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Detection of Bi–Directionality in Strain–Gage Balance Calibration Data

(Extended Abstract of Proposed Conference Paper)

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An indicator variable was developed that may be used to visualize and detect bi–directionality in wind tunnel strain–gage balance calibration data. First, the calculation of the indicator variable is explained in detail. Then, an empirical criterion is proposed that may be used to decide which load components of a balance have bi–directional behavior. The criterion could be used, for example, to justify the selection of absolute value terms for the regression model of strain–gage outputs whenever the Iterative Method is chosen for the calibration data analysis. Finally, calibration data from NASA's MK40 Task balance is analyzed in order to illustrate the calculation of the indicator variable and the application of the proposed empirical criterion.

Nomenclature

AF	= axial force component of force balance
C	= capacity of a primary balance load component
i	= index of gage -or- index of primary gage load component
L	= balance load
n	= total number of gages -or- total number of primary gage load components
$N1$	= forward normal force component of force balance
$N2$	= aft normal force component of force balance
$R_1, R_2, \cdots, R_n$	= strain–gage outputs of a balance
RM	= rolling moment component of force balance
$S1$	= forward side force component of force balance
$S2$	= aft side force component of force balance
ρ	= natural zero of a balance strain–gage

Summary

Many multi–piece strain–gage balances are known to show "bi–directionality" when strain–gage outputs are plotted versus the corresponding primary gage loads. This phenomenon is often the result of limitations of certain balance designs that try to give a balance a highly linear behavior. The bi–directionality can be characterised by the fact the slope of the fitted gage outputs changes slightly whenever either only positive or only negative primary gage loads are used for the regression analysis of the gage outputs.

Unfortunately, bi–directionality is difficult to "spot" in experimental data (see, for example, Fig. 1 that shows the plot of the gage outputs R_1 and R_2 versus $N1$ and $N2$ for the calibration data set of NASA's MK40 Task balance). It is necessary to display the slope for positive and negative loads on a different scale. Therefore, an indicator variable was developed at the Ames Balance Calibration Laboratory that may be used to visualize and detect bi–directionality in strain–gage balance data.

In principle, the indicator variable is computed as the difference between the gage output obtained from two piecewise linear fits and the gage output that is obtained from the arithmetic mean of the slope of the

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two piecewise linear fits. The calculation of the indicator variable for the detection of bi–directionality can be summarized as follows:

Calculation of Indicator Variable

The indicator variable for bi–directionality is computed by (1) performing separate linear fits of the gage outputs for positive and negative loads and by (2) subtracting the fitted gage outputs for the mean slope from the fitted gage outputs of the two piecewise fits.

Naturally every balance will show some degree of bi–directionality because of (i) balance design characteristics, (ii) machining and assembly imperfections, and (iii) calibration load schedule design constraints. A threshold based criterion could be applied, for example, to determine if a gage output of a balance has bi–directional behavior that should not be neglected. The following empirical criterion was developed at the Ames Balance Calibration Laboratory for that purpose:

Empirical Criterion for Bi–Directionality

A strain–gage output is assumed to be "bi–directional" if the magnitude of the indicator variable of the primary gage load exceeds 0.5 % of a characteristic gage output reference of the balance.

The gage output reference could be the largest difference of the strain–gage output relative to the natural zero after it is scaled to the load capacity of the gage. The scaling is performed by using the ratio between (i) the capacity of the primary gage load component and (ii) the absolute value of the load that causes the largest output difference. This choice can be expressed as:

$$REFERENCE \quad = \quad A_i \; \cdot \; \frac{C_i}{\mid L_i(A_i) \mid} \qquad (1a)$$

where

$$A_i \quad = \quad max \, [\; \mid R_i - \rho_i \mid \;] \qquad (1b)$$

The gage output reference will not be the same for each strain–gage as it is an electrical output difference that is scaled to the specific load capacity of the gage. The gage output reference defined in Eq. ($1a$) will be discussed in more detail in the proposed conference paper.

Figure 2 shows values of the indicator variable for a calibration data set of the NASA's MK40 Task balance. The gage output reference defined in Eq. ($1a$) was used to determine bi–directionality. It can be seen in Fig. 2 that the first four gages, i.e., R_1, R_2, R_3, and R_4 appear to have bi–directional behavior. Therefore, they support the use of the absolute value term of the corresponding primary gage loads if the Iterative Method is used for the analysis of the balance calibration data (see Ref. [1] for a discussion of the Iterative Method). The last two gages, i.e., the rolling moment gage R_5 and the axial force gage $R6$, on the other hand, do not seem to have bi–directionality. Therefore, they do not support the use of the absolute value term of the corresponding primary gage load in a regression model of the gage outputs.

A more detailed discussion of the interpretation and use of the indicator variable for bi–directionality will be given in the final manuscript of the paper. In addition, data from the calibration of a typical single–piece balance will be reviewed in more detail in the final manuscript to illustrate differences between the bi–directionality characteristics of different balance types.

References

[1] AIAA/GTTC Internal Balance Technology Working Group, "Recommended Practice, Calibration and Use of Internal Strain–Gage Balances with Application to Wind Tunnel Testing," AIAA R–091–2003, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2003.

