New Verification Concept for ETW's 25 kN Balance Calibration Machine

J.H. You[1], H. Quix[2], J. Semmelmann[3], T. Baumgart[4], F.-J. Ernst[5], and W. Strudthoff[6]
European Transonic Windtunnel GmbH, 51147 Cologne, Germany

A precise calibration of internal strain-gauge balances prior to wind tunnel test campaigns is the mandatory requirement for accurate and reliable measurements of aerodynamic loads acting on full span aircraft models. Therefore, the European Transonic Windtunnel (ETW), a cryogenic high Reynolds number test facility, operates a fully automatic 25 kN Balance Calibration Machine (BCM) for the calibration of six-component strain-gauge balances over the full cryogenic temperature range of ETW. The present paper describes a new two-step verification method introduced to assess and maintain the BCM's high level of accuracy, reliability, and repeatability. As the first step, the accuracy of BCM's force measurement is verified by using high precision external load cells installed in specifically designed load cell adapters. In the second step, the reliability of the BCM's moment measurement is assessed in an indirect way by using two pairs of offset adapters in conjunction with a calibrated ETW standard flange balance. Unlike the master calibration procedure performed in the past, the new verification method does not require any mechanical modifications of the BCM's subsystems, so that the integrity of the BCM remains unchanged during the whole verification process. As a result, the new verification procedure can check the validity of the BCM's force and moment measurement without introducing any risks and uncertainties generated by the dismantling of the BCM. This paper presents a detailed overview of the first application of the new verification concept and discusses the results of this first application.

Nomenclature

δ	=	Adapter offset
F_x	=	Axial force
F_y	=	Side force
F_z	=	Normal force
M_x	=	Rolling moment
M_y	=	Pitching moment
M_z	=	Yawing moment

I. Introduction

The European Transonic Windtunnel (ETW) is a closed circuit, pressurized continuous transonic wind tunnel for testing scaled aircrafts both at real flight Reynolds numbers and Mach numbers. The facility uses gaseous nitrogen as the working medium for the test temperature range between 110 K to 313 K and pressure range between 1.1 bar to 4.5 bar. The operational Mach number range varies between 0.15 to 1.35.

[1] Test and Data Systems Engineer, jhy@etw.de
[2] Group leader, Test and Data Systems, haq@etw.de
[3] Test Engineer, jes@etw.de
[4] Instrumentation Technician, fje@etw.de
[5] Instrumentation Technician, twb@etw.de
[6] Consultant, Test and Data Systems, ws@etw.de

Aerodynamic forces and moments are the primary physical quantities to be measured in wind tunnel testing. Therefore, ETW provides for customers a set of high precision internal strain-gauge balances. Currently, 9 internal balances and two boom balances are available at ETW for testing full span aircraft models. Crucial for achieving high levels of accuracy for aerodynamic force/moment measurements is the precise balance calibration, which establishes a link between measured electric outputs and the aerodynamic loads acting on the aircraft models. For this reason, all ETW's internal strain-gauge balances are calibrated by ETW's fully automatic 25 kN Balance Calibration Machine (BCM) over the entire operational temperature range of ETW prior to use in the wind tunnel. Therefore, maintaining the highest level of accuracy, reliability, and repeatability of the BCM is an essential prerequisite for the precise measurement of aerodynamic loads and, by extension, successful wind tunnel testing. To meet these requirements, the BCM has re-calibrated in the past at regular intervals, referred to as master calibrations.

Based upon the experience gained from the previous master calibrations, the calibration procedure has a substantial influence on the integrity of the BCM as it involves major mechanical adaptions and extensive dismantling of BCM's subsystems. Any mechanical disassembles of the BCM however increases the probability for implying a large risk to the integrity of the BCM, and consequently affects the validity of the master calibration. For this reason, a completely new procedure is required to verify the accuracy and reliability of the BCM without affecting the BCM's integrity, and eventually to replace the previous master calibration procedure.

The newly developed verification procedure is a two-step approach. As the first step, the accuracy of the BCM's force measurement with respect to international load standards is verified in a direct manner by using high precision external load cells connected directly to the BCM's measuring unit. In order to install the external load cells in the BCM, a pair of unique load cell adapters labeled as Force Verification Adapters (FVA) has been developed.

As the next step, verification of the measured rolling, pitching, and yawing moments is performed by using two pairs of specifically designed balance adapters, called Axial Offset Adapters (AOA) and Lateral Offset Adapters (LOA), in conjunction with one of ETW's standard flange balances. The use of each offset adapter pair enables the internal balance to be installed with either an axial offset (x-direction) or a lateral offset (y- or z-direction). By applying a pure force on the internal balance installed in any offset adapters, the balance, which is calibrated using ETW's standard calibration adapters, has to read an addition moment corresponding to the value of the applied pure force multiplied by the known offset δ.

This paper firstly aims to provide a general overview of the BCM and its previous master calibration procedure, and secondly explains the new force and moment verification procedure and its setup. Selected results of the first application of the verification concept are also presented and discussed.

II. ETW's Balance Calibration Machine

ETW's BCM is a computer controlled, 25 kN calibration machine for the hands-off calibration of six-component internal strain-gauge balances over an extensive temperature range, including cryogenic conditions, to a high degree of accuracy. The BCM has been fully operational since the commissioning in spring 1993. With over 25 years of BCM operation, ETW has gained extensive and valuable experiences in terms of the correct handling of the machine, precise and effective calibration procedures for different balance types, calibration at ambient and cryogenic conditions, and maintenance of the subsystems. ETW's effort is still focused on the technical and procedural optimization in order to maintain the BCM's accuracy beyond 0.1% of the BCM's full load range [1], see Table 1.

