# TIGER: Development of Thermal Gradient Compensation Algorithms and Techniques

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## I. Introduction

In a wind tunnel facility, the direct measurement of forces and moments induced on the model are performed by a force measurement balance.  The measurement balance is a precision-machined device that has strain gages at strategic locations to measure the strain (i.e., deformations) due to applied forces and moments.  The strain gages convert the strain (and hence the applied force) to an electrical voltage that is measured by external instruments.

To address the problem of thermal gradients on the force measurement balance NASA-LaRC has initiated a research program called TIGER - Thermally-Induced Gradients Effects Research.  The ultimate goals of the TIGER program are to (a) understand the physics of the thermally-induced strain and its subsequent impact on load measurements and (b) develop a robust thermal gradient compensation technique.  This paper will discuss the impact of thermal gradients on force measurement balances, specific aspects of the TIGER program (the design of a special-purpose balance, data acquisition and data analysis challenges), and give an overall summary.

## II. Impact of Thermal Gradients

Several general comments about thermal gradients on force measurement balances:

- Thermal gradients do occur and can be quite large.  In an environment like the National Transonic Facility, temperature gradients of as much as 45° C (80° F) can appear on the force measurement balance.  In more conventional wind tunnels, the temperature gradients can be as much as 17° C (30° F).  (For conventional wind tunnels, the temperature of the tunnel gas rises due to heat from the fan motors.)

- Thermal gradients on the balance cause <u>real</u> strain.  That is, varying temperatures on the balance will cause the balance to bend and deform and thus produce strain on the balance.  This strain occurs because of differential expansion (or contraction) of the balance due to the different temperatures.  One corollary: because the thermal gradients produce real strain, the impact of the gradients at the strain gage sensor is indistinguishable from an external force.

- Thermal gradients primarily affect the axial force measurement.  This results from a combination of (a) the design of the balance and (b) the axial (drag) measurement is usually more sensitive than the other measurements such as normal.

- Awareness of the impact of thermal gradients is not new and not confined to NASA. A technical paper from as early as 1961 discuss the "possible effects of temperature gradients on zero drift".[1] The Dutch authors describe using strips of copper wire to ensure no zero drift for a uniform rise in temperature but acknowledge that the compensation can make the problem worse if there is a temperature gradient. A more recent Dutch paper has the following quote:

  > "The drag element as a whole, being a redundant parallelogram construction, is susceptible to temperature gradients which cannot be compensated for with clever strain-gauge bridge configurations. Bridge compensation with temperature senosrs, positioned strategically all over the drag element, is conceivable, but promises many experimental difficulties. "[2]

- French researchers have also studied the thermal gradient problem. They dismiss using temperature sensors to solve the problem:

  > "Furthermore, the correction of these effects, calculated from measurements of point temperatures performed by thermocouples, appeared as very unreliable and unrepeatable for large integral balances as the thermocouples, although numerous, insufficiently analyze the thermal variations occurring within the structure." [3]

  Instead of using temperature sensors to compensate for axial strain output due to thermal gradients, DuBois and others propose measuring the force due to temperature gradients using a second strain-gage bridge. They state, qualitatively, that their results with the second bridge show better thermal gradient compensation with less time lag and less hysteresis.

## III. Present thermal gradient compensation techniques

A. Cryogenic balances

Current NASA-LaRC NTF cryogenic state of the art internal balances are fabricated from VascoMax C-200 (Teledyne Vasco, 18% Nickel maraging steel). These monolithic balances require intricate machining in order to gain the required resolution and accuracy of all forces and moments in six degrees of freedom as well as carry all aerodynamic loads induced on the model to the tunnel support structure.

These balances are instrumented with twelve 350 $\Omega$ foil resistive strain gage bridges, a complete primary and redundant set of component measurements, and nine 100 $\Omega$ platinum resistive temperature detectors. The individual strain gages are cryogenically tested and matched into optimum bridge configurations prior to installation on the actual balance. After strain gage installation the isothermal temperature effects on the electrical zero of the balance is compensated by installing a section of temperature sensitive wire within the proper leg of the strain gage bridge. This compensation only addresses steady state isothermal temperature changes of the balance, not steady state or transient thermal gradient effects. The design of the strain gage layout is optimized to minimize thermal gradient effects.

