Africa, Sweden, United Kingdom, and the United States. The program opened with a panel discussion, followed by technical paper sessions, and guided tours of the National Transonic Facility (NTF) wind tunnel, a local commercial balance fabrication facility, and the LaRC balance calibration laboratory. Vendor exhibits were also available.

The opening panel discussion addressed "Future Trends in Balance Development and Applications." The nine panel members included eminent balance users and designers representing eight organizations and five countries. Formal presentation of papers in technical sessions followed the panel discussion. Forty-six technical papers were presented in 11 technical sessions covering the following areas: calibration, automatic calibration, data reduction, facility reports, design, accuracy and uncertainty analysis, strain gauges, instrumentation, balance design, thermal effects, finite element analysis, applications, and special balances. A general overview of the past several years' activities of the AIAA/GTTC (Ground Testing Techniques Committee) Internal Balance Technology Working Group was presented. The group's activities has prompted sufficient interest among the foreign Symposium attendees, that a separate Euro-Asian Inter-Nation Internal Balance Working Group was contemplated. At the conclusion of the Symposium, a steering committee representing most of the nations and several US organizations attending the Symposium was established to initiate planning for a second international balance symposium, to be held within 2 or 3 years in the UK.

The Workshop on Angle of Attack and Model Deformation Measurement Techniques was held immediately following the Symposium for assessment of the state of the art in AOA and model deformation measurement techniques and to discuss future developments. Twelve presentations from industry and government in the United States, Europe, and Asia covered various AOA and model deformation measurement techniques, applications, and concerns. The Workshop concluded with an open panel discussion.

The following summaries of the panel discussion and selected technical papers were obtained orally and from video tape recordings of the presentations. The authors of this report disclaim responsibility for accuracy of the transcribed notes and regret any misinterpretations of the panelists' and symposium authors' intentions. Panelists and symposium authors should be contacted directly for further elaboration; contact information is available from NASA LaRC representatives.

---

[*] Co-Chairs of the International Balance Symposium
[#] Authors of comments on Workshop on AoA/Model Deformation Measurement Techniques

3. PANEL DISCUSSION

The Symposium opened with a panel discussion entitled "Future Trends in Balance Development and Applications." The panel consisted of the following members:

Ron D. Law, Defense Research Agency (DRA), Bedford, UK, Panel Chair

Maurice Bazin, Office National D'Ètudes et de Recherches Aèrospatiales (ONERA), France

David M. Cahill, Sverdrup Technology Inc./AEDC Group, USA

Prof. Bernd Ewald, Technische Hochschule Darmstadt (TUD), Germany

Pieter H. Fuykschot, Nationaal Lucht-En Ruimtevaartlaboratorium (NLR), the Netherlands

Steven Hatten, Boeing Commercial Airplane Group, USA

James G. Mitchell, Microcraft, Inc., USA

Lawrence E. Putnam, NASA Langley Research Center (LaRC), USA

Paul W. Roberts, NASA Langley Research Center, USA.

Each panelist briefly presented his views regarding future trends in balance development and applications. Important areas covered included materials, temperature compensation, gauging, analysis methods, and calibration efficiency. The panel members agreed that the existing balance technology will continue to prevail in the foreseeable future, with only evolutionary improvements possible. No radically new basic technologies such as fiber optics techniques are expected to offer any competition in terms of accuracy and reliability. It was agreed that international standards for nomenclature, calibration procedures, accuracy reporting methods, etc. should be adopted in the future following the precedent of the North American Internal Balance Working Group, although agreement is not presently feasible. However, this Symposium is an important first step in establishing formal international discussions about these concerns, especially in regard to agreement on terminology. After the individual presentations a group discussion followed.

Selected observations from the panel discussion follow.

Ron D. Law, DRA Bedford, UK, Panel Chair

Stiffer balances are needed for tests at high angles of incidence under unstable flow conditions. Since the balance forms part of the spring system of the model and its supporting structure, unwanted dynamic oscillations within the balance itself will corrupt test data. Although an infinitely stiff balance would eliminate this problem, it is unrealizable. Stiffer balances are especially needed for half-models and for heavy models. Replacement of strain-gauged flexures with sensitive piezo-electric cells provides greatly increased stiffness with good signal output. The use of high-output platinum strain gauges provides high sensitivity for stiff designs although temperature sensitivity is greater. Composite materials, such as carbon-fiber layered flexures, have been suc-

cessfully tested in lighter weight balances used for low speed testing. Improved semiconductor strain gauges also offer increased sensitivity. Finite element analysis can be employed during design to predict balance dynamic behavior.

Maurice Bazin, ONERA, France

ONERA has developed balances which provide good drag-count resolution for all wind tunnel applications including cryogenic testing. Future trends are difficult to predict at present. Advanced technology may offer better ways of measuring strain, such as the use of doped materials or micro-laser techniques

David M. Cahill, Sverdrup Technology Inc./AEDC Group.

Analysis of elastic and anelastic hysteresis, and study of fabrication and heat treatment techniques for metallic and non-metallic materials are areas where additional emphasis is needed. Development of alternative techniques for strain measurement would be beneficial. Hardware as well as software compensation techniques for temperature effects are recommended. Calibration techniques need to be examined, including: the number of loadings required for calibration, application of combination loadings including third order and above, and the inclusion of calibration uncertainty analysis. Standardization is needed in the following areas: terminology for forces and moments, and the axis systems; the calibration matrix and the matrix format; treatment of calibration tares; data reduction to forces and moments by the non-iterative mathematical model and the iterative mathematical model; and inclusion of model weight as part of the tares during data reduction.

Prof. Bernd Ewald, TUD, Germany.

TUD has developed a new single-piece balance from copper-beryllium alloy for the European Wind Tunnel (ETW). Although copper-beryllium imposes some inconvenient manufacturing requirements, it is an excellent spring material, has very low hysteresis, and has very high heat conductivity. Tests of titanium alloy at TUD disclosed no detectable hysteresis indicating that it is a promising material for future balance fabrication. Machine calibration is seen as becoming mandatory because of its accuracy and reliability, and because of the excessive manpower requirements for manual calibration. The maximum resolution of the conventional strain gauge is on the order of 25×10^{-9} mm or approximately 1/20000 of the wavelength of visible light. It is unlikely that potential strain measurement alternatives can match this resolution at present. Electric and pneumatic lines bridging the balance in the test model produce measurement bias errors due to unknown residual forces. TUD has considered integrating these lines into the balance structure. The resulting effects of residual forces would then be removed by calibration.

Pieter H. Fuykschot, NLR, the Netherlands.