	F_x	F_y	F_z	M_x	M_y	M_z
Design loads	± 2000 N	± 3000 N	± 25000 N	± 2000 Nm	± 1500 Nm	± 1000 Nm
Operation loads	± 1500 N	± 3000 N	± 20000 N	± 2000 Nm	± 1200 Nm	± 1000 Nm

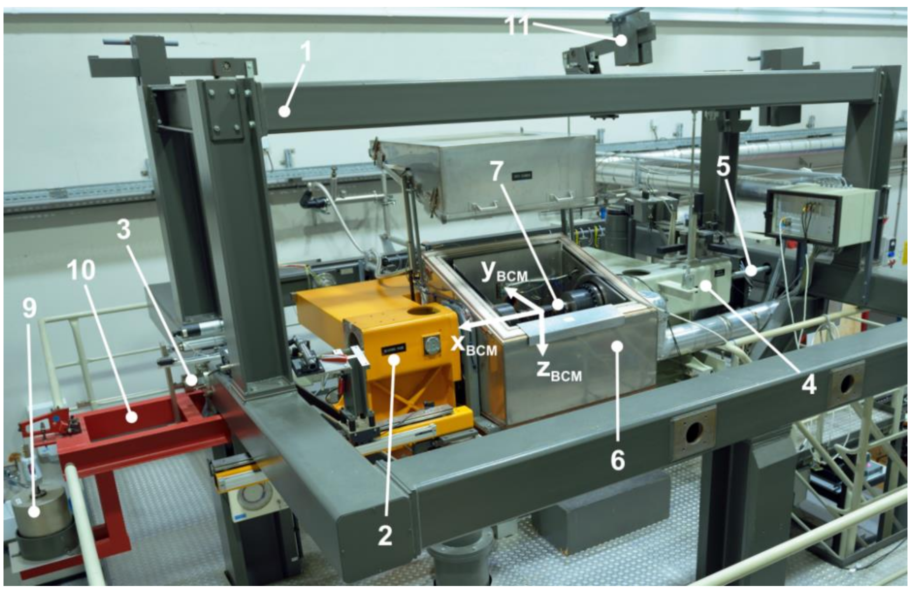
Table 1 BCM operating envelope.

The BCM consists of the base frame, see (1) in Fig. 1, measuring frame (2), loading frame (4), and cryo-chamber (6). The cryo-chamber allows the BCM to calibrate the internal balance over the full working temperature range of ETW, typically in 10 K steps. The measuring frame is equipped with six high precision load cells, labeled as master load cells (3). As a whole, the measuring frame can be considered as an external balance measuring the forces/moments acting on the candidate internal balance mounted between the measuring and loading frames.

Applying the required forces and moments to the candidate balance is achieved by six force generator units (5) connected via rods to the loading frame. The push-pull acting pneumatic force generators allow the BCM to apply any desired pure force or moment as well as any load combinations within a very short time period. If there are no forces/moments acting on the candidate balance, the loading frame is effectively 'floating' and has no influence on the candidate balance as the weight of loading frame is compensated by introducing three counter weight units (11).

The internal balance (7) to be calibrated is located in the cryo-chamber and connected to the measuring frame and loading frame via calibration adapters. Contrary to the conventional installation of the balance in an aircraft model, for the calibration in the BCM, the sting end of the balance is mounted to the loading frame and loaded, whereas the model end is fixed to the measuring frame and regarded as the calibration reference surface [2].

In 2014, within the framework of modernizing the BCM, both hardware and software upgrades have been conducted. With respect to the hardware upgrade, the modernization included the introduction of two new Hottinger HBM amplifiers to measure both the external and internal balance signals and new Pressure Generator Units (PGUs) for more precise controlling of the force generator units. The previously installed switching valves for pressurized chambers in a feedback loop were replaced by two PGUs for positive and negative force directions, respectively [3].



1	Base frame
2	Measuring frame
3	Master load cell
4	Loading frame
5	Force generator unit
6	Cryo-Chamber
7	Candidate balance
8	Calibration model
9	Check weight
10	Load suspension
11	Counter weight

Fig. 1 ETW's 25 kN Balance Calibration Machine.

To fulfil ETW's requirements on accuracy, a high precision calibration of the BCM's measuring side (master calibration) was conducted in the past by using specifically developed calibration equipment. For the master calibration process, developed and conducted by the BCM's manufacturer, most parts of the BCM including the cyro-chamber, loading frame, and force generator units are removed, and a calibration model (8) is mounted on the measuring frame (see Fig. 2 right). The measuring side, an external balance, is then calibrated in all six degrees of freedom by the use of precision check weights (9). The elastic behavior of the measuring side during the master calibration is also taken into account by measuring all deflections of the measuring frame as well as the load suspensions and by correcting the output signals of the master load cells [4].

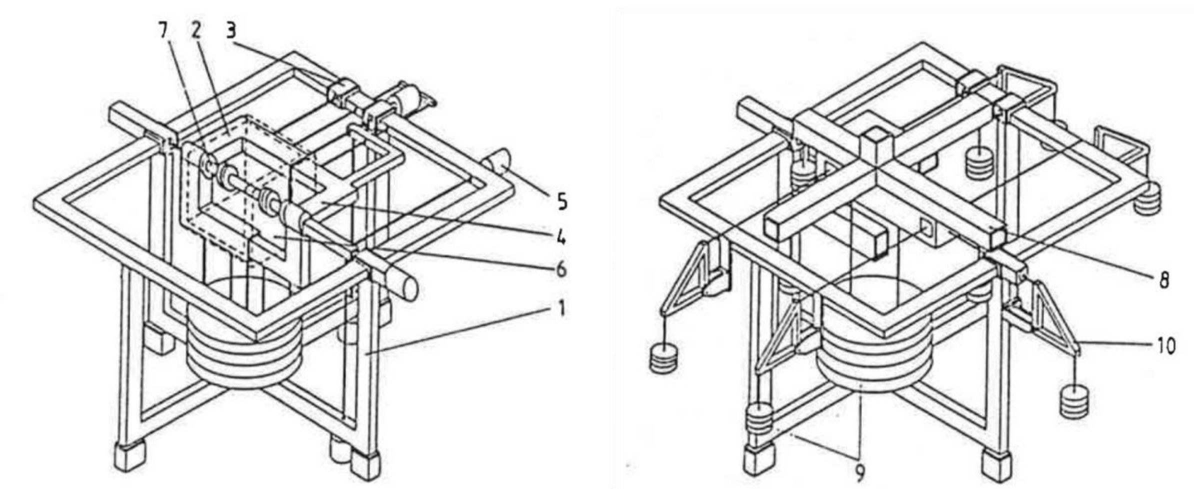


Fig. 2 Schematic description of the Balance Calibration Machine [4].