B. Present thermal gradient compensation techniques

Presently there are procedures used at NASA-LaRC to account for the strain due to thermal gradients. The most complex thermal gradient compensation techniques are required for the axial force component.

The balance has a primary (AFB1) and a secondary (AFB2) axial force strain gage bridge. These bridges (AFB1 and AFB2) are completely electrically isolated from each other and are gaged in symmetric locations on the balance to provide identical resolution and accuracy. AFB1 utilizes a thermal gradient compensation technique developed by NASA-LaRC in which temperature sensitive Nickel wire is installed in four strategic locations on the balance structure and is wired into two opposing legs of the strain gage bridge. This technique requires an iterative process of repeated temperature excursions and adjustment of the sensor's position and resistance. AFB2 utilizes the same strategy for thermal compensation except instead of Nickel sensors, which are integrated electrically into the strain gage bridge, four of the nine platinum temperature sensors are strategically placed on the balance structure and the compensation technique derives an algorithm which is performed analytically within the software of the data acquisition system. This approach provides significant improvement to the reliability and ruggedness of the balance as well as reduces the number of cryogenic excursions required to perform the thermal gradient compensation.

Both of the thermal compensation techniques which are currently in use do not fully compensate the effects on the axial force component for any gradient profile or magnitude. Wind tunnel testing procedures such as frequent wind off zeroes and active temperature conditioning of the balance are utilized in order to minimize the effects of thermal gradients. The residual thermal gradient effects, which are currently uncompensated for, have a direct effect on tunnel productivity and data quality.

## IV. TIGER project

To address the thermal gradient issue, NASA-LaRC has initiated a research program called Thermally-Induced Gradient Effects Research (TIGER). The approach in TIGER is to generate various steady state and gradient temperature profiles on a specially-prepared "research" balance. The research balance is instrumented with 118 temperature sensors, 64 strain gages, and 40 foil resistive heater elements. This balance will then be subjected to a variety of temperature and load configurations.

A. FEA

One Finite Element Analysis (FEA) has already been performed on a standard NTF balance at Langley Research Center.[4] That analysis focussed primarily on the structural aspects of the NTF balance, rather than the thermal behavior. Its intent was to compare the FEA results with actual experimental and thus refine and validate the use of FEA as a design tool. The correlation studies from the study showed very good agreement between the FEA analyses and data measured with strain gages and therefore the studies give higher confidence for using finite element analyses to analyze and optimize balance designs in the future.

The next step is to use the research balance (and its 118 temperature sensors) as a validation tool for a thermal FEA of an NTF balance. The heaters on the research balance allow the user to apply a variety of thermal conditions and the temperature sensors give a fairly complete map of the thermal profile of the balance. This experimental profile can then be compared to the FEA results and hopefully lead to a robust FEA tool for predicting thermal gradients on a balance.

B. Detailed description of research balance

The operational balance NTF-101AR was selected as the primary instrument to be used in this research program. The monolithic balance was manufactured from 200 CVM (cobalt strengthened, maraging steel). This balance was originally designed in 1977 for an axis symmetric wind tunnel model to be tested in the NTF. NTF-101AR is 2.375 inches in diameter and 15.565 inches long. The cylindrical balance consists of a model attachment, a support structure attachment, and three measuring sections. Each of the measurement sections is designed with multiple flexures to provide the maximum resolution of the simultaneous application of load in six axes. The balance was fabricated using electrical discharge machining to allow for intricate flexure design.