No major revolution, rather evolution, is seen in balance technology. Two major problem areas are interactions and temperature effects. Balances should be designed for minimum interactions and maximum linearity, rather than using calibration to remove their effects. Nonlinearity can cause bias errors due to rectification effects during dynamic test conditions, which cannot be corrected by calibration. Materials with a low coefficient of thermal expansion, such as titanium, should be considered. Compensation for tempera-

728

ture gradients is important. Balance convection screens can be installed within the model to reduce heat transfer within the flexures. Dynamic modeling should be done during the design phase to minimize resonant vibrations during tests. Standardized model-to-balance couplings should be adopted for inter-laboratory compatibility. Automatic calibration is an important future trend. The balance should be calibrated through zero load to attain positive and negative loadings rather than by mechanical inversion as usually done during manual calibration. The balance should be calibrated with couplings identical to those used during tests.

Steven Hatten, Boeing Commercial Airplane Group.
Corporate concerns have resulted in an emphasis on reducing the development cycle times for both production aircraft and for test models. Simplified designs and procedures are emphasized, such as parametric spreadsheet design tools. Parametric finite element models are employed to analyze stiffness and dynamic behavior. Older balances in the inventory are being recycled for new testing. External balance calibration is being automated. Balance users at Boeing are demanding improved balance measurement accuracy, especially in drag. Ways to increase drag accuracy are being investigated. Uncertainty due to mechanical hysteresis is being reduced via a redesigned model attachment interface. Effort is also being applied to thermal gradient correction methods for improved accuracy.

James G. Mitchell, Microcraft, Inc.
Progress in strain gauge balances has been slow, with 40-50 year-old strain gauge and design methodology still in use. The strain gauge balance design community should exploit new technology in related fields such as optics, microelectronics, and smart structures. Balance customers, i.e, test facilities and test engineers, are asking for "better, faster, and cheaper." The response is as follows: Better: Uncertainties can be reduced through study of calibration practices, increased load per unit diameter, increased stiffness, improved math models, and calibration using combined loadings. Faster: While balance design, fabrication, and gauging can be accelerated, the large opportunity is in the area of calibration with automated machines. Balance calibration times are reduced from days and weeks to a few hours. Cheaper: Reduced cycle times result in lower costs.

Lawrence E. Putnam, NASA LaRC, USA.
Comments were made from a wind tunnel user's point of view. LaRC balances must function over test environments ranging from cryogenic conditions at the NTF wind tunnel to high temperatures at the eight-foot high temperature structures tunnel. Drag uncertainty provided by LaRC balances, based on calibration laboratory data, is on the order of 0.6 drag counts, which is adequate for customer requirements. However, operational accuracy in the wind tunnel is worse. Temperature gradients during tests are a major source of uncertainty. Multiple calibrations are needed to estimate precision uncertainties which are not currently done with manual calibration. This is feasible only with automated calibration equipment. Improved balance robustness is needed to reduce down time during tests. Problem areas include strain gauges, cement, and moisture proofing.

Paul W. Roberts, NASA LaRC, USA.

Future improvements in balance design and performance can be expected in a number of areas. Areas in calibration include the experimental design, estimation of separate precision and bias uncertainties, and custom calibration for specific wind tunnel tests. The mathematical model will be extended to include higher order interactions. Although interactions and nonlinearities should be minimized, balance physical size constraints dictated by the test facility may preclude this. More complete uncertainty analysis than is now provided will be available. Real-time compensation for thermal gradients and other effects are being developed. More sensitive strain measurement sensors, although not presently feasible, can be expected over the long term. New fabrication methods with shortened production time are possible. Finally, automatic balance calibration systems are an essential need for the future.

4. OVERVIEW OF TECHNICAL PRESENTATIONS
The majority of the three-and-one-half-day symposium was devoted to 46 papers delivered in 11 technical sessions. A list of the scheduled paper presentations and authors is given in the Appendix. Several papers were not presented due to the authors' inability to attend the Symposium. Brief summaries of selected topics representing important areas of the balance technology are now presented.

4.1 Balance Design
Nearly half of the technical papers presented described unique balance design techniques. Several innovative axial section designs for improved sensitivity and reduced thermal effects were discussed. Finite element analysis methods have disclosed unexpected local stress concentrations, approaching yield limits of the material in some cases, which could not be readily predicted by conventional design methods. Varied techniques for thermal gradient characterization and compensation were described. State-of-the-art methods in strain gauge manufacturing and application were described. Other papers were given on conventional and unique balance applications, including unusual balance designs for special applications.

4.1.1 J. Zhai, TUD, Germany, discussed optimization of internal strain gauge balance design using finite element computation. The aim of the TUD study was to improve accuracy by reducing interferences (interactions) and by increasing stiffness. Sources of linear interactions include the structure, strain gauges, and manufacturing tolerance errors. Strain gauge effects include gauge factor, position, and direction. Product interactions result primarily from deformation of the material. Quadratic and cubic interferences arise from nonlinearity of the material. These effects can be reduced by structural redesign. The linear interaction on drag can be reduced by decreasing the stiffness of the measuring spring, decreasing spacing between measuring beams, and increasing the slope of the main beam. The shape of the drag sensing element can be changed to provide additional decoupling. TUD attained a 38% reduction in drag interaction by choosing suitable dimensions and a 92% reduction in drag interaction by use of a point-symmetrical configuration. Low stiffness causes large nonlinear interactions and a lower natural frequency of the model-balance-sting system which, in turn, increases measurement errors during dynamic test conditions. Stiffness in the X direction was increased 60% by changing the drag-sensing element from a bending beam to a

shear spring. Similarly, stiffness in the Z direction was increased 65% by changing the bending moment measuring system from a bending beam to a shear spring. Additionally, stiffness in the Z direction was increased 21% through the use of combined main beams.

4.1.2 Prof. Bernd Evald, TUD, Germany, discussed advanced internal balances for cryogenic and conventional wind tunnels. Only gradual improvements based on careful research and development are anticipated. Three general rules for balance users and designers include the following: selection of the load range to match the test requirements as closely as possible; employment of geometric dimensions as large as possible; and design of the balance structure to be as stiff as possible. Three types of balances are generally needed for industrial aircraft development: very sensitive balances for cruise optimization; less sensitive balances for buffet, maximum lift, and dive testing; and an envelope balance for stability and control, control surface deflection, and large AoA and yaw angle tests. Balances with high stiffness are difficult to fabricate with conventional electric-discharge machining techniques. Now, electron beam welding technology gives the balance designer complete freedom to fabricate any desired internal structure. TUD employs an interactive software package for design via fundamental stress and strain analysis methods. Research and optimization are done via FEA software. Maraging steels, which are good for electron beam welding, are used for cryogenic and conventional balances. Special heat treatment methods are applied to reduce hysteresis. Although some authorities advocate the use of heated balances for cryogenic use, Prof. Evald prefers balance designs which tolerate thermal gradients by mechanical cancellation methods and by electrical compensation. He proposes future development of a "black box" plug-and-play balance concept in which all necessary parameters would be stored in a memory chip integrated into the balance structure. The balance identification, calibration matrix, and electrical connection information would be stored on-board. The proper electrical connections and data reduction would be automatically configured by wind tunnel data systems. Future developments would also provide an optical telemetry link from the balance to the wind tunnel data acquisition system to eliminate mechanical bridging caused by strain gauge conductors.