III. Verification Process for Force Measurement

The newly developed BCM verification procedure is a stepwise approach divided into two steps. Firstly, the accuracy of the BCM's force measurement with respect to international load standards is evaluated. Based on this assessment, the reliability of the BCM's moment measurement is verified in the next step (Sec. IV).

The force verification process uses high precision external load cells to check the accuracy of pure forces, namely F_x, F_y, and F_z, measured by the master load cells of the BCM. ETW owns four high precision external load cells supplied by Interface; two of them have a load range of up to 9 kN in tension and compression, whereas two have a load range up to 45 kN. These load cells are regularly calibrated by a certified calibration institute according to the DIN EN ISO 376. Therefore, within the BCM verification process, the readings from the load cells provide an independent transfer standard between the BCM master load cells and traceable international load standards.

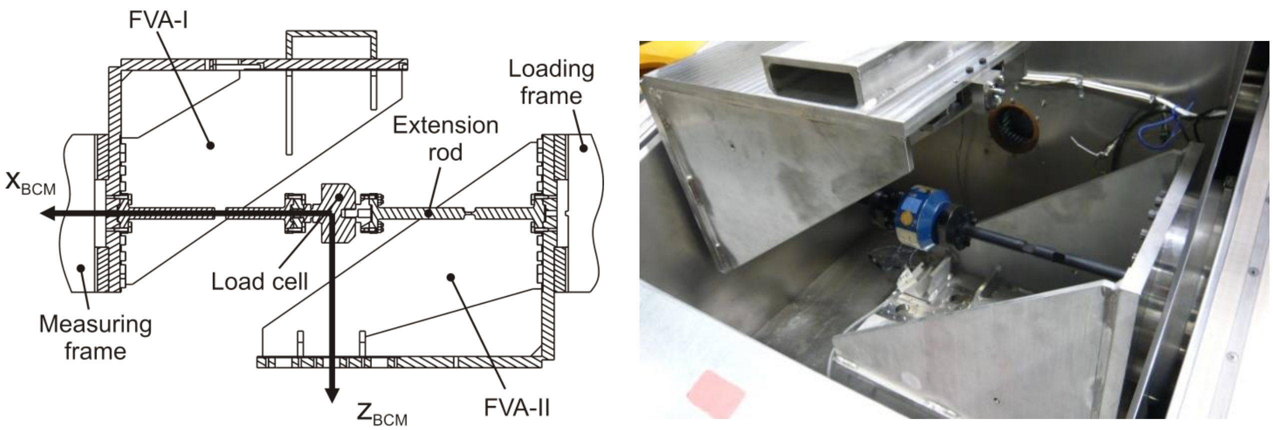
A pair of Force Verification Adapters (FVA-I & FVA-II) has been developed to apply desired loads to the external load cells in the axial, lateral, and normal directions. The total weight of the FVA is close to that of the standard balance adapters used for BCM's productive balance calibration, resulting in that the BCM is verified in the condition very close to its typical use. Because the strain-gauge load cells are extremely sensitive against non-axial loads, the load cell is connected to the adapter using two extension rods with two blade flexures on both ends. Pure forces are then applied using the BCM's standard load chain up to the maximum allowed load range of the BCM. According to ETW's accuracy requirements, the deviation between the readings of the master and external load cells should be less than 0.1%.

A. Axial Force Verification

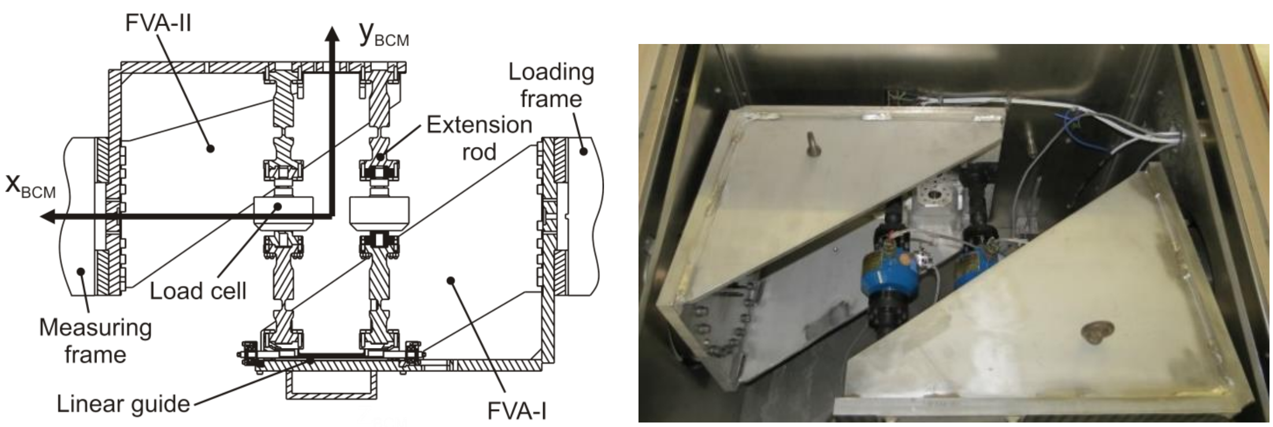
For the axial force verification, a single load cell arrangement is used as shown in Fig. 3a. To ensure the accuracy of the force readings at relatively low load ranges, the 9 kN load cell is used. The load cell is located on the virtual center of the BCM, which is the reference point of the balance calibration. Both the vertical (z) and horizontal (y) alignment of the load-cell assembly is achieved by adjusting the loading frame. The maximum load applied is 2000 N both in compression and tension.