The balance was completely instrumented to measure strain in 1995 with 64 foil resistive strain gages. Primary strain gage locations are based on the standard location of the Wheatstone bridges installed on currently operational NTF balances. In addition to these primary gages, 38 experimental research gages were installed to measure the thermally induced strain across the entire structure of the balance. All of these strain gages will be monitored as single gages using a custom instrument developed and fabricated at NASA LaRC. Platinum resistive temperature detectors (PRTD) will be used to measure the temperature of the balance during experimental testing. There are 118 PRTDs installed on the balance in the locations required to provide a complete temperature map of the balance as well as localized temperatures in the vicinity of each individual strain gage. The balance also has a matrix of 40 foil resistive heater elements bonded to the outer diameter. This matrix of heater elements combined with eight temperature controllers will provide the capability to induce a predetermined temperature gradient across the balance.
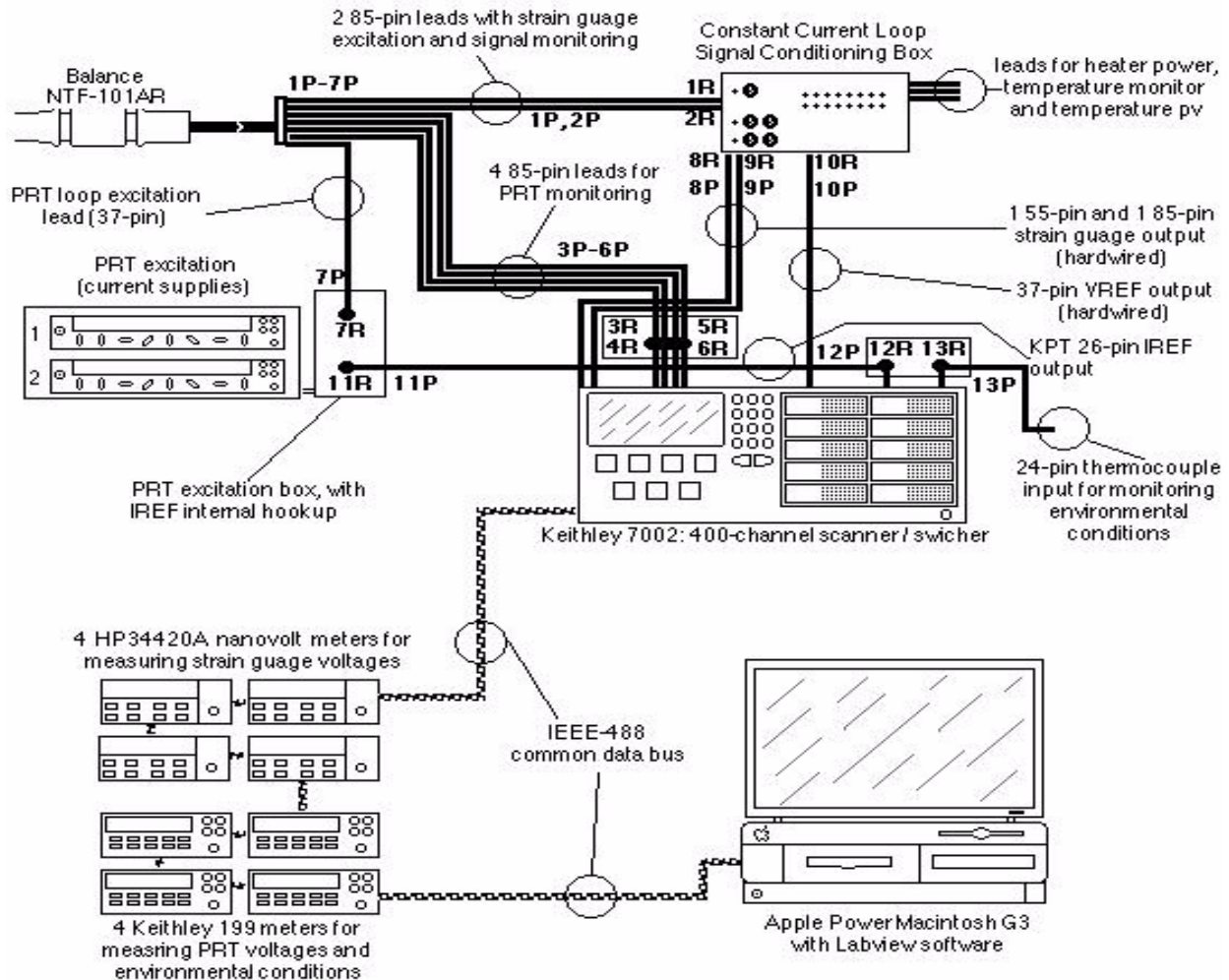
C. Data acquisition set-up

Acquiring data from a balance with 118 PRTDs and 64 strain gages (with individual readout of each gage, not as part of a bridge) is not a simple task. Accounting for the wires/conductors is itself a formidable task. NTF-101AR has a total of 315 individual conductors proceeding from the sensors installed on the balance. Various creative techniques were implemented to minimize the number of conductors required to support all of the balance sensors. One of these techniques involved wiring the PRTDs in constant current loops and sharing the measurement leads with adjacent sensors. To ensure accuracy and repeatability, the inner loop connections were performed by welding .003 inch diameter pure platinum wire to the supplied platinum ribbons which are an integral part of the sensors. This technique eliminated solder joints which would produce unwanted Seebeck voltages. The use of pure platinum was

determined to be necessary to eliminate the repeatability problems experienced with the cryogenic cycling of copper wire.  As an example, the number of conductors required was reduced from 40 to 13 for a ten PRTD loop.  There are 15 PRTD loops on the balance with a maximum of ten PRTDs in a single loop.  These 15 loops on the balance will be externally combined and connected to seven individual current sources.  A maximum of 10 PRTDs per loop was based on the reliability and ease of troubleshooting.