4.1.3 The design philosophy of a high-quality balance at NASA LaRC is briefly presented. All LaRC balances are custom designed to meet the load ranges, physical size, thermal environment, and accuracy requirements for given research projects. Single-piece construction techniques using high-quality maraging steel are employed whenever possible. Most LaRC balances are of the direct-reading type; moment-type balances are typically used in extreme thermal conditions such as the cryogenic environment at the National Transonic Facility (NTF). All LaRC balances employ modulus compensated transducer quality strain gauges. Where extreme thermal environments are anticipated, a patented apparent-strain gauge-matching technique is used. Thermal compensation is provided by pure nickel wire placed in the Wheatstone bridge circuit to reduce temperature effects on the bridge output to less than 0.005 percent full scale per degree Fahrenheit. Balance temperatures and gradients are measured by means of resistance temperature detectors (RTD). These temperature measurements allow linear cor-

rections to be applied for thermal sensitivity shifts and second-order corrections for apparent strain.

4.2 Automatic Balance Calibration
Presentations were given describing four different automatic calibration machines at DRA-Bedford, CARDC, IAI, and TUD. Significant advantages of automatic calibration include manpower savings, decreased calibration time, expanded experimental loading schedules, the ability to apply multiple loadings, and improved calibration accuracy. However, differing results with respect to loading accuracy and repeatability were reported. Primary sources of calibration inaccuracy are load vector misalignment, force measurement sensor inaccuracy, and precise repeatability of the balance mechanical position within test fixtures. Highlights of reported experience with automatic calibration are summarized

4.2.1 China Aerodynamics Research and Development Center (CARDC)
CARDC reports the best calibration accuracy although verification data were not available. It is possible that the cited Chinese calibration accuracy is estimated based on the accuracy of the load cells used and the assumption that the system is perfectly realigned after each load application.

4.2.2 Israel Aircraft Industries (IAI)
Michael Levkovitch, IAI, gave an unscheduled presentation describing the IAI automatic calibration machine. He indicated that a new machine with a larger load capacity is under development. The presentation indicated that the IAI machine does not reposition to correct loading deflections, but rather measures deflections. Thus, inaccuracies in measurement of angular alignment may dominate the total machine uncertainty. The authors note that since the machine is not designed to function as a repositioning servomechanism, machine accuracy could be improved with better displacement measurement sensors. Without improved positioning measurement accuracy, the use of expensive highly accurate load cells would produce only marginal improvements in overall calibration machine accuracy at present.

4.2.3 Technische Hochschule Darmstädt (TUD)
A first generation automatic calibration machine was designed by TUD and manufactured by Schenk for the European Wind Tunnel (ETW.) A second generation prototype is being developed at TUD. The needs for machine calibration include manpower costs, reduced calibration time, avoidance of human errors, and convenient inclusion of temperature as a calibration parameter. The machine is able to generate loadings in any order in all possible component combinations up to sixth order, thus allowing estimation of third and higher order coefficients. Zero readings are obtained automatically. Loads are generated by actuators and measured independently by load cells, such that the actual applied loads are determined. The balance may be enclosed in a temperature-controlled chamber for cryogenic calibration. The design avoids thermal gradients during temperature-controlled calibration.

4.2.4 DRA Bedford
DRA recently developed a six-component precision automatic balance calibration machine for in-house use. Forces are applied using pneumatic actuators and are measured using sensors. Forces are applied such that the need for reposi-

tioning is avoided. An example was given of calibration of a balance to be installed away from its virtual center. Since the measured outputs depend on the moment arm length in this configuration, the balance must be calibrated at two positions to permit correction for positioning at any displacement from center during tests. The automatic machine facilitates the multiple calibrations necessary for this application. A second example illustrated static calibration of a dynamic balance by automatic machine where loads must be applied and removed quickly.

4.2.5 *IAI Balance Calibration Consortium*
In 1995 Microcraft established a consortium to calibrate selected balances using the IAI automatic calibration machine at the San Diego, California facility. Two papers related to this effort were given. A paper containing some of the calibration results is summarized in Section 4.3. A summary of the other paper is now presented.

4.2.6 *IAI Machine Calibration of NASA LaRC Balance*
Ping Tcheng, NASA LaRC, presented a comparison of machine calibration accuracy versus manually loaded calibration accuracy. The paper contained a general discussion covering primarily data reduction and uncertainty analysis. Uncertainty analyses of eight sets of machine calibration data indicated that its calibration accuracy is adequate for many applications, providing better than 0.5 percent full-scale accuracy. The authors believe that manual calibration, albeit time consuming and labor intensive, is necessary to attain the best calibration accuracy at present. The IAI machine was user-friendly, easy to operate, with sophisticated supporting software providing immediate data reduction following calibration.

Inconsistencies noted among the eight calibration data sets were traced to poor repeatability of the balance center position caused by slack in the balance-to-test-fixture attachments following removal and re-installation of the balance. It was of interest to note that comments were received describing "spatial relocation error" problems with the Schenk automatic calibration machine at ETW similar to those observed by LaRC during IAI automatic machine calibrations at San Diego.

4.2.7 *Comments by Participants in IAI Calibration Consortium*
Additional comments were received from other Consortium participants regarding the consistencies of the automatic calibration machine. It was agreed by all participants that further improvements would be desirable. Boeing indicated that, in hindsight, a balance with larger interactions should have been selected for test calibration on the IAI machine. This would have better discriminated between the performance of the machine calibration and that of manual calibration. Moreover, the performance of higher order mathematical models and expanded loading schedules could have been better investigated and evaluated. In addition, during the consortium tests, LaRC engineers attempted to evaluate an enhanced calibration experimental design and mathematical model intended for balances experiencing significant third order interactions. Inasmuch as the test balance possessed only second order interaction effects with no apparent third order effects at all, the test of the enhanced calibration design and

expanded mathematical model was not well-posed. Therefore, the results were inconclusive.

4.3 Mathematical Modeling
Several presentations covered the interdependent areas of mathematical modeling, calibration experimental design, and calibration uncertainty analysis. It is clear that potentially significant improvements in balance accuracy lie in improved mathematical modeling and in the calibration experimental design. Additional resources may be profitably allocated to further development effort in this area.

4.3.1 Richard S. Crooks, Microcraft San Diego, presented a paper on the limitations of balance calibration mathematical models. This paper, of a general philosophical nature, was illustrated by comparative studies of the robustness, or predictive accuracy, of various polynomial-based mathematical models for three differently sized calibration experimental designs. The calibration data sets were obtained using the IAI automatic machine to calibrate a single balance. It was seen that the largest and most comprehensive experimental design (1322 points) produced the lowest calibration residuals and, consequently, the least overall standard error.

