

A Baseline Load Schedule for the Manual Calibration of a Force Balance (Extended Abstract of Proposed Conference Paper)

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A baseline load schedule for the manual calibration of a force balance is defined that takes current capabilities at the NASA Ames Balance Calibration Laboratory into account. The chosen load schedule consists of 18 load series with a total of 194 data points. It was designed to satisfy six requirements: (i) positive and negative loadings should be applied for each load component; (ii) at least three loadings should be applied between 0 % and 100 % load capacity; (iii) normal and side force loadings should be applied at the forward gage location, aft gage location, and the balance moment center; (iv) the balance should be used in “up” and “down” orientation to get positive and negative axial force loadings; (v) the constant normal and side force approaches should be used to get the rolling moment loadings; (vi) rolling moment loadings should be obtained for 0, 90, 180, and 270 degrees balance orientation. In addition, three different approaches are discussed in the paper that may be used to independently estimate the natural zeros, i.e., the gage outputs of the absolute load datum of the balance. These three approaches provide gage output differences that can be used to estimate the weight of both the metric and non-metric part of the balance. Data from the calibration of a six-component force balance will be used in the final manuscript of the paper to illustrate characteristics of the proposed baseline load schedule.

Nomenclature

AF	= axial force
c_0	= x -coordinate of the center of the rolling moment arm
c_1	= x -coordinate of the center of the forward gage
c_2	= x -coordinate of the center of the aft gage
d	= distance between forward and aft gage
d_0	= coordinate difference between μ and c_0
d_1	= coordinate difference between μ and c_1
d_2	= coordinate difference between μ and c_2
F	= total normal or side force caused by rolling moment weights
$F1$	= normal or side force component at the forward gage of the balance
$F2$	= normal or side force component at the aft gage of the balance
\vec{g}	= gravitational acceleration
M	= total pitching or yawing moment caused by rolling moment weights
NF	= total normal force that acts on a balance

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$N1$	= normal force component at the forward normal force gage of the balance
$N2$	= normal force component at the aft normal force gage of the balance
RM	= rolling moment
SF	= total side force that acts on a balance
$S1$	= side force component at the forward side force gage of the balance
$S2$	= side force component at the aft side force gage of the balance
x	= coordinate along the roll axis of the balance
μ	= x -coordinate of the balance moment center

I. Introduction

A baseline load schedule for the manual calibration of a force balance was developed at the NASA Ames Balance Calibration Laboratory. The load schedule was designed to best capture the physical behavior of a force balance while taking limitations of the manual calibration process and of the calibration hardware at the Ames Balance Calibration Laboratory into account.

The baseline load schedule consists of 18 load series with a total of 194 data points. The load schedule assumes that gravity weights are used to apply the loadings. Therefore, the balance orientation for each load series must be specified. The balance orientation essentially describes the location of the roll axis of the balance relative to the gravitational acceleration. Figure 1a shows the six distinct orientations that the baseline load schedule uses.

In general, the baseline load schedule satisfies six requirements: (1) Positive and negative loads are applied for each load component so that the symmetry/asymmetry of the balance behavior and its “bi-directionality” characteristics are captured. (2) At least three loadings are applied between 0 % and 100 % load capacity so that a better definition of the quadratic and/or cubic terms in the regression model of the balance calibration data is achieved. (3) Normal and side forces are applied at the forward gage location, aft gage location, and the balance moment center so that relationships between the location of the applied forces and the location of the strain-gage measurements are described. (4) The “up” and “down” balance orientation is used to apply positive and negative axial force loadings as the direction of the gravitational acceleration may be used for the alignment of axial forces. (5) The “constant” normal and side force approaches are used to get the rolling moment loadings as the balance may not have to be re-leveled whenever a rolling moment loading is changed by shifting gravity weights from weight pan to weight pan. (6) Rolling moment loadings are performed for 0, 90, 180, and 270 degrees balance orientation in order to capture the symmetry/asymmetry of the balance behavior. The table in Fig. 1b summarizes important characteristics of the baseline load schedule.

The natural zeros, i.e., the gage outputs of the absolute load datum of the balance, also have to be determined during the calibration. These gage outputs are an important “universal” reference point for each strain-gage balance. In addition, they are needed whenever a balance calibration data analysis requires a tare load iteration (see Refs. [1] and [2] for a discussion of the tare load iteration process). Three independent methods are used at the Ames Balance Calibration Laboratory to determine the natural zeros. These three approaches do not just provide the gage outputs of the absolute load datum of the balance. They can also be used to numerically assess the weight of both the metric and non-metric part of the balance.

Key elements of the baseline load schedule are discussed in the next part of the paper. Then, three independent methods are discussed that may be used to determine the natural zeros of a balance.

II. Baseline Load Schedule

A. General Remarks

The baseline load schedule defined in Fig. 1b assumes that the gravity weight inventory of a balance calibration laboratory will allow for the application of at least three loadings between 0 % and 100 % load capacity. For simplicity, “ideal” load levels are used in Fig. 1b to describe sets of loadings that fulfill this requirement (i.e., 0 %, ± 25 %, ± 50 %, \dots). Ideally, individual loads are applied in a gradually increasing/decreasing fashion using more or less equally spaced increments from 0 % to 100 % capacity. A

“real-world” balance calibration laboratory may only have specific sets of gravity weights that may not allow for an even spacing between 0 % and ± 100 % load capacity. Then, the “ideal” load levels listed in Fig. 1b should be approximated as closely as possible by the available weights.

Repeat points are also a part of each load series that is listed in Fig. 1b. Repeat points approach an already existing load of a series by subtracting instead of adding weights (or vice versa). Therefore, repeat points help characterize the hysteresis behavior of the balance.

B. Normal Force Components

Six load series with a total of 54 calibration points is needed to apply the normal force loadings. The 54 calibration points consist of 30 unique data points and 24 repeat points. Figures 2a and 2b show a typical setup of a force balance before and during the application of gravity weights whenever normal force components are applied. Load series 1, 2, and 3 apply gravity weights such that the positive normal force is in the direction of the gravitational acceleration (orientation $\Rightarrow 0$). Load series 4, 5, and 6 apply gravity weights such that the negative normal force is in the direction of the gravitational acceleration (orientation $\Rightarrow 180$). The individual loadings are applied at three locations on the calibration body: forward gage location, aft gage location, and balance moment center (BMC).

C. Side Force Components

The application of side force loadings is very similar to the application of normal force loadings. Again, six load series with a total of 54 calibration points is needed to apply the side force loadings. The 54 calibration points consist of 30 unique data points and 24 repeat points.

Figures 2a and 2b show a typical setup of a force balance before and during the application of gravity weights whenever side force components are applied. Load series 7, 8, and 9 apply gravity weights such that the positive side force is in the direction of the gravitational acceleration (orientation $\Rightarrow 90$). Load series 10, 11, and 12 apply gravity weights such that the negative side force is in the direction of the gravitational acceleration (orientation $\Rightarrow 270$). Again, as it was the case with the normal force loadings, the individual loads are applied at three locations on the calibration body: forward gage location, aft gage location, and balance moment center (BMC).