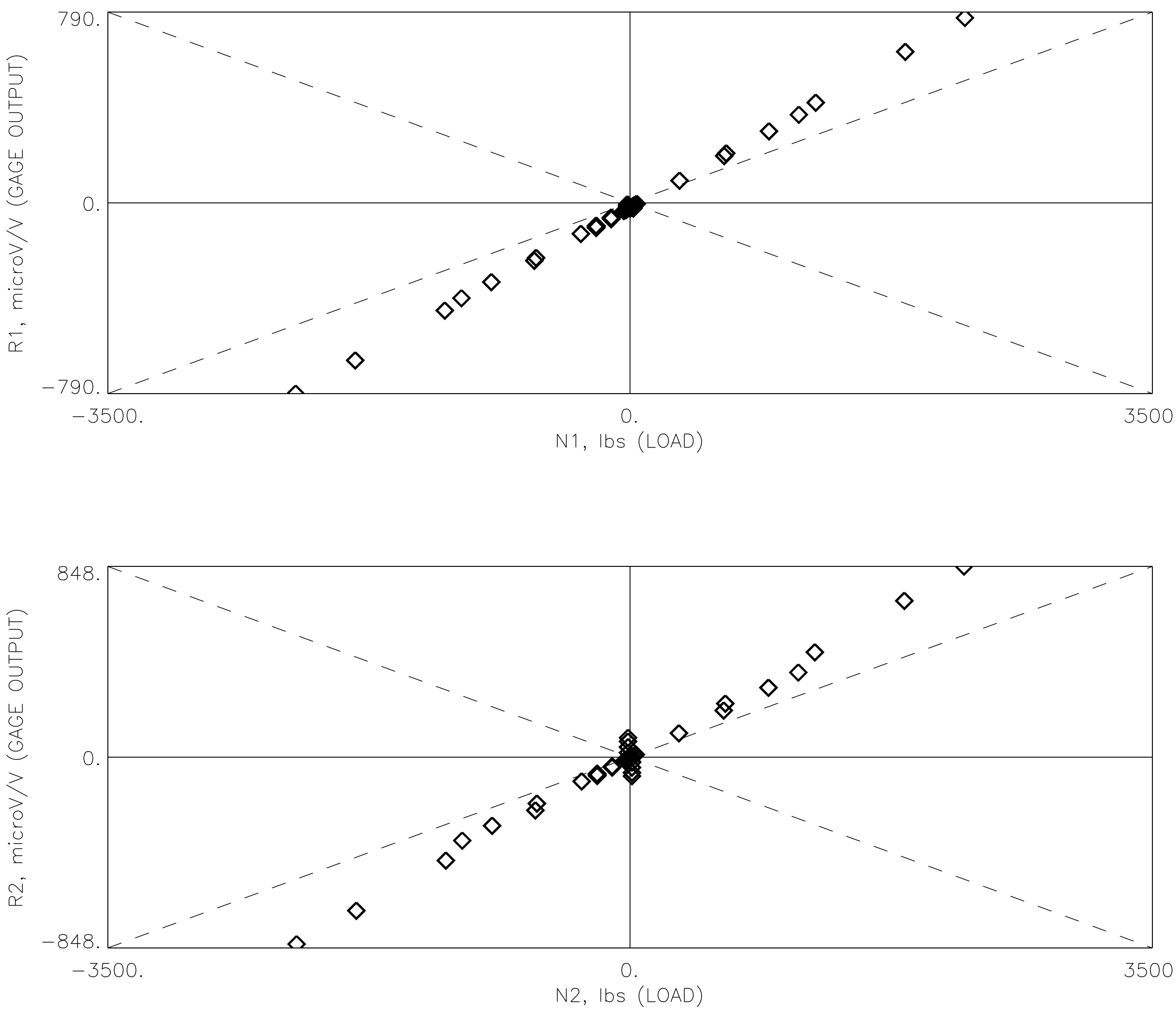

Fig. 1 Strain–gage outputs $R1$ & $R2$ versus load components $N1$ & $N2$ for the MK40 Task Balance.

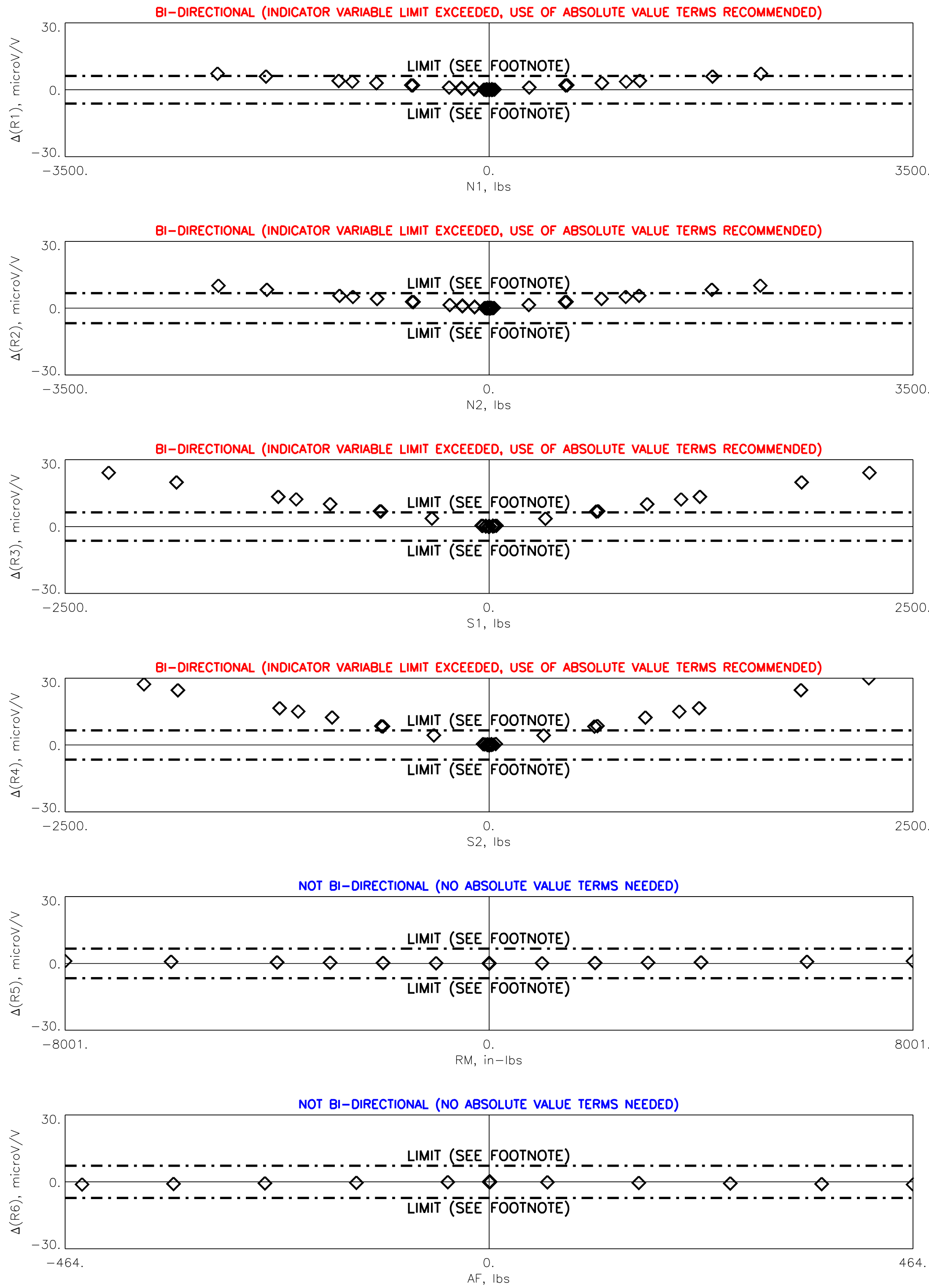

Fig. 2 Indicator variable for the detection of bi–directionality for the MK40 Task Balance. (0.5 % of the gage output reference defined in Eq. (1a) was used as the detection limit)

Detection of Bi–Directionality in Strain–Gage Balance Calibration Data

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An indicator variable was developed for both visualization and detection of bi–directionality in wind tunnel strain–gage balance calibration data. First, the calculation of the indicator variable is explained in detail. Then, a criterion is discussed that may be used to decide which gage outputs of a balance have bi–directional behavior. The result of this analysis could be used, for example, to justify the selection of certain absolute value or other even function terms in the regression model of gage outputs whenever the Iterative Method is chosen for the balance calibration data analysis. Calibration data of NASA's MK40 Task balance is analyzed to illustrate both the calculation of the indicator variable and the application of the proposed criterion. Finally, bi–directionality characteristics of typical multi–piece, hybrid, single–piece, and semispan balances are determined and discussed.