B. Side Force Verification

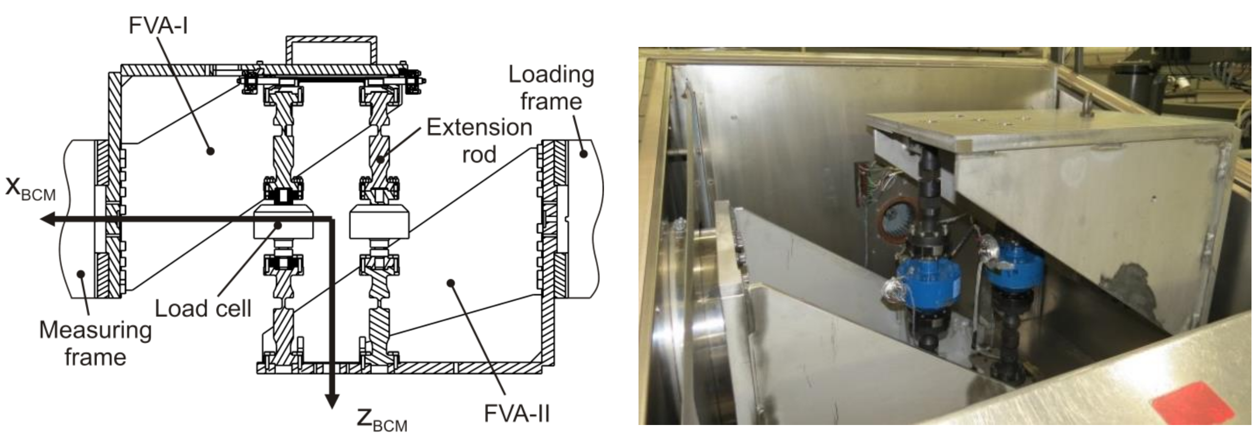
The side force verification adopts a double load cell arrangement using two 9 kN load cells in order to enhance the mechanical stability as well as accuracy. The distance between both load-cell assemblies are adjusted by using a linear guide mounted on FVA-I and the loading frame (see Fig. 3b). The load range is up to ±3000 N in 250 N steps. To investigate the influence of non-symmetric mass distribution of the FVA with respect to the xz-plane, two adapter installation configurations are tested: FVA-I-LEFT and FVA-I-RIGHT.



a) Axial force



b) Side force



c) Normal force

Fig. 3 Adapter assemblies for force verification procedure.

C. Normal Force Verification

Similar to the side force case, the normal force verification process uses the double load cell arrangement using two 45 kN load cells. The load range to be applied is up to 22500 N both in compression and tension. It indicates that in the parallel arrangement each extension rod is loaded by forces up to ±11250 N. In case of compression, it exceeds the permitted loads limit of the extension rod (20000 N in tension and 10000 N in compression). Therefore, two adapter installation configurations are considered. In the first configuration (FVA-II-BOTTOM), the bottom of FVA-II is located on the lower side (see Fig. 3c left). This configuration is designed for positive load cases as here the extension rod is subjected to tensile loads. In contrast, the negative load case is achieved by using the second configuration (FVA-II-TOP), in which the bottom of FVA-II is located on the upper side (see Fig. 3c right). Here, the extension rods are also subjected to tensile forces, while the FVA-II moves upwards to apply negative normal forces to the external balance. Both the installation alignment and the distance between both load-cell assemblies are checked by using the linear guide and loading frame.

IV. Moment Verification Process

The verification of the BCM's moment measurements is performed by shifting the calibration center of the ETW's standard flange balance either in the axial direction (x-direction) or the lateral direction (y- or z- direction) using two pairs of specifically developed balance adapters (AOA and LOA) in combination with ETW's B005 strain-gauge balance. To increase the level of reliability and flexibility of the process, each adapter pair has been designed to be interchangeable allowing shifting the balance center both in positive and negative directions for generating additional negative as well as positive moments. Deviation between the measured additional moments and the theoretical values resulting from applied pure forces, verified in the previous step (see Sec. III), and the known adapter offset δ should not exceed 0.1% of BCM's accuracy limits.

A. B005 Strain-Gauge Balance

The B005 internal balance is one of ETW's standard flange balances with a high load range for testing full span aircraft model. The balance has been fabricated from copper beryllium, which has a higher thermal conductivity than the maraging steel grades commonly used for ETW's other balances. As a result, B005 shows a better characteristics regarding temperature distribution across the length axis. In total, six strain-gauge bridges plus one additional bridge for the axial force reading along with 10 PT100 resistance temperature detectors (RTDs) are attached to the balance body.

Since B005 together with its calibration matrix is considered as a 'transfer standard', the B005 balance is calibrated prior to the moment verification process using ETW's standard calibration adapters and loading scheme up to the maximum allowed load limits (see Table 2) under ambient conditions.

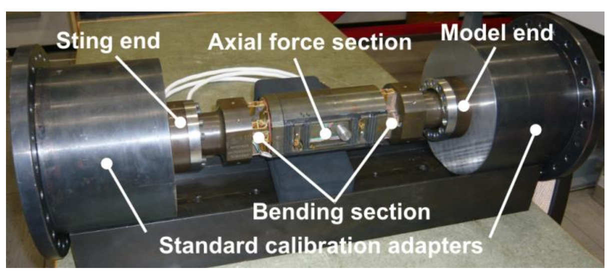


Fig. 4 ETW's B005 strain-gauge balance.