D. Rolling Moment with Constant Normal and Side Force

Four load series with a total of 68 calibration points are needed to apply the rolling moment loadings at constant total normal and side force. These 68 calibration points consist of 36 unique data points and 32 repeat points.

The application of rolling moment loadings starts by first attaching the rolling moment hardware to the calibration body such that the rolling moment arm is perpendicular to (i) the direction of the normal force and (ii) the direction of the roll axis of the balance. Then, the balance is aligned such that the positive total normal force NF points in the direction of the gravitational acceleration (orientation $\Rightarrow 0$). In the next step, loadings at constant total normal force NF are applied. This approach has the advantage that the balance has to be leveled only once for the entire load series as balance deflections remain more or less constant as long as (i) the total normal force does not change and (ii) the balance support is symmetric relative to the plane that is defined by the roll axis of the balance and the direction of the gravitational acceleration. An equal number of gravity weights is placed on each of the two weight pans at the ends of the rolling moment arm to establish a zero rolling moment at constant normal force. Weights are then shifted from one weight pan to another to get the desired rolling moment loadings. This situation is described in load series 13 (see Fig. 1b).

In the next step, the balance is rotated such that the negative total normal force NF is in the direction of the gravitational acceleration (orientation $\Rightarrow 180$). Then, the balance is leveled and the loadings of load series 14 are applied (see Fig. 1b). Load series 14 is the mirror image of load series 13 for negative total normal force NF .

The rolling moments for constant total side force SF need to be applied next. Now, the rolling moment hardware is attached to the calibration body such that the rolling moment arm is perpendicular to (i) the direction of the side force and (ii) the direction of the roll axis of the balance. Then, the balance is aligned such that the positive total side force SF points in the direction of the gravitational acceleration (orientation $\Rightarrow 90$). In the next step, the loadings at constant total side force SF are applied. An equal number of

weights is placed on each of the two weight pans at the ends of the rolling moment arm to establish a zero rolling moment at constant side force. Weights are then shifted from one weight pan to another and back to get the desired rolling moment loadings. This situation is described in load series 15 (see Fig. 1b).

Now, the balance is rotated such that the negative total side force SF is in the direction of the gravitational acceleration (orientation $\Rightarrow 270$). Then, the balance is leveled and the loadings of load series 16 are applied (see Fig. 1b). Load series 16 is the mirror image of load series 15 for negative total side force SF .

It is important to point out that all rolling moment loadings of load series 13, 14, 15, and 16 are “combined” loadings as the forward and aft normal (or side force) components are loaded at the same time. The total normal force NF (or the total side force SF) is the force F that is caused by the gravity weights. Therefore, relationships between the “known” total force F and the “unknown” force components $F1$ and $F2$ at the forward and aft gages are derived in the appendix of the paper so that the final balance calibration load table can be prepared in the correct format (see Eqs. (11a) and (11b) in the appendix).

Calibration hardware limitations may not always allow for the application of all four sets of rolling moment loadings that the baseline load schedule recommends (i.e., load series 13, 14, 15, and 16). In that case, an attempt should be made to apply the rolling moment loadings at least for $\pm NF$ (or $\pm SF$) so that the symmetry/asymmetry between the rolling moment gage outputs and the rolling moment loadings can be captured.

E. Axial Force

Two load series with a total of 18 calibration points are needed to apply the axial force loadings. The 18 calibration points consist of 10 actual data points and 8 repeat points.

Figures 3a and 3b show a typical setup of a force balance before and during the application of gravity weights whenever axial force loadings are applied. Knife edges are typically used to establish a contact line between calibration body and yoke assembly.

Load series 17 applies gravity weights such that the positive axial force points in the direction of the gravitational acceleration (orientation \Rightarrow “up”). Load series 18 applies gravity weights such that the negative axial force points in the direction of the gravitational acceleration (orientation \Rightarrow “down”).

It may not always be possible to align the roll axis of a balance parallel to the direction of the gravitational acceleration. Then, an alternate loading hardware setup has to be used to apply axial forces.

The natural zeros of the balance also need to be determined so that the balance behavior can be described correctly. This process is explained in detail in the next section of the paper.

III. Natural Zeros

Data points need to be recorded during the manual calibration of a force balance that make it possible to determine the gage outputs of the absolute load datum of the balance. These gage outputs are called the “natural zeros” of the balance. “Natural zeros” are also measured as a part of the standard electrical checks on the balance. An unexpected shift of the “natural zeros” may indicate a possible damage of the balance since it was last used.

The absolute load datum is assumed to be a zero load condition of the balance. Corresponding gage outputs, i.e., the “natural zeros,” would be obtained if the balance is in a “weightless” condition (see Fig. 4a). Unfortunately, it is not directly possible to put a balance into “weightless” state in a balance calibration laboratory. Instead, outputs of a “weightless” balance have to be approximated by using the arithmetic mean of outputs that are measured for different orientations of the balance.

In principle, three independent methods are available to determine the natural zeros of a balance. The table in Fig. 4b compares characteristics of these three methods. All three methods determine the natural zeros by averaging gage outputs that are measured for different combinations of balance orientations.

Figure 5a shows the setup of a balance assuming that Method A is applied. In this case, the roll axis of the balance is perpendicular to the gravity vector. The balance is rotated four times (0, 90, 180, 270 degrees) and corresponding gage outputs are recorded. These gage outputs are caused by the weight of the shell of the balance, i.e., by the weight of the metric part. Then, the arithmetic mean of the outputs is computed for each gage. These values are the first estimate of the natural zeros of the balance.

Sometimes, a better horizontal alignment of the balance can be achieved by keeping the calibration

body attached to the balance (see Fig. 5b). In that case, the rotation of the balance and the calculation of the natural zeros is still performed as outlined in the previous paragraph. The influence of the calibration body weight on the natural zeros is removed by the averaging of the gage outputs of the four orientations. However, the gage outputs for each balance orientation are now caused by the shell assembly weight, i.e., the weight of the calibration body and the metric part, assuming that the weight of sensors required for the leveling of the balance is negligible.

Figure 6a shows the setup of a balance assuming that Method B is applied. In this case, the roll axis of the balance is parallel to the gravity vector. The balance is rotated two times (orientations “up” and “down”) and corresponding gage outputs are recorded. Again, gage outputs are caused by the weight of the shell of the balance, i.e., by the weight of the metric part. Then, the arithmetic mean of the outputs is computed for each gage. These values are the second independent estimate of the natural zeros of the balance.

A better vertical alignment of the balance can often be achieved by keeping the calibration body attached to the balance (see Fig. 6b). In that case, the rotation of the balance and the calculation of the natural zeros is still performed as outlined in the previous paragraph as the influence of the calibration body weight on the gage outputs is removed by the averaging of the outputs of each gage.