In order to investigate balance model robustness Crooks has taken advantage of the "proof-load" technique. He found that proof-load residuals were significantly reduced by the addition of a single third-order cross-interaction (non-cubic) term to the standard second-order polynomial model. The particular third-order term was selected by trial and error balance coefficient estimation with proof-load test data appended to the normal calibration data set. However replicated calibrations had not yet been conducted to estimate the uncertainty of the significant third-order term and to verify that it is not merely a spurious effect due to random errors, i.e., fitting data to measurement noise.

4.3.2 The authors believe that the practice of attaching proof-load data to calibration data prior to coefficient estimation invalidates subsequent tests for calibration design and model robustness based on proof-load data. Indeed, predictive validation of the model should be based on independent proof-load data acquired at loading combinations and levels absent from the calibration experimental design.

4.4 Uncertainty Analysis
Frank L. Wright, Boeing, discussed how balance accuracy requirements are specified by balance designers and users. In the past accuracy has been imprecisely defined in widely varying ways. Now AGARD Standard 304 is coming into use wherein bias and precision uncertainties, and their combined uncertainty are specified at a given confidence level. The user must clearly state the factors such as test conditions, the coordinate system being used, units, etc. at which the accuracy is being quoted. In the commercial aircraft industry the most important wind tunnel quantity is drag coefficient. Customers now ask for ½ drag count uncertainty at a 95 percent confidence level. Computations for a typical wind tunnel test show that uncertainties of $\pm0.002°$ in angle-of attack, ±2.5 lb in normal force, and ±0.8 lb in axial force are necessary to attain this requirement, which is probably not currently possible. Normal force and axial force precision uncertainties during tunnel tests may be estimated from balance calibration data by the following rules of thumb: tunnel re-

731

peat-point uncertainty is estimated from repeated back-to-back component calibrations; uncertainty within a Mach number run is estimated from multiple component calibrations interspersed over a five-day calibration; uncertainty over a complete test is estimated from the overall calibration standard error at the desired confidence level; and long term balance bias shift is estimated from zero shifts observed over a four-year period.

John S. Tripp, NASA LaRC, presented an overview of strain gauge balance uncertainty analysis techniques developed at LaRC. A second-order multivariate polynomial direct model is employed; i.e., balance voltage outputs are represented as functions of the applied input loads in accordance with the physical process being modeled. A Newton-Raphson iterative inversion method is employed for data reduction. The uncertainty analysis employs a global regression technique for least-squares estimation of the polynomial coefficient matrix. Equations are obtained therefrom for computation of calibration confidence intervals and prediction intervals as functions of the applied loadings. This is an extension of the previous method of reporting balance uncertainty as simple percentages of the full scale per component. It is noted that the calibration confidence intervals become fossilized bias errors subsequent to calibration. Additional sources of calibration bias uncertainties include calibration standard errors and mathematical modeling errors. Concepts for selection of calibration experimental design based on analytic methods developed by G. E. P. Box were presented for minimization of overall precision uncertainty and overall bias uncertainty. Statistical techniques for detection and estimation of calibration bias errors have been developed. It was pointed out that present procedures of lumping calibration bias and precision errors together in a single computation may significantly underestimate total calibration uncertainty. If the contributions of highly-correlated systematic errors are additive, then for the large calibration experimental designs typically used for balance calibration the usual RMS standard error underestimates the total uncertainty. Methods for separate estimation of bias and precision uncertainties are being developed.

Mark E. Kammeyer, formerly of the Naval Surface Weapons Center, Dahlgren Division, Silver Spring, MD presented an uncertainty analysis for force testing in production wind tunnels. It is an overview of a complete uncertainty analysis to provide bias and precision limits for computed model attitude and force coefficients inferred from measurements in Hypervelocity Wind Tunnel 9 at Dahlgren. Calibration and measurement uncertainties were propagated through the data reduction equations in accordance with the standard procedures specified by ASME, AIAA, and IOS. A jitter approach using computer software rather than analytical computation was used to propagate the bias and precision limits into the inferred reduced data in order to keep the computational requirements manageable. Results using actual test data show that balance load uncertainties are by far the dominant contributors to overall uncertainties in the reduced parameters. It was also found that precision errors in balance axial force measurements are dominant, whereas bias errors in the other balance components are dominant. These results are helpful in pinpointing areas wherein balance measurement accuracy improvements are needed.

The Dahlgren approach is similar to that reported in an uncertainty study conducted by Batill of Notre Dame (ref. 2) for the NTF wind tunnel in 1993. However, Dahlgren's analysis was more manageable because of the lower complexity of the Dahlgren facility compared to NTF.

4.5 Finite Element Analysis

Three agencies reported activities in finite element analysis (FEA): LaRC, NLR, and TUD. Notable progress in the application of FEA to balance stress analysis has been made recently. The technique is especially suited to determination of stress concentrations, to which conventional stress analysis techniques are not generally applicable. TUD reported using the technique for optimizing stress beam design as described above in Section 4.1.1. The consensus seems to be, however, that FEA is not yet sufficient to replace conventional stress analysis techniques. None of the above agencies report temperature effect analysis using FEA techniques. However, papers have previously been published at ONERA, France, on this topic by Bazin, et al. (ref 3).

Michael C. Lindell, NASA LaRC, presented an FEA study of an existing LaRC cryogenic balance. The purpose was to correlate FEA predicted strain levels with experimental values obtained from loadings, and to identify high-stress concentrations within the balance structure. The FEA software, which is adaptive, does not require prior knowledge of stress concentrations. Strain levels for a single full-scale load in each of the six components were computed and compared with measured values. Differences varied from 0.2% in predicted normal force to 11% in yawing moment. Maximum predicted stress was as large as 40% of yield under a full-scale normal force load, and 50% of yield under a full-scale pitching moment load. The analysis predicted maximum stress on the order of 100% of yield under simultaneous full-scale six-component loading. It was planned to verify this result experimentally. The study concluded that stress levels are predicted accurately by FEA and that stress concentrations can be predicted. Thus, FEA can improve the balance design cycle, and can be used to optimize the design to accommodate higher loads with lower weight and higher safety factors.

4.6 Thermal Gradient Compensation

Maurice Bazin, ONERA, France, discussed methods for balance thermal compensation. ONERA follows multiple approaches, namely bridge resistive compensation, mechanical design to minimize thermal effects, and numerical correction. Mechanical design methods to minimize thermal gradient effects are emphasized since error correction is very difficult compared to error prevention. Design methods to reduce temperature gradient effects include a traction-compression push-pull arrangement and a bending push-pull arrangement. Conventional gauging methods are used.

4.7 Facility Reports

Several presentations provided general descriptions of internal balance development and applications at major facilities.