The data acquisition system is based around a central switching unit which distributes the sensor signals to an array of digital voltmeters.  (See Figure 1.) Sensor signals are processed through scanner cards and digital voltmeters which are appropriate for the accuracy required for the measurement obtained from a particular sensor.  An array of digital voltmeters was utilized to provide the maximum integration time for signals (i.e. highest accuracy) but also minimize the overall scanning time of all the balance sensors by simultaneously acquiring data from multiple digital voltmeters.  The data acquisition system will record all of the signals from the sensors installed on the balance as well as a large number of supply voltages, current supplies, and laboratory environmental measurements.  Approximately 210 channels of data will be recorded at each data point during the testing of the balance.

**Figure 1: Data Acquisition for TIGER project**

A complete calibration of the instrumentation system has been completed to ensure that the design accuracy and manufacture specifications were obtained as an assembled system. This calibration consisted of individual instrument calibrations and then a system calibration in which signal levels were injected which are in the range anticipated from the balance sensors. All of the most sensitive measurement signal carrying leads are insulated pure copper wire encased in a continuous braided metallic shield and all connections are accomplished with crimped pure copper junctions wherever feasible to eliminate unwanted Seebeck voltages. The system accuracy on the most sensitive channels is less than 70 nanovolts deviation from a standard 1 millivolt signal. Computer control will be accomplished using a Power Macintosh G3 computer.

LabVIEW based software will be developed for the graphical real time display of data during testing as well the logging of data for subsequent in depth analysis.

## V. Data analysis

A. Genetic Algorithm

A key challenge in the TIGER program is how to analyze the data from the special research balance. Considering just all combinations of temperature sensors in finding a gradient compensation algorithm leads to more than $3.6x10^{35}$ possible combinations and that does not even include adjustments to the sensor weights. Clearly, an exhaustive search to find the best combination is unfeasible.

Four data analysis techniques were considered: linear regression, neural network, eigenvector decomposition, and genetic algorithms. The final recommendation, after considering advantages and disadvantages of each technique, was to use a genetic algorithm (GA). The GA was chosen because of its suitability to the task of finding the optimal or near-optimal solution in a multivariable search space.

Genetic algorithms are used to find a global maximum or minimum in a search space.[5] Unlike other search mechanisms that sample the search space at one point and then move to a better point based on the slope (gradient) information at that point, genetic algorithms work with a population which is a sampling of several points. Each point that is sampled is assigned a "fitness" value. Fitness is simply a number that portrays how useful that point is in solving the problem at hand. The "points" are actually strings or sets of characteristics. For example, a string could be the weights applied to the temperature sensors.

Once each string is assigned a fitness value, the next population is produced by the operations of selection, crossover, and mutation. Selection means that those strings with the greatest fitness values survive. Crossover is the recombination of traits of the selected strings; it is accomplished by swapping parts of randomly-selected strings. Mutation randomizes small parts of the resulting strings.

The overall strategy is to define a "string" or weight vector that specifies the weight to apply to each temperature sensor on the balance. For example, if the weight is 0 then that sensor is not used. If the weight is +1 then the result from that sensor is added. If -1, then the result is subtracted. Finally, we solve to determine the weight vector that gives the best performance.

We define best performance as the combination of weights that has the greatest impact on the apparent strain. This impact will be quantified using the correlation between the (weighted) temperature measurement(s) and the output from the bridge. The correlation, ρ, is defined by the following equations:

$$\rho = E\{(\frac{AFB - \overline{AFB}}{\sigma_{AFB}})(\frac{WT - \overline{WT}}{\sigma_{WT}})\}$$

$$= \frac{1/(N-1)\sum_{i=1}^{N}(AFB_i - \overline{AFB})(WT_i - \overline{WT})}{\sigma_{AFB}\sigma_{WT}}$$

In the above equations, WT and AFB are random variables that correspond to weighted sum of the temperature measurements and the axial force bridge output, respectively. *E{}* represents the expectation operator.