Figure 7a shows the setup of a balance assuming that Method C is applied. In this case, the roll axis of the balance is perpendicular to the gravity vector as the balance is assumed to be placed on a leveling table using a vee block. Again, the balance is rotated four times (0, 90, 180, 270 degrees) and corresponding gage outputs are recorded. In this case, the gage outputs of each orientation are caused by the weight of the core of the balance, i.e., by the weight of the non-metric part. Then, the arithmetic mean of the outputs is computed for each gage. These values are the third estimate of the natural zeros of the balance. Method C may also be repeated with the calibration body left attached to the balance (see Fig. 7b). In theory, the gage outputs measured for the situations depicted in Figs. 7a and 7b should be very close as the gages only see loads caused by the balance core (non-metric part).

Experience at the Ames Balance Calibration Laboratory has shown that Method A, Method B, and Method C will lead to the same natural zero estimates as long as small balance alignment and gage output measurement errors are neglected. Ultimately, the choice of methods used is determined in part by the equipment available at the time of the calibration. The preferred method at Ames is to use the balance with calibration body attached to insure accurate horizontal/vertical alignment and rotations.

IV. Discussion of Example

Manual calibration data from a six-component force balance will be used in the final manuscript of the paper to illustrate characteristics of the baseline load schedule. In addition, an analysis of the calibration data will be performed in order to compare predicted tare loads with known loads that are caused by (i) the weight of the calibration fixtures and (ii) the weight of both the metric and non-metric part of the balance (see Refs. [1] and [2] for a discussion of the tare load iteration process).

References

¹AIAA/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.

²Ulbrich, N., “A Universal Tare Load Prediction Algorithm for Strain-Gage Balance Calibration Data Analysis,” AIAA 2011-6090, paper presented at the 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, California, July/August 2011.

Appendix: Force Components of Rolling Moment Weights

The application of the rolling moment loadings during the manual calibration of a balance is always associated with force components that act on the forward and aft gages whenever gravity weights and a simple rolling moment arm are used to apply the loadings. Therefore, it is necessary to determine the normal or side force components at the forward and aft gages that are caused by the gravity weights at the location of the rolling moment arm on the calibration body.

The derivation of the normal and side force components leads to similar relationships as long as the correct coordinates of the gages and of the balance moment center are used. Therefore, in order to simplify the derivation, the normal and side force components $N1$ and $S1$ at the forward gages are replaced by the variable $F1$. Similarly, the normal and side force components $N2$ and $S2$ at the aft gages are replaced by the variable $F2$.

Relationships between the force components $F1$ and $F2$ at the forward and aft gages, the total force F caused by the gravity weights, and the rolling moment arm coordinate c_0 can easily be derived with the help of Fig. 8. First, the total force F and the total moment M at the balance moment center (BMC) are replaced by two forces $F1$ and $F2$ at the location of the gages. The sum of these two forces equals the total force caused by the gravity weights. We get:

$$F = F1 + F2 \quad (1)$$

Similarly, we know that the total moment at the BMC equals the sum of the moment contributions from the two forces that replace the force and moment at the BMC. It is assumed that the location of both the BMC and of the gages is described in a one-dimensional coordinate system. This coordinate system is placed on the line that is defined by the roll axis of the balance (see Fig. 8). Then, the BMC has the coordinate μ , the center of the rolling moment arm the coordinate c_0 , the center of the forward gage the coordinate c_1 , and the center of the aft gage the coordinate c_2 . Now, three coordinate differences d_0 , d_1 , and d_2 may be defined that describe distances between the BMC and the forces F , $F1$, and $F2$. We get:

$$d_0 = \mu - c_0 \quad (2a)$$

$$d_1 = \mu - c_1 \quad (2b)$$

$$d_2 = \mu - c_2 \quad (2c)$$

In the next step, using the sign definitions of (i) the balance loads and of (ii) the coordinates that are depicted in Fig. 8, the total moment at the BMC can be expressed as follows:

$$M = F1 \cdot d_1 - F2 \cdot (-d_2) \quad (3)$$

From Eq. (1) we know that:

$$F2 = F - F1 \quad (4)$$

The right hand side of Eq. (4) may be used to replace the force $F2$ in Eq. (3). We get:

$$M = F1 \cdot d_1 - (F - F1) \cdot (-d_2) \quad (5)$$

Rearranging terms in Eq. (5) and after some algebra we get:

$$F1 = F \cdot \frac{(-d_2)}{d_1 - d_2} + M \cdot \frac{1}{d_1 - d_2} \quad (6)$$

Similarly, using Eq. (6) to replace force $F1$ in Eq. (4) and after some algebra, we get:

$$F2 = F \cdot \frac{d_1}{d_1 - d_2} - M \cdot \frac{1}{d_1 - d_2} \quad (7)$$

We also know that the moment at the BMC is exclusively caused by the gravity weights that are used to apply the rolling moment loadings. Therefore, we can write:

$$M = F \cdot d_0 \quad (8)$$

Then, using Eq. (8) to replace the moment M in (6) & (7), we get:

$$F1 = F \cdot \frac{(-d_2)}{d_1 - d_2} + F \cdot \frac{d_0}{d_1 - d_2} \quad (9a)$$

$$F2 = F \cdot \frac{d_1}{d_1 - d_2} - F \cdot \frac{d_0}{d_1 - d_2} \quad (9b)$$

In the next step, after simplifying Eqs. (9a) and (9b) further, we get the equations:

$$F1 = F \cdot \frac{d_0 - d_2}{d_1 - d_2} \quad (10a)$$

$$F2 = F \cdot \frac{d_1 - d_0}{d_1 - d_2} \quad (10b)$$

Now, using Eqs. (2a), (2b), (2c) to replace the moment arms in Eqs. (10a) and (10b) and after some algebra, we get the relationships between the force components $F1$ and $F2$, the total force F caused by the gravity weights, and the rolling moment arm coordinate c_0 :

$F1 = F \cdot \left[\frac{c_2 - c_0}{c_2 - c_1} \right] \quad (11a)$
$F2 = F \cdot \left[\frac{c_0 - c_1}{c_2 - c_1} \right] \quad (11b)$

The validity of Eqs. (11a) and (11b) may be examined by looking at three limiting cases and comparing the calculated force components $F1$ and $F2$ with corresponding expected values.

Limiting Case 1: It is assumed that the coordinate c_0 of the center of the rolling moment arm is at the forward gage location. Then, we get the relationship:

$$c_0 = c_1 \quad (12a)$$

Now, after using Eq. (12a) to replace c_0 in Eqs. (11a) and (11b), we get:

$$F1 = F \quad (12b)$$

$$F2 = 0 \quad (12c)$$

Limiting Case 2: It is assumed that the coordinate c_0 of the center of the rolling moment arm is at the aft gage location. Then, we get the relationship:

$$c_0 = c_2 \quad (13a)$$

Now, after using Eq. (13a) to replace c_0 in Eqs. (11a) and (11b), we get:

$$F1 = 0 \quad (13b)$$

$$F2 = F \quad (13c)$$

Limiting Case 3: It is assumed that (i) the coordinate c_0 of the center of the rolling moment arm is at the BMC of the balance and that (ii) the BMC is located halfway between the forward and aft gage. Then, we get the relationship:

$$c_0 = \frac{c_1 + c_2}{2} \quad (14a)$$

Now, after using Eq. (14a) to replace c_0 in Eqs. (11a) and (11b), we get:

$$F1 = \frac{F}{2} \quad (14b)$$

$$F2 = \frac{F}{2} \quad (14c)$$

Results for the three limiting cases, i.e., Eqs. (12b), (12c), (13b), (13c), (14b), (14c), meet expectations as (i) the total force has to equal the corresponding force at a gage location whenever the coordinate of the center of the rolling moment arm matches the coordinate of a gage and (ii) the total force is equally divided between the forces at the gage locations whenever the coordinate of the center of the rolling moment arm is halfway between the coordinates of the forward and aft gages.