	F_x	F_y	F_z	M_x	M_y	M_z
Maximum single loads	± 3000 N	± 2500 N	± 20000 N	± 500 Nm	± 1800 Nm	± 250 Nm
Combined static loads	± 2000 N	± 1500 N	± 20000 N	± 350 Nm	± 1250 Nm	± 180 Nm

Table 2 B005 operating envelope.

B. Setup for Moment Verification using Axial Offset Adapters

The AOA pair has been developed to verify the BCM's moment measurements, in particular for pitching and yawing moments. The B005 with its standard calibration matrix reads an additional M_y and M_z, if pure F_z and F_y, respectively, are applied to the BCM center. The newly developed adapter pairs differ to the ETW's standard BCM adapter only in the axial dimension. In combination with B005, the AOA pair results in an offset of the balance center of δ in the axial direction (see Fig. 5). Two installation configurations are considered: SHORT and LONG. In the SHORT configuration, the short adapter is mounted to the measuring frame, while the LONG adapter is fitted on the loading frame and vice versa, to shift the balance center both in the positive and negative direction (see Fig. 6).

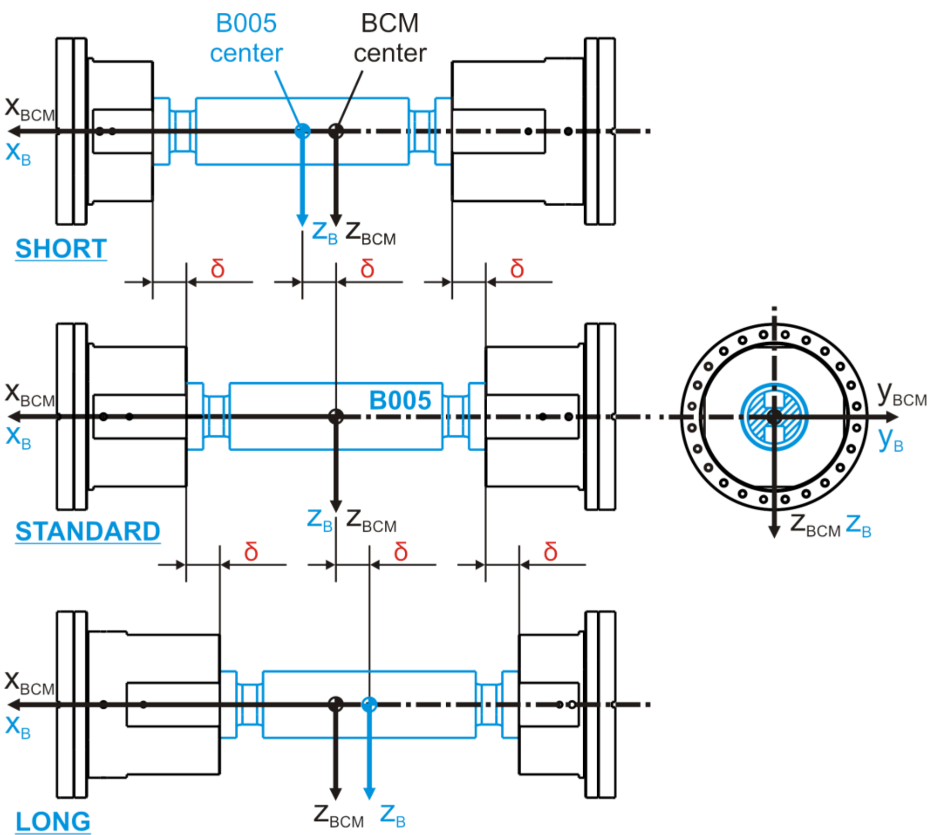
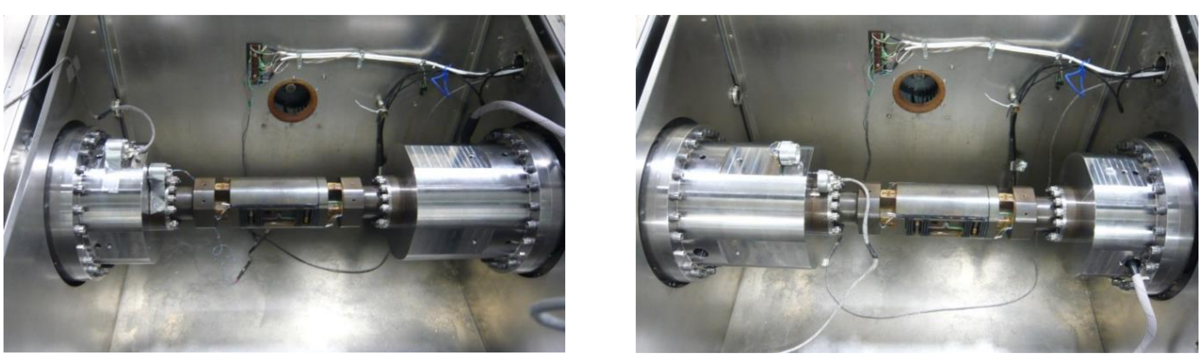


Fig. 5 Schematic description of SHORT and LONG configuration.



a) SHORT configuration

b) LONG configuration

Fig. 6 Installation of Axial Offset Adapters.

C. Setup for Moment Verification using Lateral Offset Adapters

Using the LOA pair, two pairs of installation configurations can be tested: LEFT-RIGHT (see Fig. 7) and TOP-BOTTOM configuration (see Fig. 8). The first installation configuration pair is used to verify measured rolling moments by applying pure normal forces, whereas the measured yawing moments can be verified by applying the pure axial forces. The TOP-BOTTOM configuration is used to support the rolling moment verification. The configuration change is achieved by rotating the adapters through 90° around its length axis, while the balance is fixed to the adapters, resulting in that the balance fixed reference axis is also rotated. The load schemes are carefully adjusted according to the theoretical values of induced moments to avoid overload problems.