Henk-Jan Alons, NLR, the Netherlands, gave a presentation co-authored with H. B. Vos describing balance development at NLR. NLR has investigated the performance of model-to-balance and balance-to-sting attachments. A hysteresis angle of 0.01° produces a 0.17% FS error in normal force, which is

excessive. In an effort to minimize attachment hysteresis NLR investigated taper joint, cylindrical tap, and end face flange attachments. The hysteresis angle of each of these attachments was measured under load by means of a precision inclinometer. The advantage of the taper joint is its small dimension in comparison to its high bending moment capacity. Its disadvantage is hysteresis under bending due to the unavoidable mating between the sting and the attachment socket. Typical taper joint angle hysteresis of $\pm 0.05°$ was measured. The cylindrical tap, previously thought to exhibit lower hysteresis, was found to be comparable to the taper joint. The tests disclosed, however, that the end face flange exhibits minimal hysteresis. Currently NLR employs the end face flange on the model end of the balance. Integral Wheatstone bridge strain gauges are provided to insure correct installation pre-stress levels. A taper joint is still employed on the balance sting end to maintain compatibility with existing wind tunnel stings.

5. STATUS REPORT ON NORTH AMERICAN INTERNAL BALANCE USERS WORKING GROUP

David M. Cahill, Sverdrup/AEDC, presented a general overview of the past several years' activities of the AIAA/GTTC Internal Balance Technology Working Group. Numerous areas of progress were cited: an increased willingness to exchange information freely among the participants; a survey of members' balance usage and methods of engineering practice; preliminary agreement on definitions of technical terms; and a 6 x 96 generalized matrix representation of balance calibration parameters. It was noted that a standardized method of computing and reporting balance measurement uncertainties will be developed and accepted soon.

6. FUTURE ACTIVITIES OF THE STRAIN GAUGE BALANCE COMMUNITY

6.1 Second International Symposium on Strain Gauge Balances

A steering committee representing most of the nations and several US organizations attending the Symposium was established to initiate planning for a second international balance symposium. Ron D. Law, DRA-Bedford, announced that DRA might be able to host a second symposium within 3 years. It was agreed that steering committee meetings in the interim should be scheduled in conjunction with other international aerospace conferences to enable as many members as possible to participate. Such an opportunity will arise at the Supersonic Tunnel Association (STA) meeting scheduled to be hosted by ARA and DRA in 1999. It was agreed that Japan should be invited to participate in future symposia. Additional discussion is needed to select a theme for the second Symposium.

6.2 International Round-Robin Balance Calibration

R. W. Galway, National Research Council, Canada, discussed the inter-facility balance calibration project proposed within STA in the fall of 1992. A round-robin test of a single balance by participating facilities had been suggested to provide an opportunity for comparison of different calibration techniques, experimental loading procedures, equipment, data reduction methods, and accuracy reporting methods. It would also provide some insight into the contribution of balance calibration uncertainty in tunnel-to-tunnel comparisons. The round-robin test results would be assembled into a

data set to allow investigation of the effects of the various calibration experimental loading designs used by the participants. This data set would be closely controlled in terms of what was measured and how.

STA contains approximately 45 participating organizations of whom about 25 were interested in the round-robin test, and of those about 15 were definitely interested. The Boeing #661 balance had been selected for testing. The STA proposal has remained inactive since the inception of the AIAA/GTTC North American Balance Working Group, the 1995 IAI automatic balance calibration consortium at Microcraft, San Diego, and this Symposium. Galway inquired whether the Symposium delegates considered a round-robin calibration of a single balance to be a "useful exercise." He volunteered to serve as the point of contact through which interested parties may register their interest in participation.

6.3 Euro-Asian Internal Balance Working Group

David M. Cahill proposed the establishment of a separate Euro-Asian Inter-Nation Balance Working Group as a result of interest indicated by several European Symposium attendees in participating in the North American Internal Balance Working Group. He also proposed that the Euro-Asian group should be established under the auspices of AIAA. He suggested that the solidarity of the new group should become established before its eventual merge with the North American Internal Balance Working Group. The feasibility of establishing a Euro-Asian group would depend upon its reception by the proposed membership.

7. CONCLUDING REMARKS ON STRAIN GAUGE BALANCES

The Symposium was very successful in the free open exchange of information, in establishing an international community for future communication on balance usage and technology, and in setting a precedent for future Symposia. It is expected that the professional relationships established during the Symposium pave the way for future international cooperation in the strain gauge balance field. The Symposium provided a previously unavailable technical forum for the exchange of information for users, designers, and manufacturers of strain gauge balances.

The Symposium augmented and extended the results gleaned from the international balance users survey conducted by LaRC in 1995. It is clear that no aerospace agency holds a commanding lead in all technical areas. NASA LaRC is the world's major strain gauge balance user in terms of existing inventory, the number of units used in tests annually, and the number of new balances fabricated annually. Automatic calibration machines, although not yet equivalent to manual calibration with respect to loading accuracy, are an increasingly significant factor in realizing time and manpower savings. They are also an important tool for developing improved mathematical models and calibration experimental designs, and for establishing balance calibration and measurement uncertainties.

Publication of the symposium proceedings is pending.

733

8. BALANCE SYMPOSIUM REFERENCES

Contractor Reports

1 Kilgore, R. A.: *Internal Strain-Gage Balances: An International Survey*. VigYAN, Inc., Hampton, VA 23666, March 1995.

2 Batill, S. M.: *Experimental Uncertainty and Drag Measurements in the National Transonic Facility*. NASA Contractor Report 4600, June 1994.

Other Reports

3 Bazin, M.; Blanche, C.: and Dupriez, F.: *Instrumentation for Cryogenic Tunnels*. ONERA, France.

9. WORKSHOP ON ANGLE OF ATTACK AND MODEL DEFORMATION

A workshop on angle of attack (AoA) and model deformation measurement techniques was held on the afternoon of the last day of the Symposium. Short review papers were requested covering AoA and model deformation requirements and needs, thoughts for the future, and problem areas, in addition to papers covering actual applications and developments. The thrust of the workshop was to assess the state of the art in AoA and model deformation measurement techniques and discuss future developments in an informal but informative atmosphere. A panel discussion on AoA and model deformation was held in conjunction with the Workshop. Co-chairs of the Workshop were Tom D. Finley and Alpheus W. Burner, NASA LaRC.

9.1 Presentations

Twelve presentations were made at the Workshop. The presenters, affiliation, country, and presentation titles are listed below.