The sign of F , i.e., of the total normal or side force caused by the gravity weights, is determined by the orientation that the balance has during the calibration (see again Fig. 1a for the definition of the orientations). Four cases have to be distinguished. Case 1 assumes that the balance orientation is 0. In that case, F has a positive sign as the gravitational acceleration \vec{g} points in the direction of positive NF . Case 2 assumes that the balance orientation of the balance is 180. Then, F has a negative sign as the gravitational acceleration \vec{g} points in the direction of negative NF . Case 3 assumes that the balance orientation is 90. In that case, F has a positive sign as the gravitational acceleration \vec{g} points in the direction of positive SF . Case 4 assumes that the balance orientation of the balance is 270. Then, F has a negative sign as the gravitational acceleration \vec{g} points in the direction of negative SF .

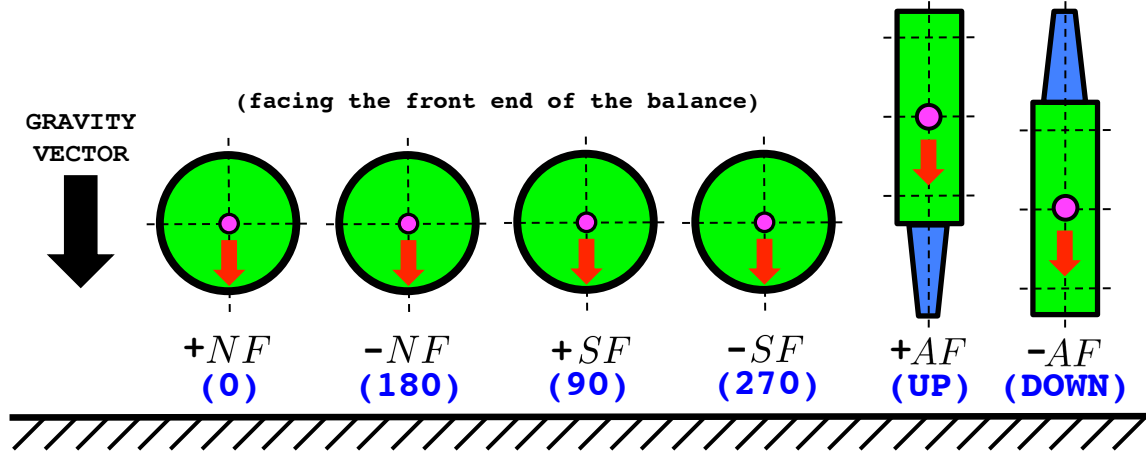


Fig. 1a Definition of balance orientations relative to the direction of the gravitational acceleration.

Series	Orient.	Type	Position [†]	List of Applied Loads in % of Capacity [‡]
1	0	$+N1$	FWD	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
2	0	$+N2$	AFT	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
3	0	$+N1$; $+N2$	BMC	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
4	180	$-N1$	FWD	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
5	180	$-N2$	AFT	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
6	180	$-N1$; $-N2$	BMC	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
7	90	$+S1$	FWD	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
8	90	$+S2$	AFT	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
9	90	$+S1$; $+S2$	BMC	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
10	270	$-S1$	FWD	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
11	270	$-S2$	AFT	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
12	270	$-S1$; $-S2$	BMC	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
13	0	$\pm RM$ ($+NF = const.$)	c_0 (see Fig. 8)	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
14	180	$\pm RM$ ($-NF = const.$)	c_0 (see Fig. 8)	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
15	90	$\pm RM$ ($+SF = const.$)	c_0 (see Fig. 8)	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
16	270	$\pm RM$ ($-SF = const.$)	c_0 (see Fig. 8)	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %
17	up	$+AF$	–	0 %, +25 %, +50 %, +75 %, +100 %, +75 %, +50 %, +25 %, 0 %
18	down	$-AF$	–	0 %, -25 %, -50 %, -75 %, -100 %, -75 %, -50 %, -25 %, 0 %

[†]FWD = load acts at the forward gage ; AFT = load acts at the aft gage ; BMC = load acts at the balance moment center.

[‡]The “ideal” spacing of 25 % is used to indicate that at least three loads should be applied between 0 % and 100 % capacity.

Fig. 1b Baseline load schedule for the manual calibration of a six-component force balance.

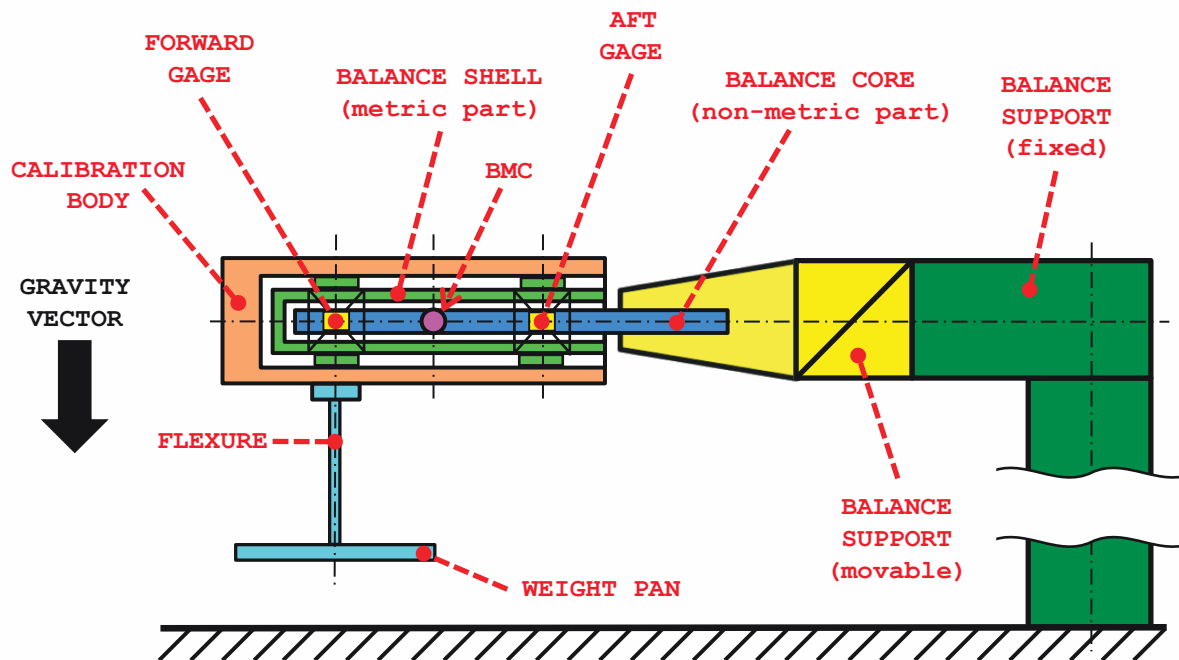


Fig. 2a Setup of balance, calibration hardware, and support for normal or side force loadings.