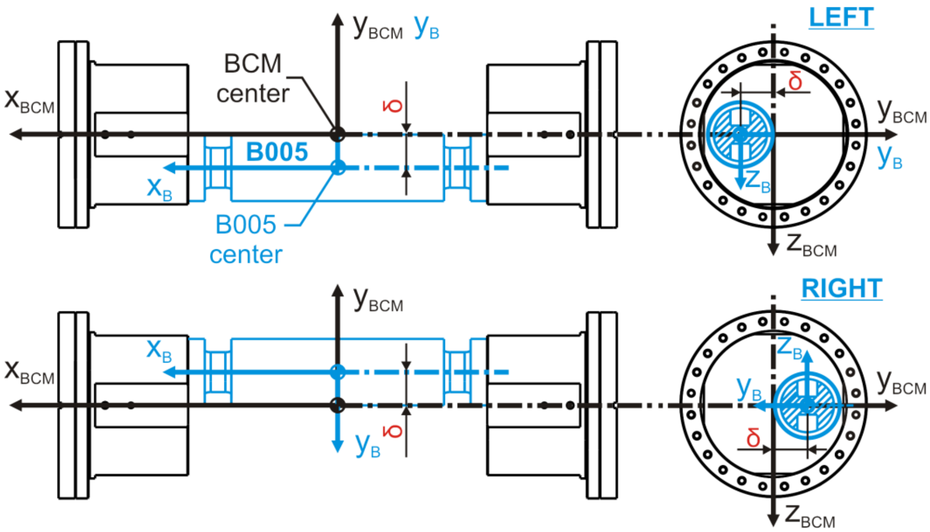


Fig. 7 Schematic description of LEFT and RIGHT configuration.

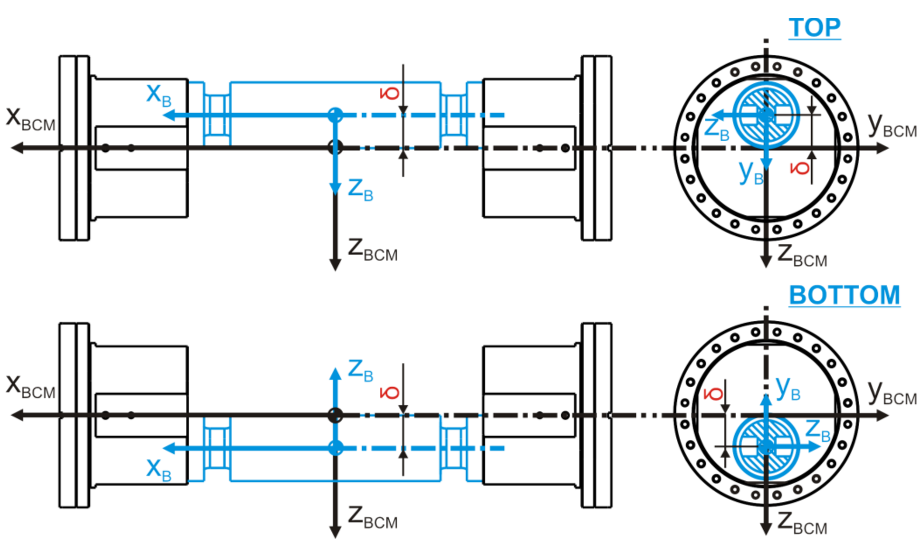
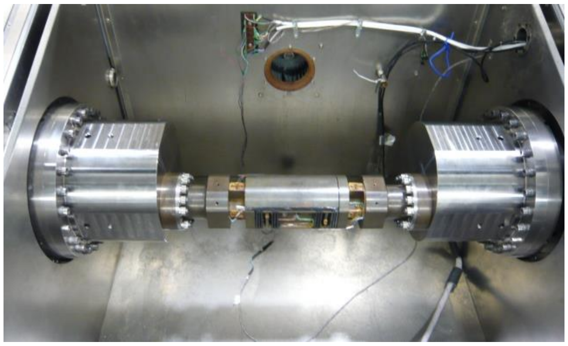
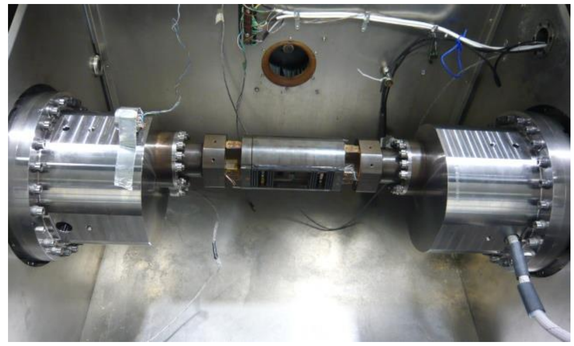


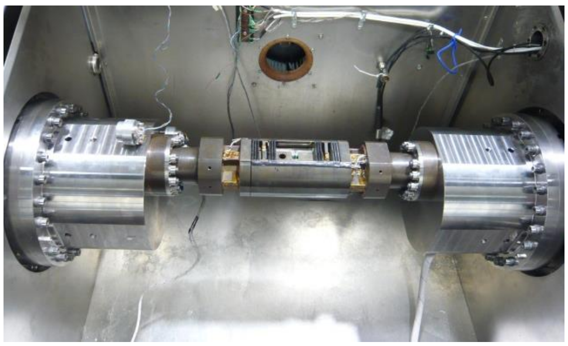
Fig. 8 Schematic description of TOP and BOTTOM configuration.