Tom D. Finley, NASA LaRC, USA: "AoA Overview"

Alpheus W. Burner, NASA LaRC, USA: "Model Deformation Overview"

Frank L. Wright, Boeing, USA: "Comparison of Model Attitude systems: Active Target Photogrammetry, Precision Accelerometer, and Laser Interferometry"

Maurice Bazin, ONERA, France: "AoA and Model Deformation at ONERA"

Peter Bauman, DLR, Germany: " DLR Model Deformation Measurement System"

Peiter H. Fuykschot, NLR, the Netherlands: "Vibration Compensation of Gravity Sensing Inclinometers in Wind Tunnels"

J. R. Hooker, McDonnell Douglas, USA: "Static Aeroelastic Analysis of Transonic Wind Tunnel Models Using Finite Element Methods"

YuFu Liu, CARDC, China: "The Model Real Time Angle of Attitude Measurement in 4m X 3m Low Speed wind Tunnel"

Sergi Fonov, TsAGI, Russia: "Model Deformation Measurements in TsAGI's T-128 Wind Tunnel by Videogrammetry System"

Gregory M. Buck, NASA LaRC, USA: "In-Situ Calibration of Sting Bending Using Optical Measurements"

Anton R. Gorbushin, TsAGI, Russia: "Angular, Linear Model Displacements, and Model Deformation During Wind Tunnel Tests"

Ralph D. Buehrle, NASA LaRC, USA: "Summary of Inertial Model Attitude Correction Techniques"

9.2 Panelists
The panel included the following members:

Frank L. Wright, Boeing, USA, Moderator
Pieter Fuyschot, NLR, the Netherlands
Tom D. Finley, NASA LaRC, USA
Richard A. Wahls, NASA LaRC, USA
Alpheus W. Burner, NASA LaRC, USA
John S. Tripp, NASA LaRC, USA

9.3 Summary of Presentations
Tom D. Finley, NASA LaRC, USA, opened the Workshop with an overview of angle of attack (AoA) measurement. He described the history of AoA measurement at LaRC, which has been based primarily on the use of precision accelerometers. He described the current state of the art of LaRC inertial AoA measurement systems including components and implementation. Specially selected high performance sensors are obtained from the manufacturer. Each unit is packaged with special output temperature compensation circuitry and mechanical isolation pads to reduce the effects of high frequency vibration.

Alpheus W. Burner, NASA LaRC, USA, presented an overview of the development of model deformation measurement capability at the Langley Research Center. Aeroelastic model deformation in wind tunnels was defined. Some fundamental questions and concerns about model deformation measurements in general were presented. The approach, described as a single camera, single view video photogrammetric technique, used to make model deformation measurements at three NASA LaRC facilities, was described. An example of the change in wing twist induced by aerodynamic loading as a function of angle-of-attack at the National Transonic Facility at various dynamic pressures was presented as a typical data example.

Frank L. Wright, Boeing, USA, presented a wind-on comparison among three independent model attitude measurement systems: the traditional inertial accelerometer measurement system, a Boeing designed and built laser interferometer system, and a commercially available photogrammetric system. Test data for the three systems, obtained at various Mach numbers, showed prediction intervals lying between 0.005 and 0.01 degrees. Two other applications of the photogrammetric system were described: flap position measurement during an aircraft flight test, and wing twist measurement of a wind tunnel model

734

Maurice Bazin, ONERA, France, described developments at ONERA in AoA and model deformation measurement techniques. Precision accelerometers are used for AoA as well as the MAMS system due to Bertin (AGARD VKI-1996) which is somewhat similar to the Boeing Laser Angle of Attack (LAM) system. Potentiometers and encoders are used as well. Model deformation measurements have been made with stereo observation with the RADAC (ONERA T.P. n° 1990-57) and ROHR (ONERA Activities 1996). The RADAC system uses special cameras that contain crossed linear arrays. The ROHR system employs two conventional cameras. The uses of optical fibers and quadrant light detectors and a polarization torsionometer for model attitude and deformation measurements are described in ONERA T.P. n° 1982-91.

Peter Bauman, DLR, Germany, discussed the use of moiré interferometry for the measurement of model deformation and hinge moments. DLR selected moiré interferometry as the technique with greatest potential over others such as coded light, holographic interferometry, and speckle interferometry. The technique currently requires diffusely reflecting surfaces that may necessitate the painting of highly polished models. Bending and twist measurements have been made in wind tunnels. Expected accuracies are 0.01° for flap angles, 0.03° for twist, and 0.1 mm for bending. Future applications in the automotive industry and for laboratory measurements on helicopter rotor blades are anticipated.

Peiter H. Fuykschot, NLR, the Netherlands, described a correction technique given in a paper presented at an Instrument Society of America conference in May 1996. The technique reduces bias errors in model AoA measurements due to centrifugal forces developed during high tunnel dynamic test conditions. He showed that this inertial error, termed a "sting whip" error, is corrected by measuring the model's linear and angular velocities and multiplying them together. The technique, which requires multiple sensors for correction in both pitch and yaw planes, provides a real-time correction without knowledge of the vibrational modes of the model. He instrumented a model and demonstrated the ability of the technique at two single frequency modes and one multi-frequency mode.

J. R. Hooker, McDonnel-Douglas, USA, discussed the use of experimental measurements to calibrate computational methods used to predict wind tunnel model aeroelastic deformations. A wind-off static loading experiment conducted in the National Transonic Facility (NTF) test section was used to calibrate both the optical technique and the finite element analysis (FEA) technique. Optical wing twist data from the NTF were presented, which were used to calibrate the FEA results with wind on. It was found that one-dimensional FEA analyses are sufficient to generate wind tunnel model jig wing definition, but that advanced three-dimensional solid FEA analyses may be required to generate wing definition suitable for computational fluid dynamic (CFD) analyses. Hooker recommended utilization of CFD methods to define the required accuracy of model deformation measurements for a given configuration and noted that the required accuracy may vary from configuration to configuration. Generally a 5% variation in wing twist is expected to result in acceptable accuracy for low wing transport configurations.

YuFu Liu, CARDC, China, described real-time attitude measurement and side-slip angle measurement systems used in the CARDC 4 by 3 meter low-speed wind tunnel. The pitch measurement system employs a QFlex accelerometer with an added temperature sensor which corrects the accelerometer output as a function of temperature. This system, used over a range from -30 degrees to 110 degrees by offsetting the accelerometer, a provides a measurement precision of 0.005 degrees. The side-slip system employs a laser and dual CCD linear scanning camera to measure yaw from -2.5 degrees to 2.5 degrees with a measurement precision of 0.005 degrees.

Sergi Fonov, TsAGI, Russia, presented examples of wing twist and bending measurements as functions of lift force and AoA at the T-128 wind tunnel using a CCD camera and reference targets with the single camera, single view videometric technique. He also presented results of flap torsion and displacement for which fluorescent strips were illuminated with a nitrogen laser. A prototype deformation measurement system was described for a full-scale helicopter rotor blade using a camera in the rotating hub with connection to the recording system by slip rings. Deformation measurements using projection moiré were also mentioned.