The correlation coefficient, $\rho$, varies from -1 to +1. If $\rho$ is near 1, then the weighted temperature measurements, WT, vary in sync with axial force measurement, AFB. If $\rho$ is near zero, then there is no pattern to how the two signals vary in relation to each other.

B. Results

Data from the research balance is expected in May 1999. Software tools have been written to visualize the data and qualitatively determine the direction of the thermal gradients and output from the axial force bridge. In addition, the GA was coded and tested on data from a standard balance; a standard balance has all strain gages wired in a Wheatstone bridge configuration and only 9 temperature sensors.

The GA was tested on data from a standard balance with 9 temperature sensors. The balance was subjected to a temperature cycle from room temperature up to about 65° C (150° F) and then down to -185° C (-300° F). During this time, the axial force bridge (AFB) was monitored. This temperature cycle was repeated in the Model Prep Area of the NTF.

The output from a temperature cycle is shown in Figure 2. Note that there is no external force acting on the balance so that any change in AFB output must be due to environmental conditions. The laboratory data shows variations in AFB of about $\pm$ 20 $\mu$V/V, which corresponds to 4% of full-scale load. Hence, thermal cycling alone causes variations that are over 10 times the specified accuracy of the balance. Since corrections are made for any uniform rise in temperature, we assume that all variations in AFB are due to thermal gradients.

The GA was used to find a set of weights, $w_i$, to apply to the temperature sensors to correct for the variations in the AFB. We applied the weights to the temperature measurements to form WT, the weighted temperature measurement:

$WT = w_1 T_1 + w_2 T_2 + \ldots + W_9 T_9$.

As noted in Section 3.3, the criteria for the best set of weights was that set of weights that resulted in WT having the highest correlation with the AFB.
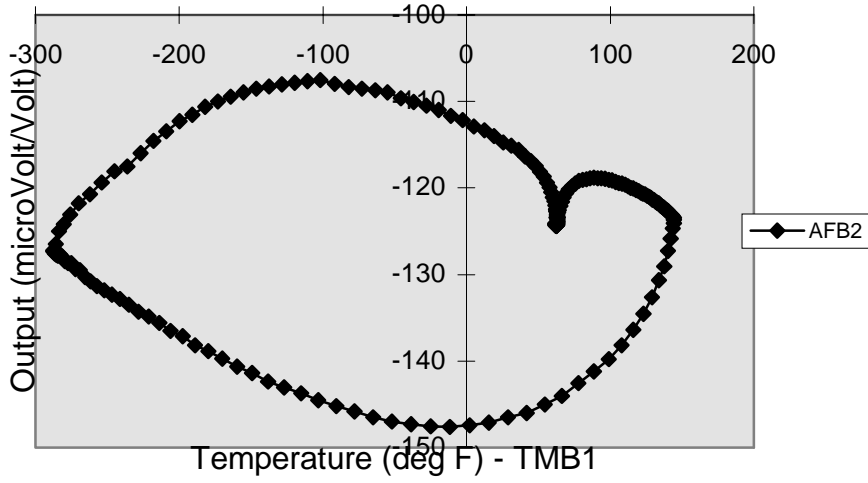
**Figure 2: Sample output of axial force bridge output during cryogenic temperature excursion.**

Once the GA calculates the weights that give the highest correlation with the AFB, a corrected output can be found using

$$\text{AFB(compensated)} = \text{AFB(raw)} - \frac{\sigma_{AFB}}{\sigma_{WT}}(\text{WT} - \text{WT}_{AVG}).$$

In the above equation sigma represents the standard deviation of the AFB and WT measurements, respectively. A plot of AFB(compensated) is shown in Figure 5. For comparison the raw AFB (AFB2, diamond shapes) is also plotted. Clearly, the variation in AFB due to thermal gradients has been reduced. The compensated AFB output, AFB(compensated), varies by only $\pm 1.5$ $\mu$V/V, which is a 10 times reduction in variation. Also shown on the plot (dotted lines) is the output that would occur if the on-board correction only was used.