Nomenclature

AF	= axial force
$C_1, \cdots, C_i, \cdots$	= capacity of a primary gage load
$D_1, \cdots, D_i, \cdots$	= largest difference between gage output and natural zero
i	= index of a gage, or, index of a primary gage load
L	= load that causes the largest difference between gage output and natural zero
NF	= normal force
$N1$	= forward normal force component of a force balance
$N2$	= aft normal force component of a force balance
PM	= pitching moment
$PM1$	= forward pitching moment component of a moment balance
$PM2$	= aft pitching moment component of a moment balance
RM	= rolling moment
$R_1, \cdots, R_i, \cdots$	= electrical output of a strain–gage
SF	= side force
$S1$	= forward side force component of a force balance
$S2$	= aft side force component of a force balance
$T_1, \cdots, T_i, \cdots$	= empirical threshold used for detection of bi–directionality
YM	= yawing moment
$YM1$	= forward yawing moment component of a moment balance
$YM2$	= aft yawing moment component of a moment balance
Λ	= indicator variable for the detection of bi–directionality
$\nu_1, \cdots, \nu_i, \cdots$	= natural zero, i.e., gage output of the global load datum of the balance

I. Introduction

Multi–piece strain–gage balances are known to show bi–directionality whenever strain–gage outputs are plotted versus the corresponding positive and negative primary gage loads. This asymmetry is often the result of balance assembly techniques that are used to connect normal or side force flexure elements to the

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metric and non–metric part of a balance. The bi–directionality can be described by the observation that the slope of the fitted gage outputs changes by a small amount whenever either only positive or only negative primary gage loads are used for the regression analysis of strain–gage outputs.

In general, an understanding of the bi–directionality characteristics of a balance is important. The presence of absolute value or other even function terms in regression models used for the analysis of balance calibration data by the "Iterative Method" can often only be justified if bi–directionality is detected (see Ref. [1] for a detailed discussion of the "Iterative Method"). Unfortunately, bi–directionality is difficult to "spot" in experimental data as the phenomenon accounts for only about 1 % to 2 % of the overall range of the electrical output of a typical balance gage. Consequently, it is necessary to display the slope of the gage outputs for positive and negative loads on a different scale so that bi–directionality, if present, can be observed. An indicator variable was developed for that purpose at the NASA Ames Balance Calibration Laboratory. The detection of bi–directionality is accomplished by first computing the value of the indicator variable for the load capacity of the gage. Then, this value is compared with an empirical threshold in order to decide whether or not the gage output of a balance is bi–directional.

In the next section of the paper the calculation of both the indicator variable and the definition of the criterion needed for the detection of bi–directionality are discussed. Then, calibration data from NASA's MK40 Task balance is used to illustrate the calculation of the indicator variable and the application of the criterion. Finally, bi–directionality characteristics of different balance types are determined and compared.

II. Detection of Bi–Directionality

An indicator variable for the detection of bi–directionality can be defined if balance calibration data is given in its "design" format. The "design" format is used whenever loads of a force/moment balance are expressed in force/moment balance format, or, whenever loads of a direct–read balance are expressed in direct–read format (see Ref. [2] for a detailed discussion of different balance formats). Only the "design" format shows the proportionality between primary gage loads and primary gage outputs that makes both description and detection of bi–directionality possible.

The indicator variable for a given balance load is computed as the difference between two gage outputs that are the result of linear fits of the balance calibration data. The first gage output is obtained from a piecewise linear fit of the gage outputs. This piecewise linear fit is done using either the positive or the negative primary gage loads depending on the sign of the given balance load. The second gage output is obtained from the arithmetic mean of the slope of the two possible piecewise linear fits of the primary gage loads. Now, the calculation of the indicator variable for the detection of bi–directionality can be summarized as follows:

Calculation of Indicator Variable

The indicator variable for the detection of bi–directionality is computed by (1) performing separate linear fits of the gage outputs for positive and negative loads and by (2) subtracting the fitted gage outputs for the mean slope from the fitted gage outputs of the two piecewise fits.

All strain–gage balances show some degree of bi–directionality because of (i) balance design characteristics, (ii) machining and assembly imperfections, and (iii) calibration load schedule design constraints. Therefore, a threshold based criterion has to be applied to determine if a primary gage output of a balance has (or has not) bi–directional behavior. The following criterion was developed for that purpose at the NASA Ames Balance Calibration Laboratory:

Criterion for Detection of Bi–Directionality

A strain–gage output is assumed to be "bi–directional" if the magnitude of the indicator variable, computed at capacity, exceeds 0.5 % of the to–capacity–scaled maximum of the difference between gage output and natural zero.

The criterion defined above may be expressed mathematically as an inequality. First, the following abbreviations are introduced that will be used in the inequality:

$$\Lambda(R_i, C_i) \equiv \textit{indicator variable value of gage output } R_i \textit{ for gage load capacity } C_i$$

$$T_i \equiv \textit{empirical threshold of the indicator variable of gage output } R_i$$

Then, the criterion can be described. A primary gage output R_i of a strain–gage balance is considered to be "bi–directional" if the following condition is fulfilled:

$$ABS\{\ \Lambda(R_i, C_i)\ \} \quad > \quad T_i \qquad (1a)$$

where

$$T_i \;=\; \underbrace{0.05}_{0.5\ \%} \cdot \underbrace{D_i}_{difference} \cdot \underbrace{\frac{C_i}{ABS\{\ L(D_i)\ \}}}_{scale\ factor} \qquad (1b)$$

$$D_i \;=\; MAX\{\ ABS\{\ R_i - \nu_i\ \}\ \} \qquad (1c)$$

An empirical constant of 0.5 % is used in Eq. (1b) to compute the threshold that is needed for the detection of bi–directionality. This constant is the result of systematically investigating the bi–directionality characteristics of a wide variety of strain–gage balance calibration data sets at the NASA Ames Balance Calibration Laboratory. Data sets from both Ames and other laboratories were processed during those past studies to make sure that the constant is not biased by the calibration approach of a specific laboratory.

It is important to point out that both the indicator variable value $\Lambda(R_i, C_i)$ and the threshold T_i are intentionally computed for (or scaled to) the capacity C_i of the corresponding primary gage load. Consequently, the criterion for bi–directionality is independent of the load range that may have been chosen for the calibration of a balance. This approach makes it possible to apply the criterion even if a balance calibration load schedule does not extend to the capacities of the balance. It is, however, required that both positive and negative primary gage loads were applied during the calibration of a balance. Only in that case the two piecewise linear fits can be obtained that are needed for the calculation of the indicator variable of the primary gage outputs.

The effects of bi–directionality on the primary gage outputs of a balance need to be included in regression models of gage outputs that the "Iterative Method" uses for the analysis of balance calibration data. Traditionally, absolute value terms are selected for that purpose whenever a gage output is bi–directional. However, other "even" functions could also unintentionally model parts of the bi–directionality of the gage outputs if they are included in the regression model of the gage outputs. Therefore, it is important that a sufficient number of calibration points is used over the entire range of a primary gage load. Only in that case the regression analysis can correctly distinguish between effects that should be modeled by absolute value terms and effects that should be modeled by, e.g., quadratic terms.

Data from the calibration of a Task balance is discussed in the next section of the paper in order to illustrate the application of the criterion.

III. Discussion of Example

Manual calibration data of the NASA MK40 Task balance is used in this section to illustrate the visualization and detection of bi–directionality. The MK40 balance is a six–component force balance that has a diameter of 2.5 [in]. The manual calibration of the balance was performed in 2006 at the NASA Ames Balance Calibration Laboratory. It consisted of 16 load series with a total of 164 data points.

Figure 1a shows the output $R3$ of the forward side force gage of the balance plotted versus the forward side force component $S1$. The near–linear relationship between gage output and primary gage load is clearly visible. It is the result of plotting the calibration data of a highly linear balance in its "design" format, i.e., in force balance format.