Gregory M. Buck, NASA LaRC, USA, presented results of tests conducted to study sting bending and model injection during wind-on and wind-off conditions at the 20-Inch Mach 6 CF_4 Tunnel. Angle and displacement measurements were made on a small section of the model that was in the field of view of a camera when the model is fully injected into the test section. A back illuminated ground glass view screen was placed in the field of view of the camera to yield a very high contrast edge from which the slope angle and intercept can be found by least squares estimation.

Anton R. Gorbushin, TsAGI, Russia, briefly discussed angle measurements using accelerometers that are manufactured in Russia. He also described a research and development project based on the development of a magnetic system to measure angular and linear model displacements and model deformations during wind tunnel tests. The purpose is to develop a prototype system for the simultaneous measurements of full angular orientation, coordinates, and deformations of a model, including wings, control surfaces, etc., during wind tunnel testing. High-sensitivity three-axis magnetometers on one-domain film structures will serve as transducers for navigation and orientation in an artificial low-frequency electromagnetic field.

Ralph D. Buehrle, NASA LaRC, USA, summarized several sting whip correction techniques proposed over the last few years. Time-domain and frequency-domain methods were not successful in extracting the small signals necessary to determine error. A modal correction technique was tested with limited success. This method requires measurement of all model vibration modes in pitch and yaw prior to wind tunnel testing. The model must be excited in both vertical and lateral directions; modal analysis of the acquired vibration data provides corrective information. During tests corrections at each mode are summed to provide a total correction. This technique requires considerable pre-test and post-test computation. The linear-angular technique of Pieter H.

Fuykschot described above has the ability to provide real time corrections without modal analysis.

9.4 Panel Discussion

Frank L. Wright, Boeing, USA, served as panel moderator. He opened the discussion with comments on the need to properly define AoA measurement accuracy requirements. Force measurement using internal strain gauge balances requires accurate AoA measurement to properly resolve normal and axial force to obtain lift and drag forces. However, Wright stressed that AoA measurement accuracy requirements vary depending on the test configuration. For instance AoA accuracy requirements are better defined at cruise conditions and are more stringent for climb-out than for approach conditions. The AoA accuracy requirements at maximum lift are also not well defined. Although $\pm 0.01°$ AoA accuracy may not be required for every test, better than $\pm 0.1°$ accuracy is probably always necessary. A comment from the audience noted that the wind tunnel user often requests "the best accuracy you can give me". Wright also stressed that repeatability is of the greatest importance during increment testing at a fixed AoA. The point was made that the confidence level is often not specified when stating a numerical accuracy requirement.

The topic turned to aeroelastic model deformation. Measurement of aerodynamic twist is needed for comparison with CFD results. As model size increases, wall interference effects become more significant while deformations may increase as well. Both effects must be accounted for. It was asked when $\pm 0.05°$ experimental wing twist measurement accuracy would be available in wind tunnels. It was pointed out that such measurement accuracies are now possible at the LaRC Unitary Plan Wind Tunnel and are also possible at the NTF wind tunnel at somewhat reduced accuracy. The required accuracy for measurement of the change in wing twist induced by aerodynamic loading is still an open question.

Uncertainty issues in general were then discussed. The uncertainty of CFD results is needed along with the uncertainty of experimental results. The CFD community is just starting to assess uncertainty.

The discussion then returned to AoA where it was stated that AoA should be separated from angle of incidence. To obtain drag, the AoA is needed, not angle of incidence. This led to the question of how well flow angularity can be measured. It was recommended that uncertainty analyses be conducted on the computation of flow angularity from upright and inverted tests. A question was then asked about the Optotrak system in use at Boeing and several other aeronautical establishments. Wright stated that the number of and position of optical markers required for wind tunnel testing with the Optotrak system had not been optimized.

The effect of high-pressure tunnel operation on testing was raised. Wright stated that drag data taken at 4 atm in the NTF wind tunnel was as accurate as data taken at 1 atm in the Boeing wind tunnel; in addition, the 4 atm drag data was as useful for predicting flight behavior as the 1 atm data.

The fragility of precision quartz flexure accelerometers was discussed. Tom D. Finley stated that the typical lifetime of quartz accelerometers is five years. Most problems with accelerometers are due to mishandling rather than excessive model vibration during tests. It was also stated that the quartz flexure is not subject to loss of response as with metal flexures. It was recommended from the audience that accelerometers be powered during transit for protection. Finley pointed out that such protection would occur only in the axial direction. Several people commented that accelerometer manufacturer's specifications are reliable and that they therefore perform no additional calibration. Frank L. Wright stated that accelerometer output data corrected for temperature using manufacturer-furnished data agrees well with temperature-controlled accelerometer output data, as commonly used at the NTF. Pieter H. Fuyschot recommended the use of precision wedges to spot-check angle measurement accuracies. The importance of the use of the local value of the gravitational constant was mentioned.

The discussion turned to the problem of setting the model to zero angle in the facility. Leveling fixtures and tooling balls combined with a bubble level may possibly be used to level horizontal models; however, fundamental leveling problems exist with floor-mounted half models. The importance of the reference surface on which the accelerometer is mounted was also mentioned.

An AGARD uncertainty document published in 1982 was mentioned as an excellent reference. However, Wright cautioned that the individual uncertainty values cited in that reference, which are associated with one drag-count uncertainty, account for the entire one drag-count error. If all of the component uncertainties are combined, approximately 2.8 drag-count uncertainty results as opposed to one drag count. A member of the audience suspected that load resistor variation caused accelerometer output drift. Finley noted that LaRC employs precision load resistors located in the AoA signal conditioning electronics package rather than resistors installed in the accelerometer package. With this arrangement no significant output drift has been observed.

The panel discussion ended with a brief discussion on the problem of measuring yaw. There appears no clear solution. However, the Optotrak system offers promise in solving the yaw measurement problem.

736

APPENDIX: STRAIN GAUGE BALANCE PAPER TITLES AND AUTHORS

Session 1 CALIBRATION & DATA REDUCTION

Authors	Title	Organization
V. Crivoruchenko & I. Panchenko	Calibration of Multi-Component Aerohydrodynamic Balances with Application of Optimal Planning Tests Methods	TsAGI, Russia
M. Quade & K. Hufnagel	The Development of a Modern Manual Calibration and Measuring System for Internal Balances	Technical University of Darmstadt, Germany
I. N. Panchenko	Transformation of Aerodynamic Balances Formulas to the Resolved Respecting To Loading Form	TsAGI, Russia
R. S. Crooks	Limitations of Internal Balance Calibration Math Models for Simulating Multicomponent Interactions	Micro Craft Technology, San Diego, USA