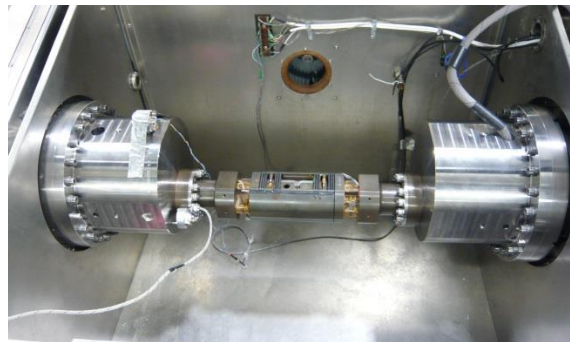
a) LEFT configuration



b) RIGHT configuration



c) TOP configuration



d) BOTTOM configuration

Fig. 9 Installation of Lateral Offset Adapters.

V. Results

In the following section selected results of the verification process are given and discussed.

A. Force Verification

In Fig. 10, 11, and 12, deviations of the axial, side, and normal forces between the readings of the master and external load cells are given, respectively. In all load cases considered, the deviations are less than 0.1% of the full range of the BCM over the entire range of applied forces, indicating that with respect to the force measurement the BCM fulfils ETW's accuracy requirements. In Fig. 10, the axial force verification data are compared to that obtained in 2016, showing an outstanding reproducibility of the verification procedure as well as the BCM's accuracy.

The result of the side force verification reveals a certain influence of the non-symmetric mass distribution of the FVA, e.g. the data distributions are axially symmetric. Nevertheless, the deviation is less than 0.1 % of the BCM's full range in both installation cases.

Similar to the side force case, the result of the normal force verification also shows axis symmetric data distributions depending on the adapter installation.

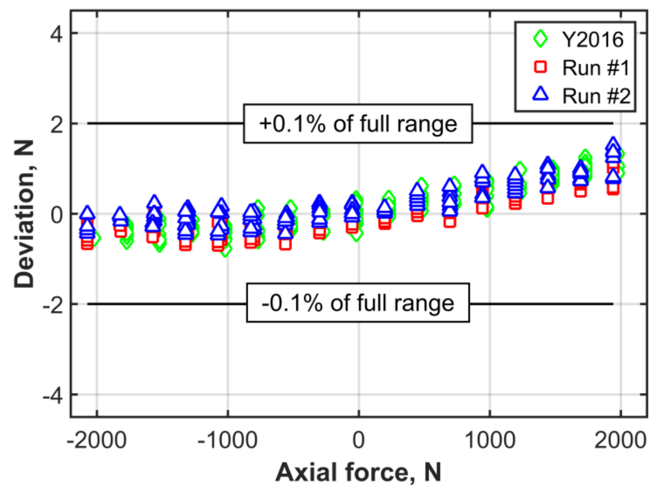


Fig. 10 Axial force deviation.

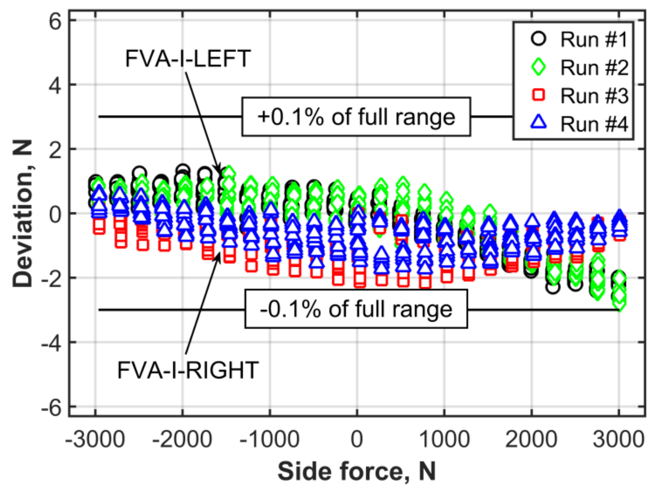


Fig. 11 Lateral force deviation.

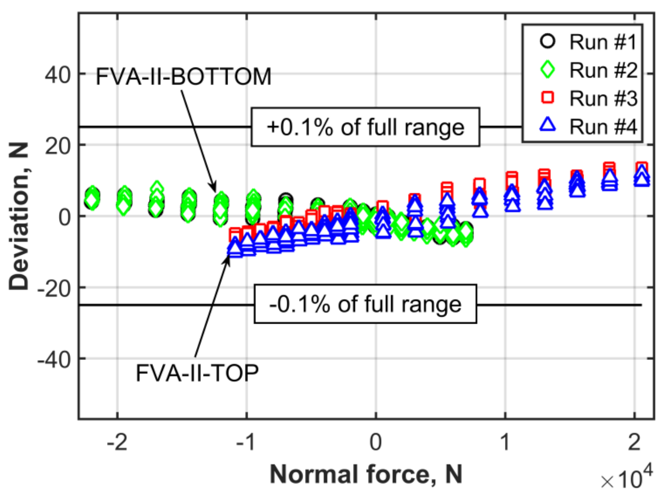
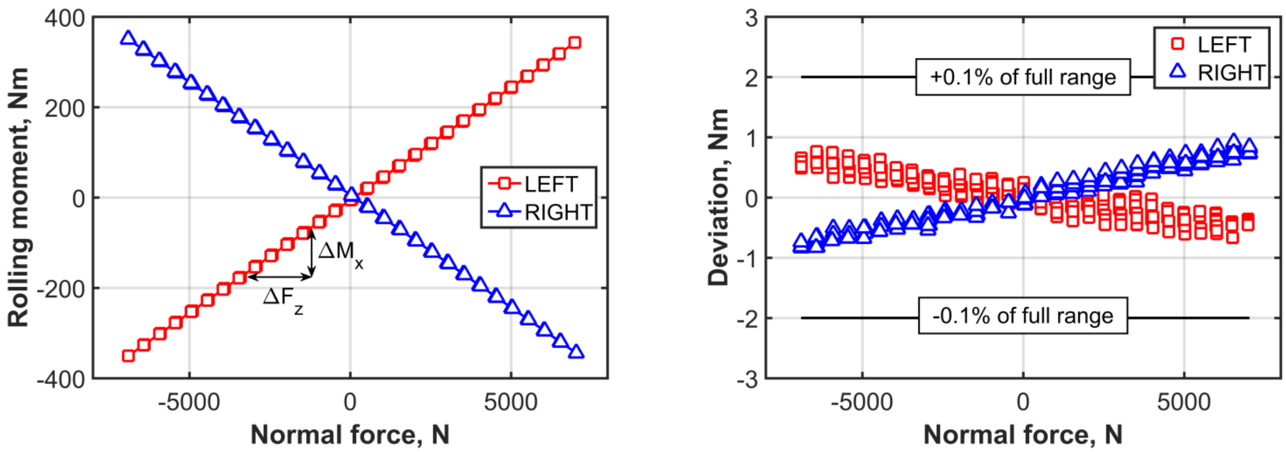