The bi–directionality characteristics of the MK40 balance are actually contained in Fig. 1a. However, because the phenomenon is very small, they are not visible. Therefore, the indicator variable $\Lambda(R3, S1)$ of the forward side force gage output was computed using the process that was outlined in the previous section. Figure 1b shows the indicator variable plotted versus the forward side force component. Two observations can be made after an inspection of Fig. 1b: (i) the indicator variable looks like an absolute value function when plotted versus the primary gage load; (ii) the threshold indicated by a dot–dashed line is exceeded. The second observation needs to be quantified. The following numerical values for the capacity and the indicator variable for capacity are obtained after reviewing the balance specifications and Fig. 1b:

$$C_3 \quad = \quad 2500 \; [lbs] \tag{2a}$$

$$ABS\{ \; \Lambda(R_3, C_3) \; \} \quad = \quad 26 \; [microV/V] \tag{2b}$$

Similarly, after applying Eq. ($1b$), we get for the threshold that is needed for the detection of bi–directionality the following value:

$$T_3 \quad = \quad 6 \; [microV/V] \tag{3}$$

Finally, after comparing the right hand side of Eq. ($2b$) with the right hand side of Eq. (3), we get the following result:

$$ABS\{ \; \Lambda(R_3, C_3) \; \} \quad > \quad T_3 \tag{4}$$

It is concluded, after comparing Eq. (4) with Eq. ($1a$), that the condition for bi–directionality is fulfilled. In other words – the gage outputs of the forward side force gage of the MK40 balance are bi–directional.

Figure 1c shows values of the indicator variable for all six primary gage outputs of the MK40 balance. The analysis of the bi–directionality characteristics revealed that only the normal and side force gage outputs of the balance are bi–directional. The axial force and rolling moment gage outputs do not appear to have this characteristic. The distinct differences between the bi–directionality characterestrics of the gage outputs of the MK40 balance can be better understood after reviewing the design of the balance.

The MK40 balance is a Task balance. A normal (or side) force flexure element of a Task balance is attached to the metric outer shell and the non–metric inner rod using pairs of opposing screws (see Fig. 2a). The flexure element and the two joints between flexure element, outer sleeve, and inner rod will be in compression for a positive normal (or side) force load. In that case, the joints transmit the load through solid metal–to–metal contact. The situation changes as soon as the sign of the normal (or side) force load becomes negative. Now, the flexure element is in tension and a small percentage of the total load will be transmitted through the threads of the screws. Consequently, a change of the sign of the normal (or side) force load causes an asymmetric gage response, i.e., the normal and side force gage outputs of a Task balance should be bi–directional.

The axial force and rolling moment flexure elements of a Task balance, on the other hand, are attached to the metric and non–metric parts of the balance by using tight press pins (see Fig. 2b). Therefore, corresponding gage outputs will be more symmetric for positive and negative loadings and bi–directionality is negligible. This conclusion is confirmed by the plots of the indicator variables of the rolling moment and axial force gages of the MK40 balance.

In the next section of the paper bi–directionality characteristics of different balance types are determined and discussed in detail.

IV. Balance Type and Bi–Directionality

A comparison of the bi–directionality characteristics of different balance types is useful. This comparison may help improve the understanding of the behavior of a specific balance type. It may also lead to a better selection of regression model terms for the analysis of balance calibration data. Therefore, the bi–directionality of four different balance types is investigated in more detail in this section.

A multi–piece (Task), hybrid, single–piece, and semispan (floor) balance were selected for the study of bi–directionality. All four balances are owned by NASA and were calibrated at Triumph Aerospace (Force Measurement Systems) in San Diego. Observations made with these data sets agreed with observations that were made using calibration data sets from other laboratories. Therefore, it was concluded that the use of data from a single laboratory for the comparative study is acceptable.

The bi–directionality of the gage outputs was analyzed by using the calibration data in its "design" format. Three of the balance calibrations were performed in Triumph's calibration machine. One calibration was performed manually. Table 1 below summarizes characteristics of the four balance calibration data sets that were used for the study.

Table 1: Description of Balance Calibration Data Sets.

BALANCE NAME	*BALANCE TYPE*	*LOAD FORMAT*	*CALIB. TYPE*
MK29B	MULTI–PIECE (TASK)	FORCE BALANCE	MACHINE
MC60D	HYBRID	FORCE BALANCE	MACHINE
NTF113C	SINGLE–PIECE	MOMENT BALANCE	MACHINE
MC400	SEMISPAN	DIRECT–READ	MANUAL

Figure 3a shows the result of the evaluation of the bi–directionality characteristics of the MK29B balance. The balance is a Task design. It shows bi–directionality characteristics that are typical for a Task balance (see also the previous discussion of the result for the MK40 balance shown in Fig. 1c). The normal and side force gages are bi–directional. Consequently, even functions like absolute value terms of the normal and side force components are probably needed in the regression models of the gage outputs. The rolling moment and axial force gages are <u>not</u> bi–directional. Therefore, absolute value terms of the rolling moment and axial force appear to be of lower importance. It seems that the level of bi–directionality of the aft normal force gage output $R2$ of the MK29B balance is relatively small (i.e., close to the threshold). This observation may be explained by the fact that the balance was recently completely overhauled and has not been used for a wind tunnel test since.

Figure 3b shows the result of the evaluation of the bi–directionality characteristics of the MC60D balance. The balance is a "hybrid" design that was developed by Triumph Aerospace. None of the six gages of the MC60D balance is bi–directional. This balance design appears to have much lower levels of bi–directionality when compared with a typical Task balance. Therefore, absolute value terms appear to be of minor importance when it comes to assembling terms for the regression models of the gage outputs.

Figure 3c shows the result of the evaluation of the bi–directionality characteristics of the NTF113C balance. The balance is a single–piece design. Again, none of the six gages of the balance is bi–directional. This balance design appears to have much lower levels of bi–directionality when compared with a typical Task balance. The levels of bi–directionality also appear to be lower than the levels observed for the MC60D "hybrid" design. Therefore, absolute value terms appear to be of minor importance when it comes to assembling the regression models of the gage outputs of the NTF113C balance.

Finally, Fig. 3d shows the result of the evaluation of the bi–directionality characteristics of the MC400 semispan balance. The five primary gage outputs of the MC400 appear to be highly symmetric. None of the six gages of the MC400 balance is bi–directional. This balance design appears to have by far the lowest levels of asymmetry of all strain–gage balance types that were investigated. Again, as it was the case with the MC60D and the NTF113C, absolute value terms appear to be of minor importance when it comes to assembling terms for the regression models of the primary gage outputs.

V. Summary and Conclusions

An indicator variable and a criterion were discussed that may be used to visualize and detect bi–directionality in strain–gage balance calibration data. The indicator variable is defined as long as (i) a balance calibration data set is given in its "design" format and (ii) both positive and negative primary gage loads were applied during the calibration. The criterion for the detection of bi–directionality compares the indicator variable with an empirical threshold in order to decide whether or not a gage output is bi–directional. The criterion was defined such that it is independent of the load range that may have been selected for the calibration of a balance. Calibration data from different balance types is used to illustrate the detection of bi–directionality.