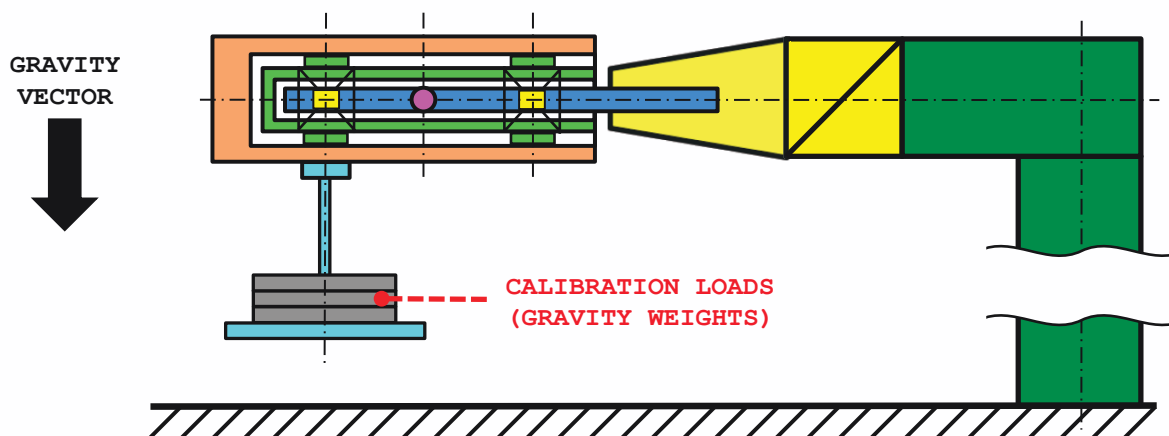


Fig. 2b Application of normal or side force loadings using gravity weights.

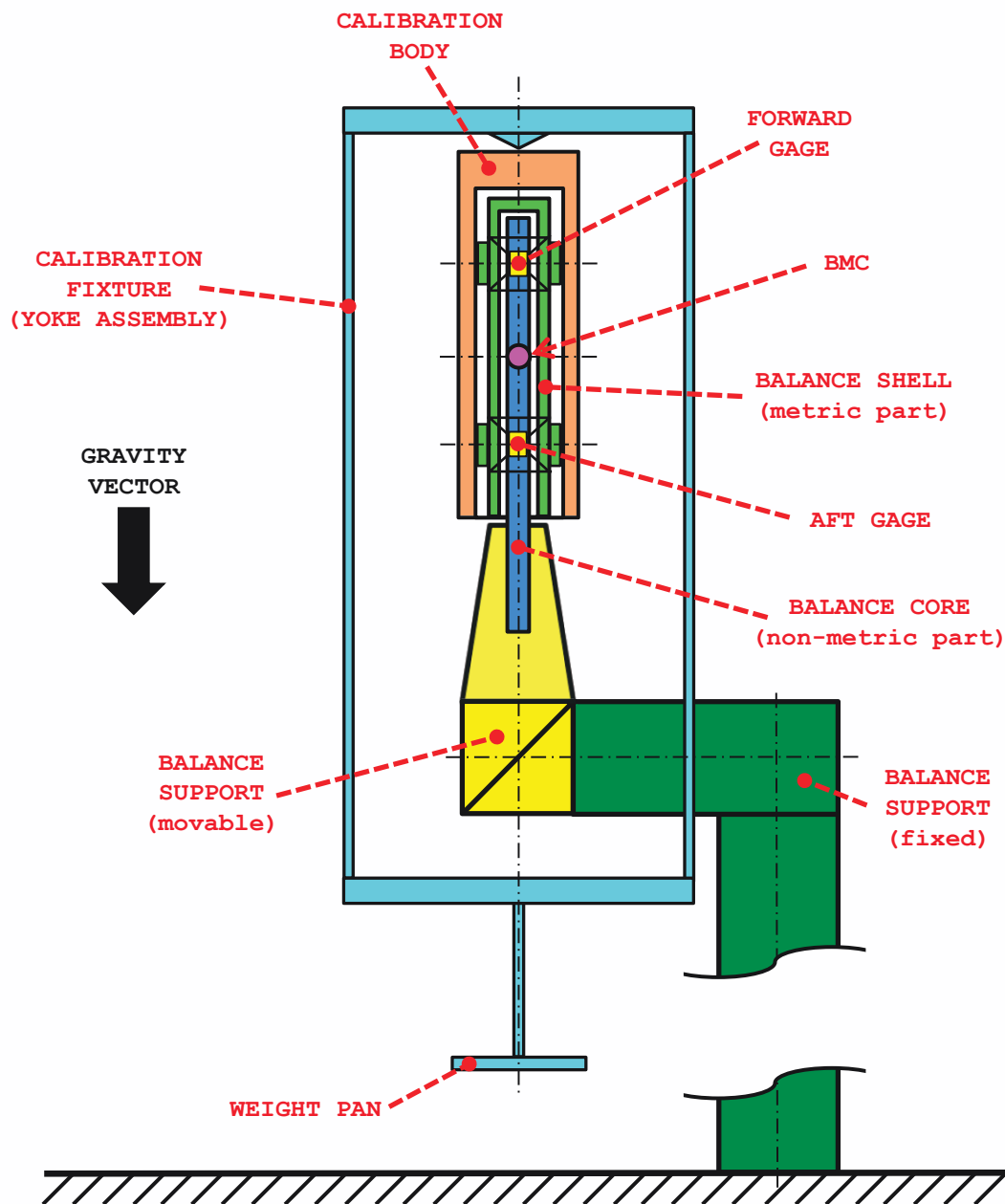


Fig. 3a Setup of balance, calibration hardware, and support for positive axial force loadings.