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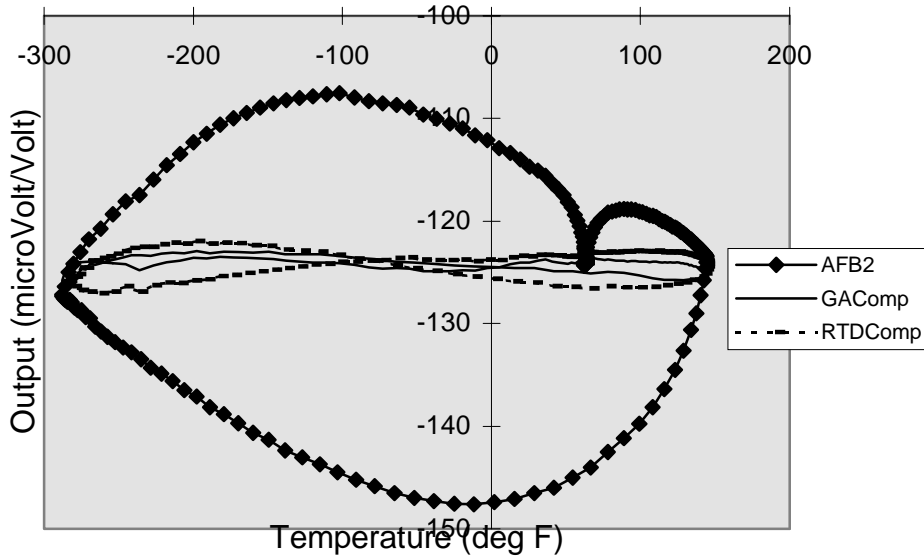
**Figure 3: AFB(raw) shown by AFB2 curve with diamond shapes, AFB compensated with GA-derived weights (GAComp), and AFB compensated with on-board correction (RTDComp).**

Two main issues came out of the GA results. The first issue we encountered was why the same input data would give different output results (i.e., different set of weights). In this case, the output was not unique. Common sense implies that the same input data should result in the same output data. The second issue arose when we tried to "test" the weights. That is, we developed a set of weights for the temperature sensors using the GA on lab data. We then applied those weights to data from the Model Prep Area but there was no improvement in the AFB response. In fact, the AFB curve showed greater variation when subjected to thermal gradients. Thus, the weights were not robust or transferable to different test conditions.

# VI. Summary/Future Work

To address the thermal gradient issue, NASA-LaRC has initiated the TIGER research program. The approach in TIGER is to generate various controlled steady state and gradient temperature profiles on a specially-prepared "research" balance. Data from the research balance will be used to (a) validate a Finite Element Analysis (FEA) model of the balance and (b) develop and validate a thermal gradient compensation algorithm. This paper provided a brief overview of the impact of thermal gradients on force measurements, discussed the TIGER project and the unique aspects of the research balance, and described the special data acquisition and data analysis techniques that are required to gather and evaluate the data from the research balance.

There are several key issues that still need to be addressed to "solve" the thermal gradient problem. Some of those issues are listed below:

- A better model of the impact of temperature and temperature gradients on strain gage output.

- Determining where to place temperature sensors on or within a balance to get a "map" of the thermal gradients.

- Determining if temperature measurements alone will be able to compensate for thermal gradients or whether some additional measurements or on-board instrumentation is also required.

- Developing an understanding or process that can be transferred from a specific balance (the research balance) to other internal balances. That is, developing tools or procedures that will allow new balances to be designed that are (relatively) immune to thermal gradient effects.

**Acknowledgements**

[1] G.F. Moss and D. G. Payne, "A Compact Design of Six Component Internal Strain Gauge Balance", Royal Aircraft Establishment, Technical Note No. AERO. 2764, July 1961, Appendix 1.

[2] J. F. Baljeu, "Development of a Multi-Component Internal Strain-Gauge Balance for Model Tests in a Cryogenic Wind Tunnel", National Aerospace Laboratory, Report # NLR TR 88157 U, October 30, 1988, pg. 17.

[3] M. DuBois, " Six-Component Strain-Gage Balances for Large Wind Tunnels," 4th International Congress on Experimental Mechanics, May 1980, pg. 7.

[4] Michael C. Lindell, "Finite Element Analysis of a NASA National Transonic Facility Wind Tunnel Balance", International Symposium on Strain-Gage Balances, October, 1996.

[5] John H. Holland, "Genetic Algorithms", Scientific American, July 1992, pp. 66 - 72.