Overall, having the ability to quantify the level of bi–directionality of the gage outputs of a balance appears to be very useful. It may lead to a selection of regression model terms for the analysis of balance calibration data that are better supported by the physical behavior of the balance. It may also provide insight that could be used to track both "status" and "health" of a balance as an unexpected large change of the indicator variable value at load capacity should always be investigated. A large change could simply indicate a worn out or damaged balance.

Acknowledgements

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References

[1]AIAA/GTTC Internal Balance Technology Working Group, "Recommended Practice, Calibration and Use of Internal Strain–Gage Balances with Application to Wind Tunnel Testing," AIAA R–091–2003, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2003.

[2]Ulbrich, N., "Influence of Primary Gage Sensitivities on the Convergence of Balance Load Iterations," AIAA 2012–0322, paper presented at the 50th AIAA Aerospace Sciences Meeting and Exhibit, Nashville, Tennessee, January 2012.

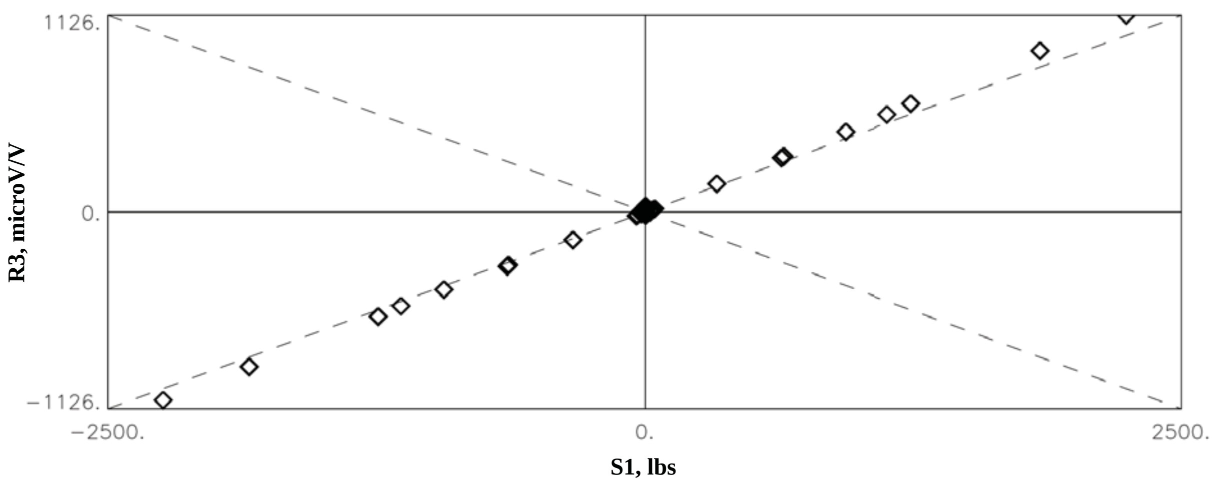
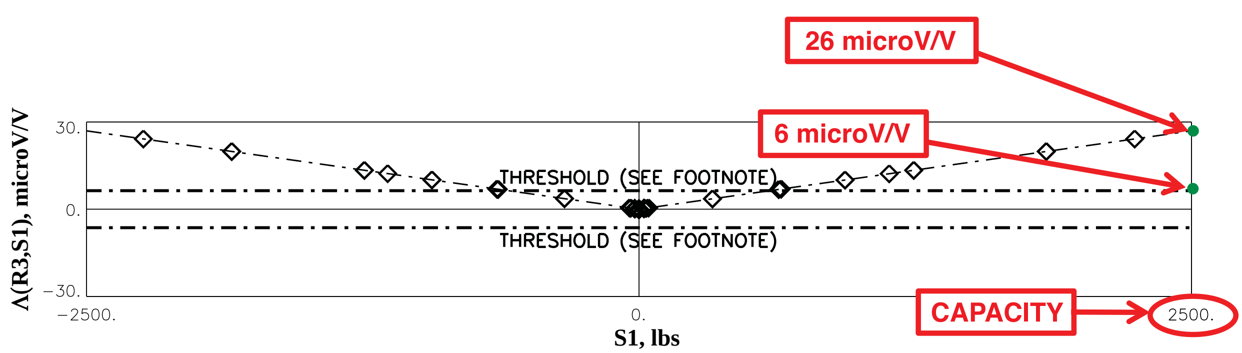
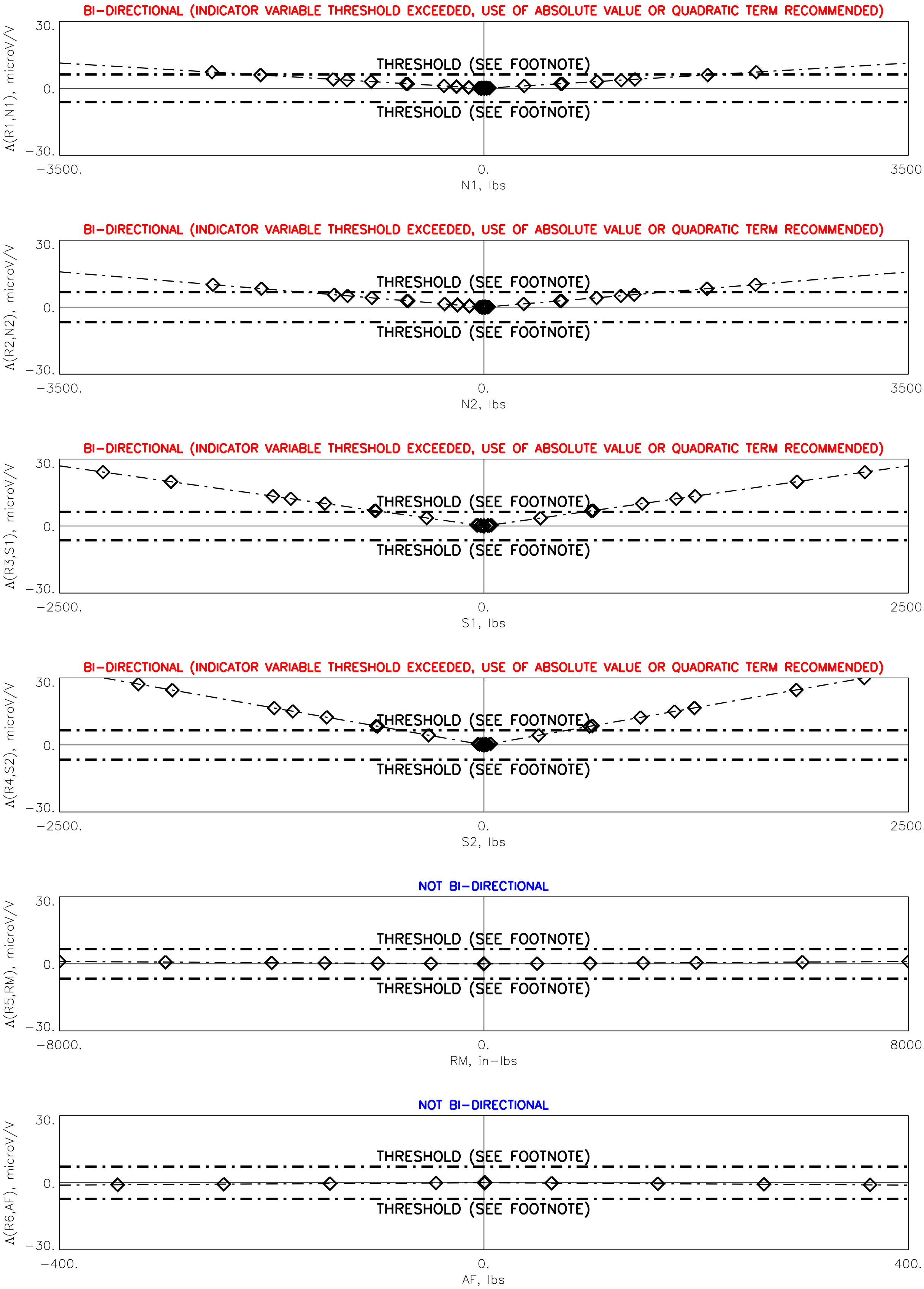


Fig. 1a Strain–gage output $R3$ versus load component $S1$ for the NASA's <u>MK40</u> Task balance.