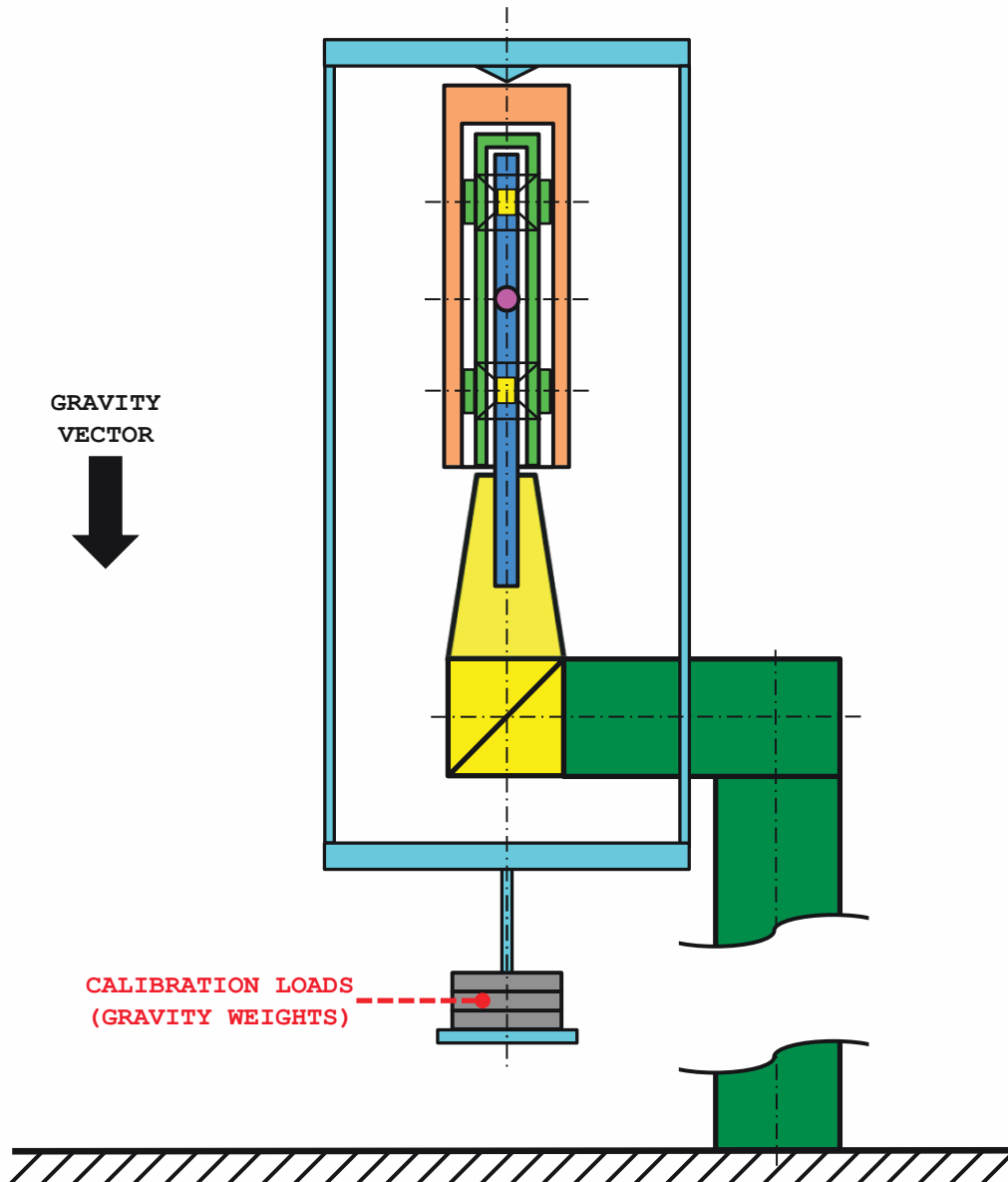


Fig. 3b Application of positive axial force loadings using gravity weights.

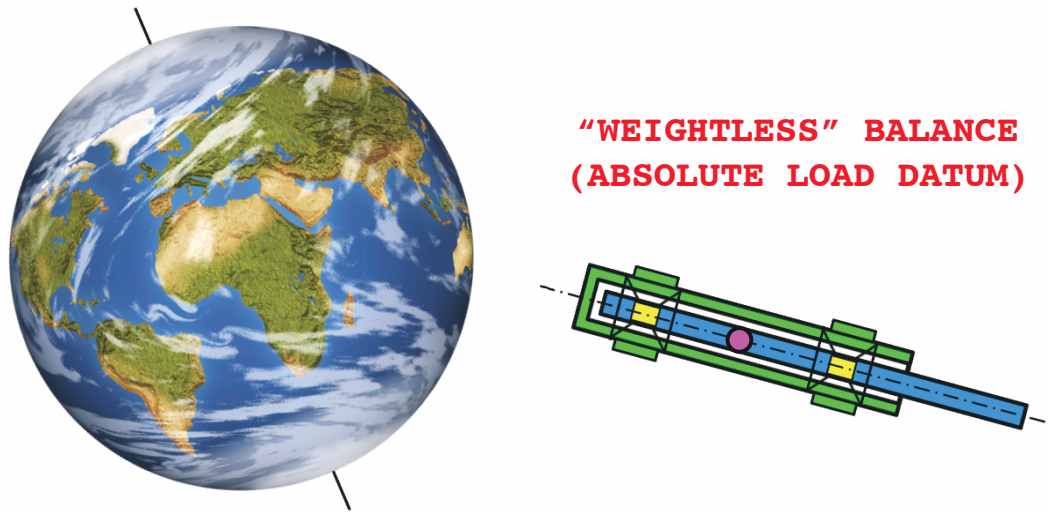


Fig. 4a Definition of the absolute load datum of a strain-gage balance.

Method	Orientations	Applied Balance Load	Mounted/Supported Balance Assembly
A	0, 90, 180, 270	<u>weight</u> of <u>shell</u> (metric part), or, <u>weight</u> of <u>shell assembly</u> (calibration body and metric part)	<u>core</u> (non-metric part)
B	<i>up</i> , <i>down</i>	<u>weight</u> of <u>shell</u> (metric part), or, <u>weight</u> of <u>shell assembly</u> (calibration body and metric part)	<u>core</u> (non-metric part)
C	0, 90, 180, 270	<u>weight</u> of <u>core</u> (non-metric part)	<u>shell</u> (metric part), or, <u>shell assembly</u> (calibration body and metric part)

Fig. 4b Comparison of three methods for the determination of the natural zeros.

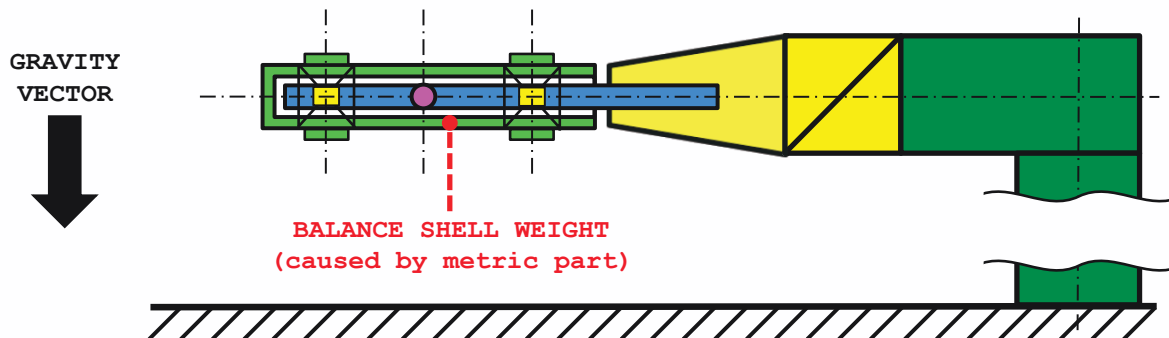


Fig. 5a Method A: Setup of balance without use of calibration body for horizontal alignment.