Session 2 FACILITY REPORTS

Authors	Title	Organization
E. Graewe, B. Ewald, & D. Eckert	Design and Development of Internal Balances for the German/Netherlands Low Speed Wind Tunnel (DNW)	Technical University of Darmstadt, Germany
D. X. He, & X. R. Gu	Recent Advances in Strain-gage Balances at CARDC	CARDC, China
D. Cahill	AIAA/GTTC Internal Balance Technology Working Group	Sverdrup/AEDC, USA
H. B. Vos	Strain Gauge Balance Development at NLR	NLR, the Netherlands
P. W. Roberts	NASA LaRC Force and Strain Measurement Capabilities	NASA LaRC, USA

Session 3 SPECIAL BALANCES I

Authors	Title	Organization
B. Ewald, K. Hufnagel, G. Viehweger, & R. Rebstock	The Half Model Balance for the Cologne Cryogenic Low Speed Tunnel (KKK)	Technical University of Darmstadt, Germany
K. Fristedt	Internal Bending Beam Strain-Gauge Wind-Tunnel Balances	AKTIEBOLAGET ROLLAB, Sweden
K. K. Guo	Hinge Moment Balance for Complete Models	Beijing Institute of Aerodynamics, China
A. Kuzin, G. Shapovalov, & N. Prohorov,	Strain-Gage Balance for Magnetic Suspension and Balance System	Moscow Aviation Technological Institute, Russia

Session 4 ACCURACY AND UNCERTAINTY ANALYSIS

Authors	Title	Organization
A. J. Day, & N. Corby	Developments to Improve the Accuracy of Half-Model Balance Measurements in the AEA 9ft x 8ft Transonic Wind Tunnel	Aircraft Research Association, Ltd., UK
P. H. Fuykschot	Looking for the Last Drag Count: Model Vibrations Vs Drag Accuracy	NLR, the Netherlands
M. E. Kammeyer	Uncertainty Analysis for Force Testing in Production Wind Tunnels	Naval Surface Weapons Center, USA
F. L. Wright	Experiences Relative to the Interaction Between the Balance Engineer and the Project Engineer with Regard to Measurement Uncertainty	Boeing Commercial Airplane Group, USA
J. S. Tripp	Strain Gauge Balance Uncertainty Analysis at NASA Langley - A Technical Overview	NASA LaRC, USA

Session 5 AUTOMATIC CALIBRATION

Authors	Title	Organization
Ewald K., Hufnagel, L. Polansky, & L. Badet	Development and Construction of Fully Automatic Calibration Machines for Internal Balances	Technical University of Darmstadt, Germany
R. D. Law	The Application of an Automatic Precision Balance Calibration Machine to the Calibration of Wind Tunnel Strain-gauged Balances	DRA-Bedford, UK
Y. P. Zhang	Fully Automatic Calibration System of the Six Component Balance for High Speed Wind Tunnels	CARDC, China
P. Tcheng & J. S. Tripp	Statistical Analysis of the NASA LaRC Evaluation of the IAI Automatic Balance Calibration Machine	NASA LaRC, USA

737

Authors	Title	Organization
Session 6 APPLICATIONS		
D. Booth	Development of a Six Component Unitized Flexured Force Balance	Micro Craft Technology, USA
V. Lapygin	Typical Balance Test tasks for Aerodynamic Facilities of TSNIIMASH	TSNIIMASH, Russia
D. Levin & M. Ringel	Accurate Axial Force Measurement with Small Diameter Balances under High Normal Loads	Technion, Israel
A. R. Gorbushin	Some Peculiarities of Balance Tests in the Transonic TsAGI T-128 Wind Tunnel	TsAGI, Russia
T. C. Moore	Strain Gages in Service at NASA Langley - A Technical Review	NASA LaRC, USA
Session 7 SPECIAL BALANCES II		
L. X. Liao & Y. Tao	A Water-cooled Six-Component Internal Balance	Beijing Institute of Aerodynamics, China
G. S. Liu, Z. G. Lu, & X. Q. Qi	Single Load and Multicomponent Balance Calibration System (SL&MBCS) of Piezoelectric Balance in Shock Tunnel	CARDC, China
P. Parker	Free Oscillation Dynamic Stability Balance System	Modern Machine & Tool Company Inc., USA
Session 8 BALANCE DESIGN		
G. Drouin, B. Girard, & K. Mackay	A Stiff Monopiece Wind Tunnel Balance	Defence Research Establishment, Canada
G. I. Johnson	A New Master Balance for the MK15 Calibration Rig at FFA	FFA, Sweden
N. R. Patel	Development of A Five-Component Balance As an Integral Part of a Control Surface	Modern Machine & Tool Company, Inc., USA
M. A. Ramaswamy	Design Features of Some Special Strain Gage Balance	India Institute of Science, India
R. D. Rhew	NASA LaRC Strain Gage Balance Design Concepts	NASA LaRC, USA
Session 9 INSTRUMENTATION, STRAIN GAUGES, & THERMAL EFFECTS		
B. Fagerstrom & P. Kemppainen	An Easy-to-use Calibration and Readout System for Small Internal Beam-Type Wind Tunnel Balances	Helsinki University of Technology, Finland
X. R. Gu & J. Q. Hu	Development of BFH-series Strain Gages	CARDC, China
A. T. Ferris	Strain Gauge Balance Calibration and Data Reduction at NASA Langley Research Center	NASA LaRC, USA
W. Liu	Temperature Effect Research on Strain-gage Balances in a Conventional Wind Tunnel	CARDC, China
M. Bazin	ONERA Balances and Dynamometers	ONERA, France
Session 10 FINITE ELEMENT ANALYSIS & NEW TECHNOLOGY		
M. Lindell	Finite Element Analysis of a NASA National Transonic Facility Wind Tunnel Balance	NASA LaRC, USA
J. Zhai & K. Hufnagel	Optimization of the Internal Strain Balances with Finite Elements Computation	Technical University of Darmstadt, Germany
V. Lagutin	New Design of Tubular Type Strain-gage Balances	TSNIIMASH, Russia
B. Ewald, K. Hufnagel, & E. Graewe	The Development of Advanced Internal Balances for Cryogenic and Conventional Tunnels	Technical University of Darmstadt, Germany
V. Bogadanov & V. S. Volobuev	The Status and Prospects for the Further Development of Load Measuring Devices for Wind Tunnel Tests	TsAGI, Russia
Session 11 SPECIAL BALANCES III		
G. Rajendra, H. S. Murthy, & G. V. Kumar	A New Balance Calibration Methodology for Long Slendered Bodies in a Blowdown Tunnel	National Aerospace Laboratories, India
C. J. Suarez, & G. N. Malcolm	Development of a 5-component Strain Gage Balance for Water Tunnel Application	Edidetics Corporation, USA
Z. Tang	Development of Microbalance in Low Density Wind Tunnel	CARDC, China
B. Vasudevan & M. A. Ramaswamy	Novel Oil Filled Bellow Type Internal Strain Gauge Balance for Water Tunnel Applications	India Institute of Science, India