<u>Footnote:</u> The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 1b Indicator variable value $\Lambda(R3, S1)$ versus load component $S1$ for the NASA's <u>MK40</u> Task balance.



Footnote: The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 1c Indicator variable values for the six primary gages of NASA's MK40 Task balance.

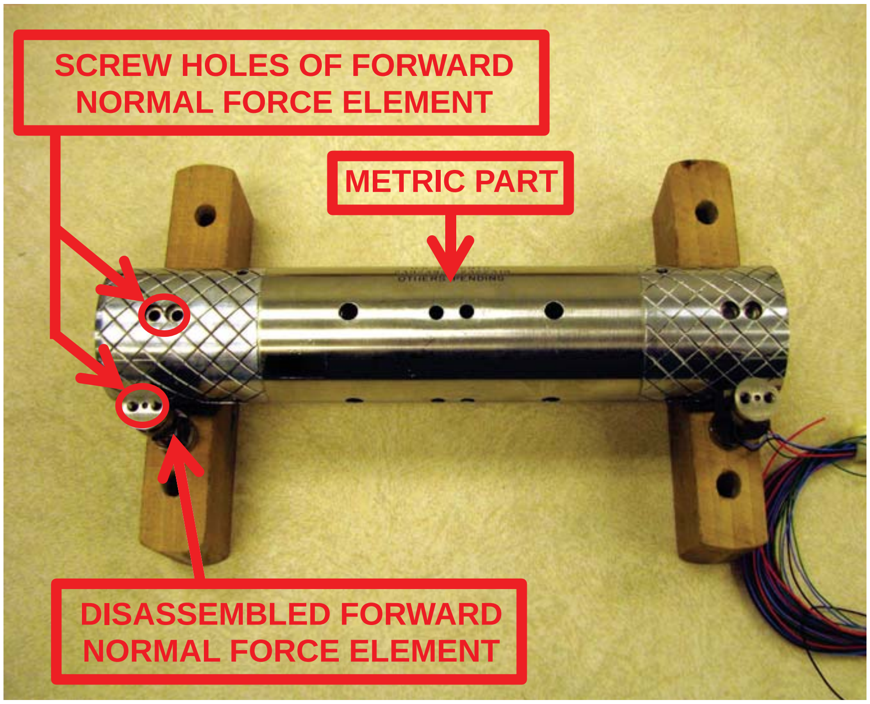


Fig. 2a Metric part and disassembled normal force elements of a Task balance.