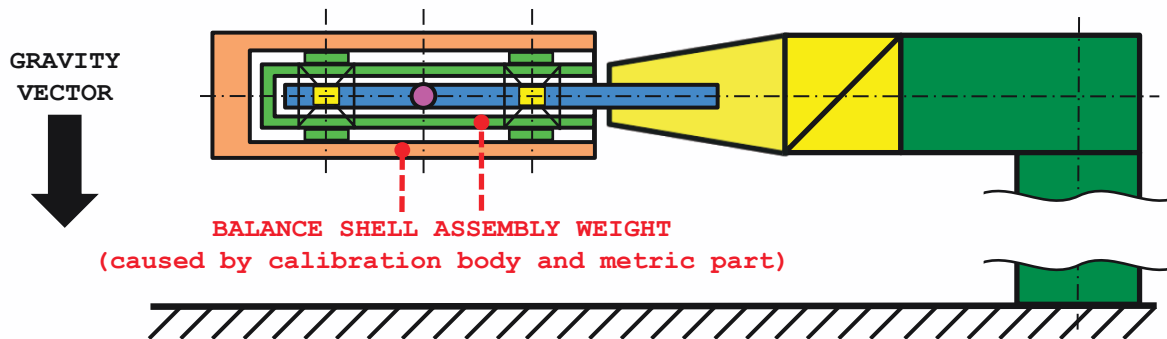


Fig. 5b Method A: Setup of balance with use of calibration body for horizontal alignment.

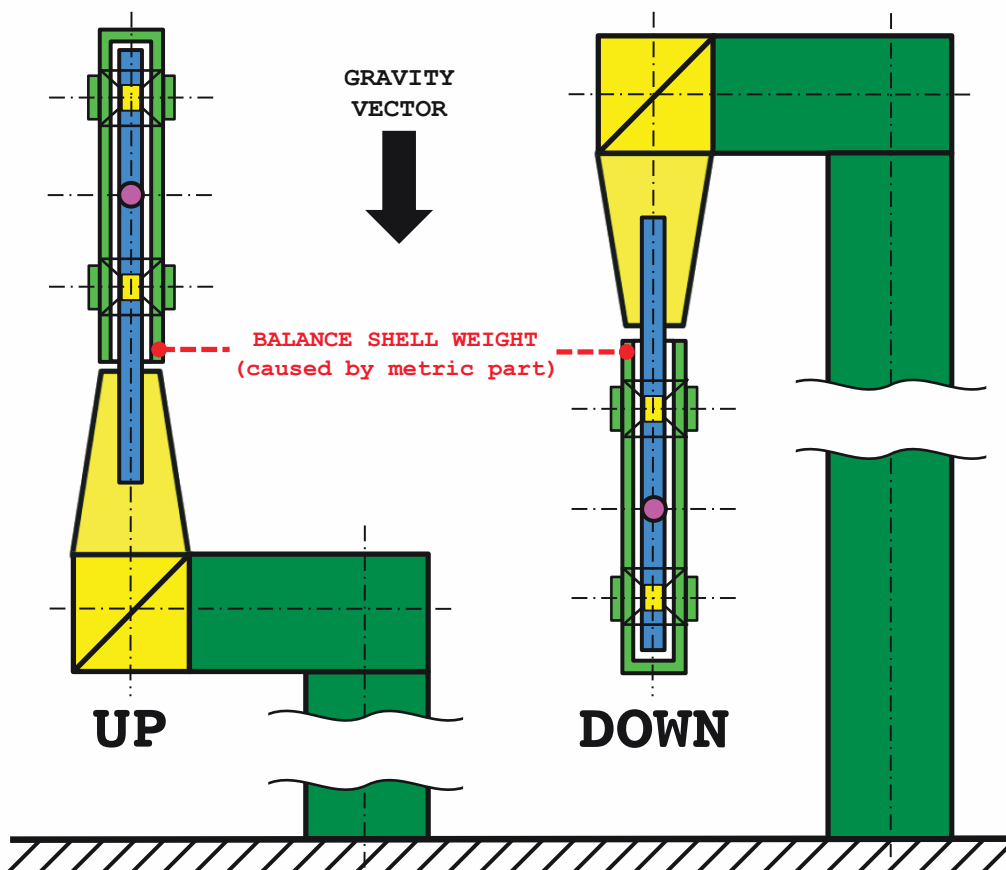


Fig. 6a Method B: Setup of balance without use of calibration body for vertical alignment.

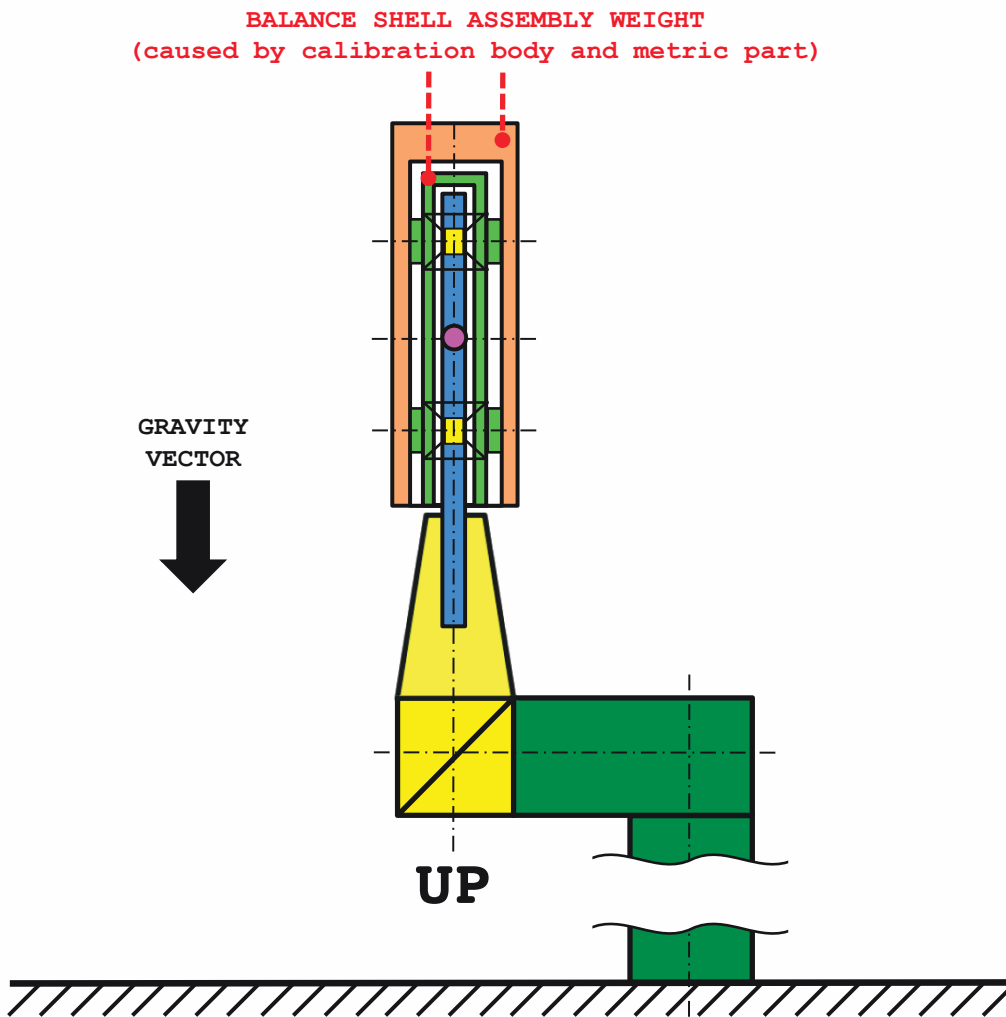


Fig. 6b Method B: Setup of balance with use of calibration body for vertical alignment.