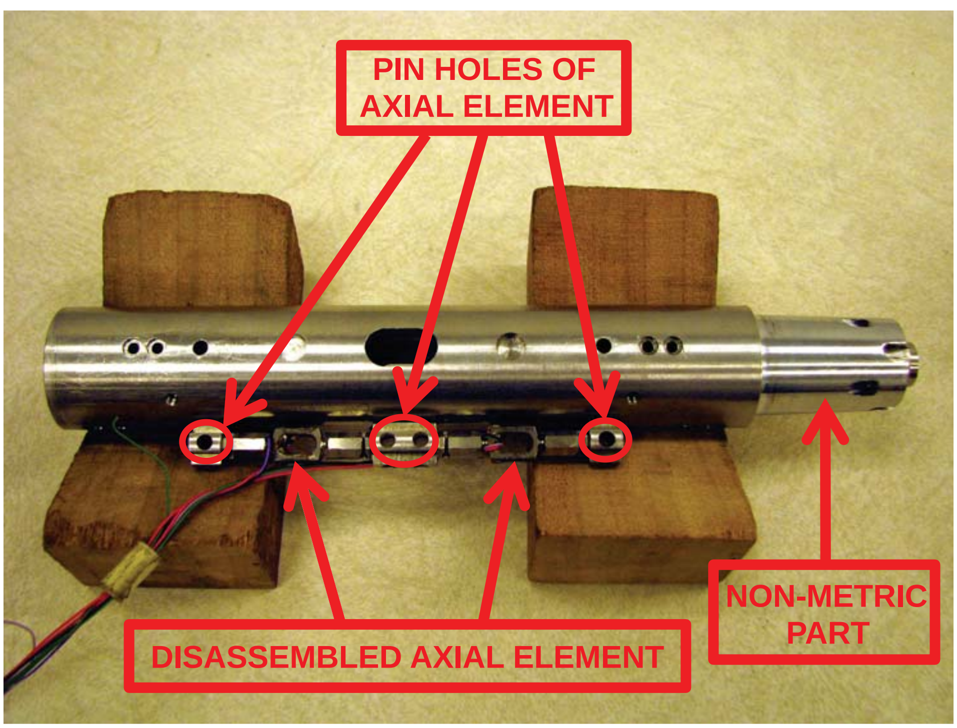
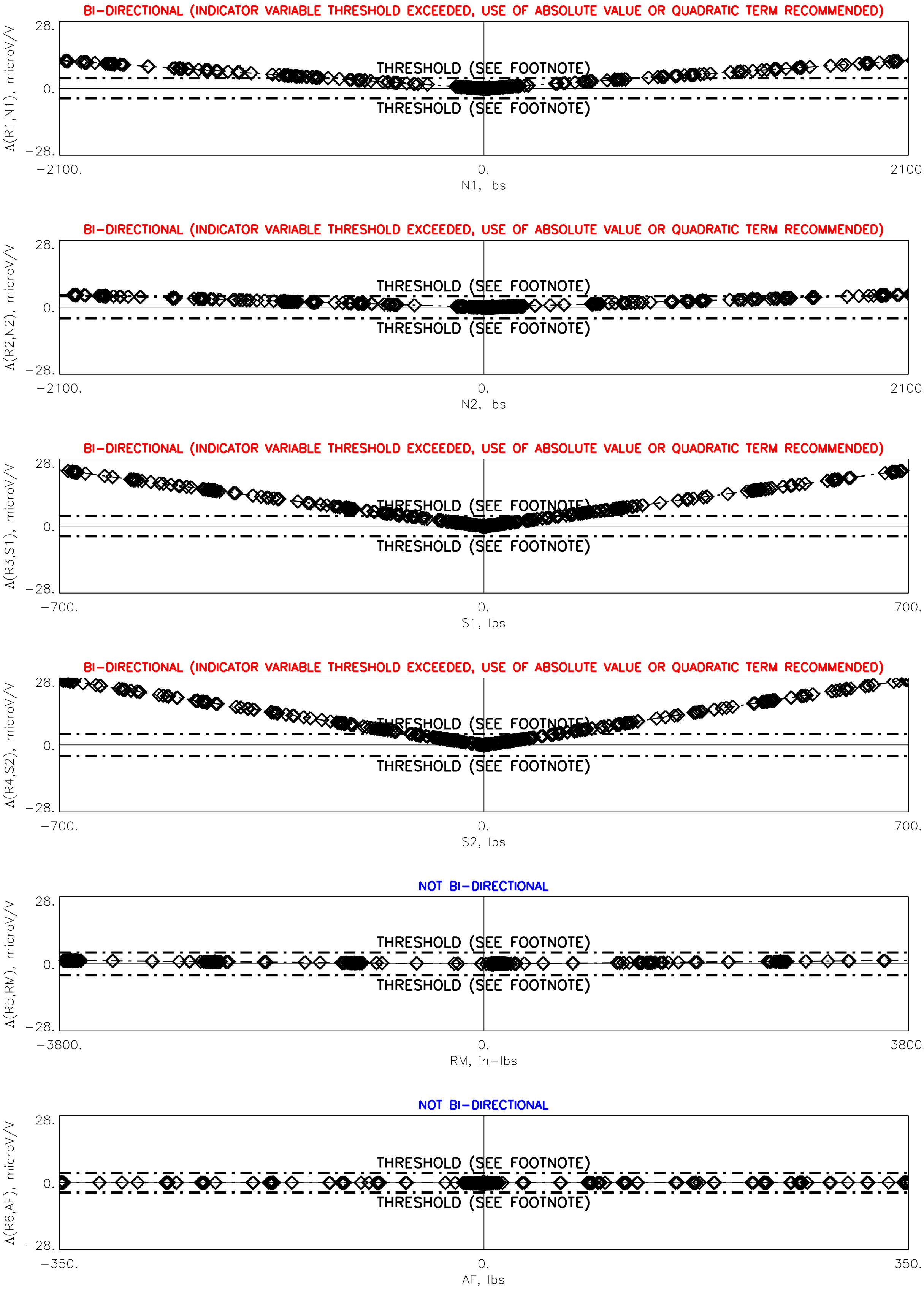
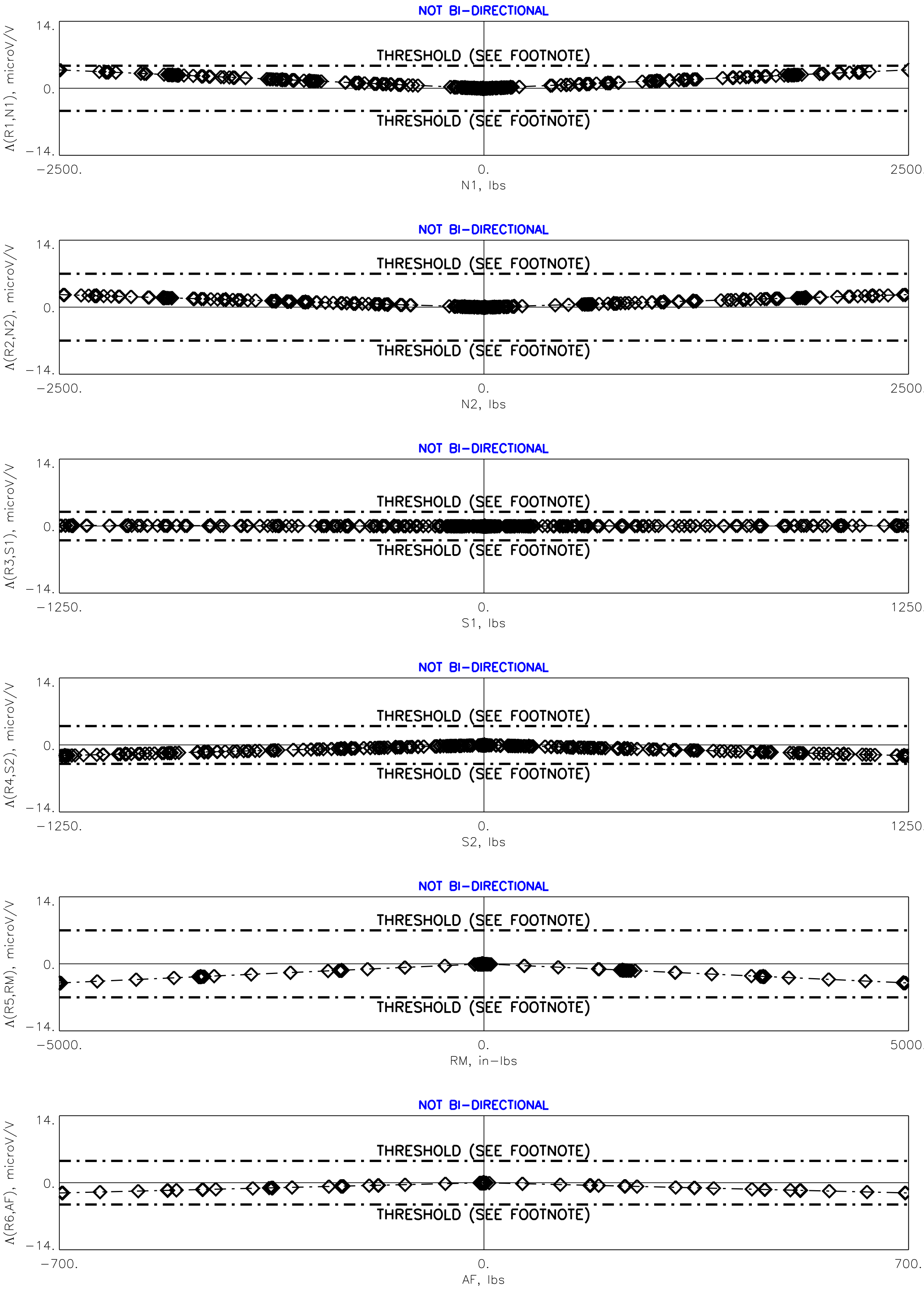


Fig. 2b Non–metric part and disassembled axial force element of a Task balance.