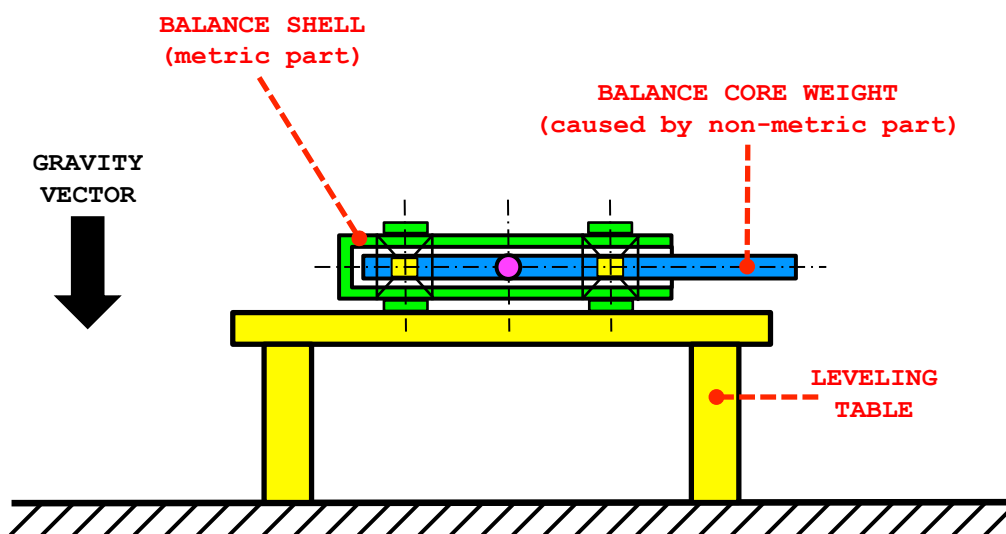


Fig. 7a Method C: Setup of balance on a leveling table (vee block not shown).

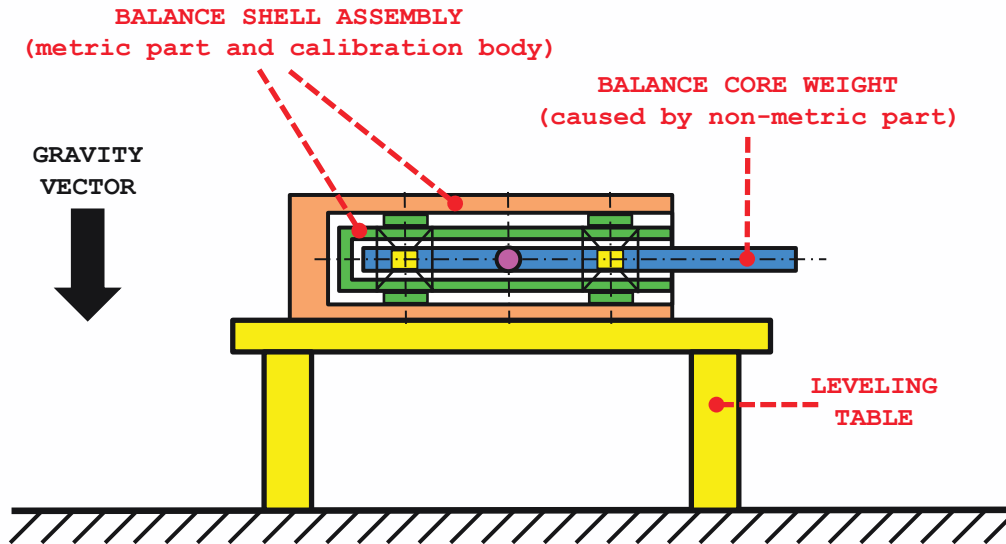
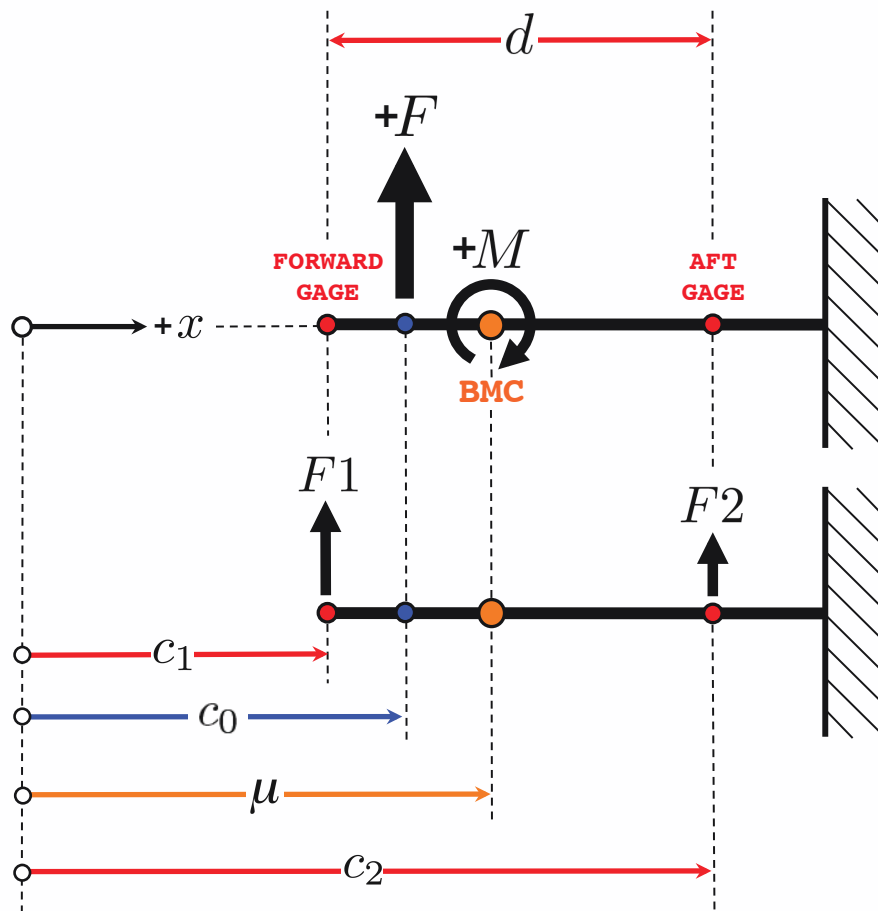


Fig. 7b Method C: Setup of balance and calibration body on a leveling table.



c_0 = COORDINATE OF THE CENTER OF THE ROLLING MOMENT ARM

Fig. 8 Calculation of gage load components $F1$ and $F2$ as a function of the total force F . (balance orientations defined in Fig. 1a determine if the total force F equals $\pm NF$ or $\pm SF$)