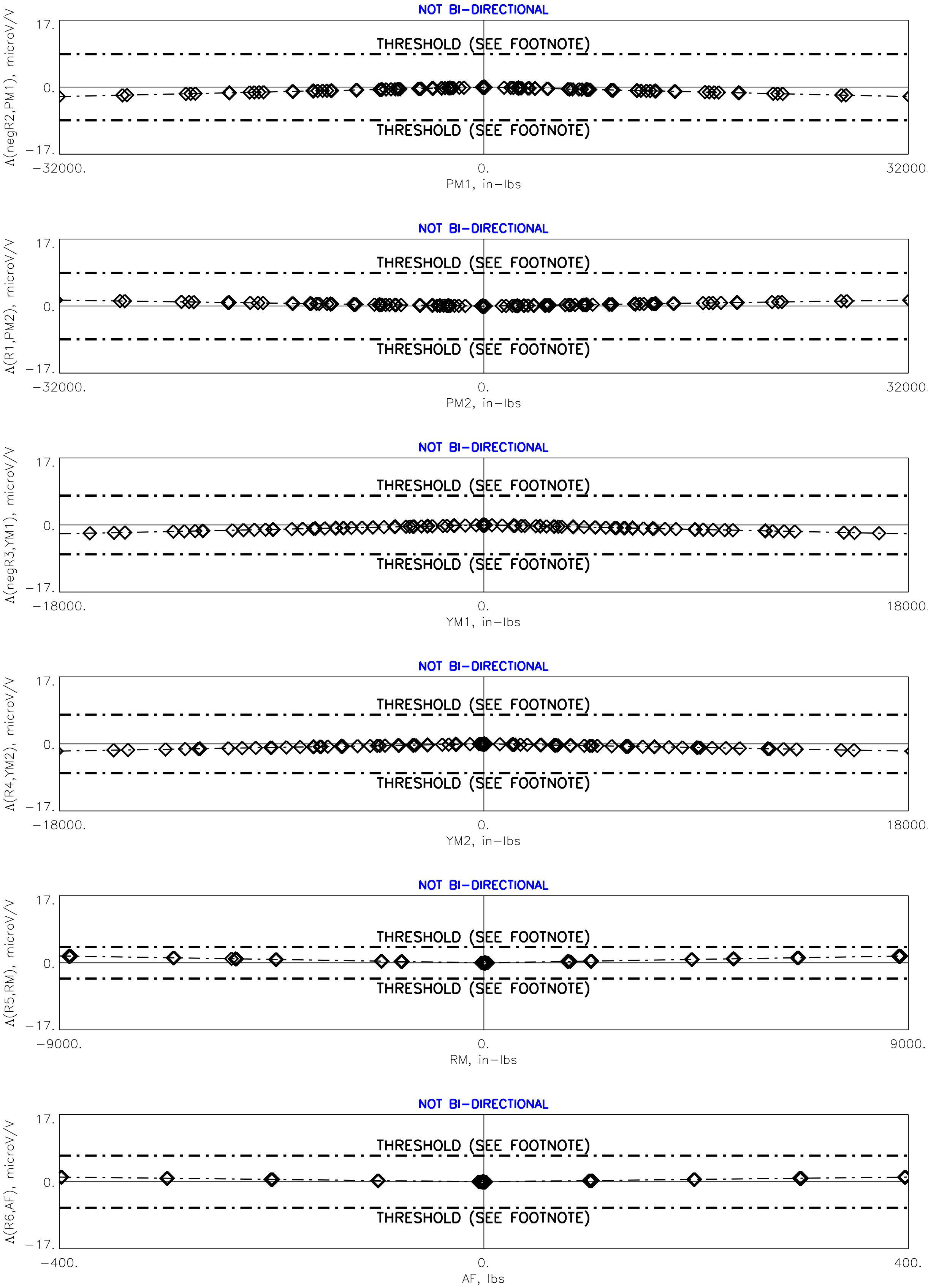
Footnote: The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 3a Indicator variable values for the six primary gages of NASA's MK29B Task balance.



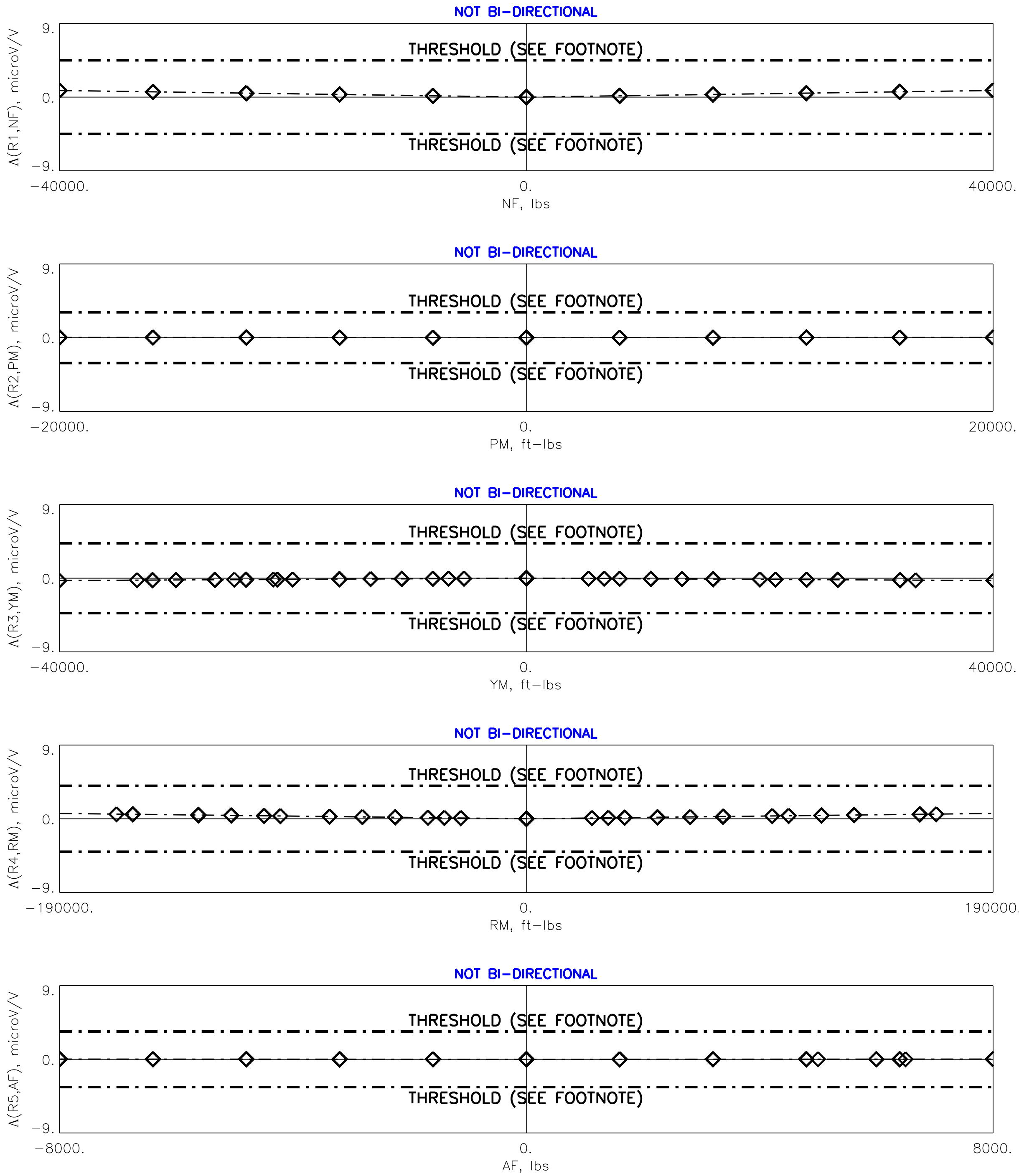
Footnote: The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 3b Indicator variable values for the six primary gages of NASA's MC60D Hybrid balance.



Footnote: The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 3c Indicator variable values for the six primary gages of NASA's NTF113C single–piece balance.



Footnote: The threshold marked as a dot–dashed line is defined in Eq. (1b) of the text.

Fig. 3d Indicator variable values for the five primary gages of NASA's MC400 semispan balance.