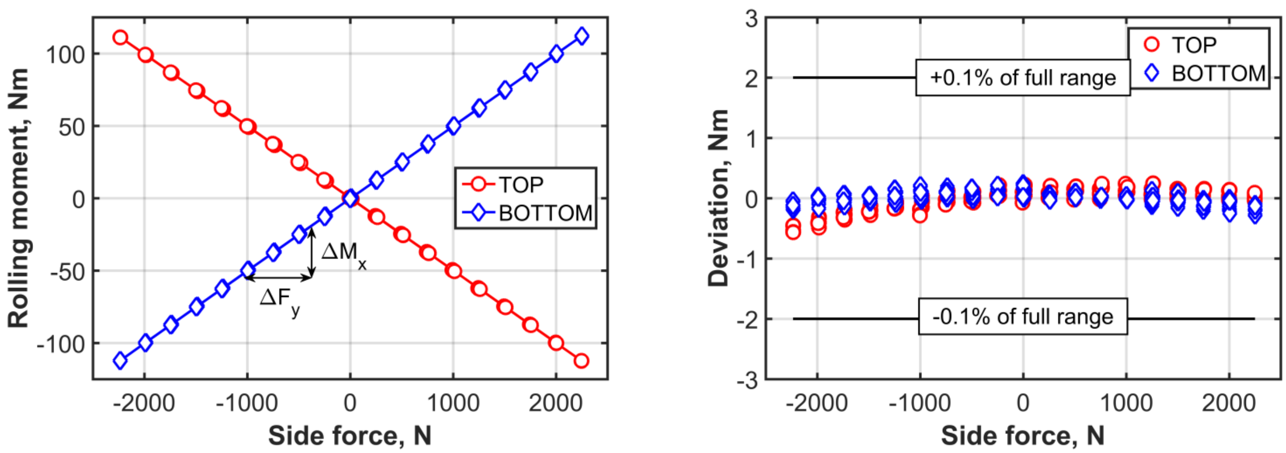
Fig. 12 Normal force deviation.

B. Moment Verification

Figure 13, 14, and 15 show the results of rolling, pitching, and yawing moment verifications, respectively. As expected, there is a quasi-linear relationship between the measured moments and the applied forces. In an ideal case, the slope of each curve (i.e. $\Delta M_x/\Delta F_z$ indicated in Fig. 13a) have to match the value of the adapter offset δ. The differences of measured slope to the theoretical value vary approximately between 0.1 % and 0.2 % depending on the installation configurations. The deviations between the measured moments and the theoretical value resulting from applied forces multiplied by δ are however less than 0.1 % of the full range of the BCM for all cases tested. It confirms that the BCM also fulfils ETW's accuracy standard with respect to the moment measurement.



a) LEFT – Right configuration



b) TOP – BOTTOM configuraton

Fig. 13 Results for rolling moment verification.

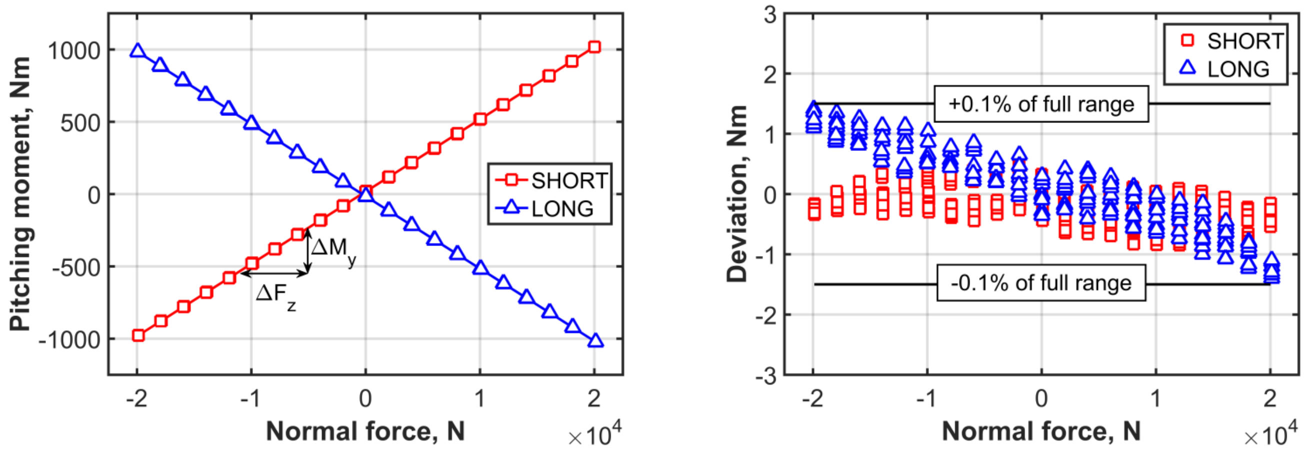
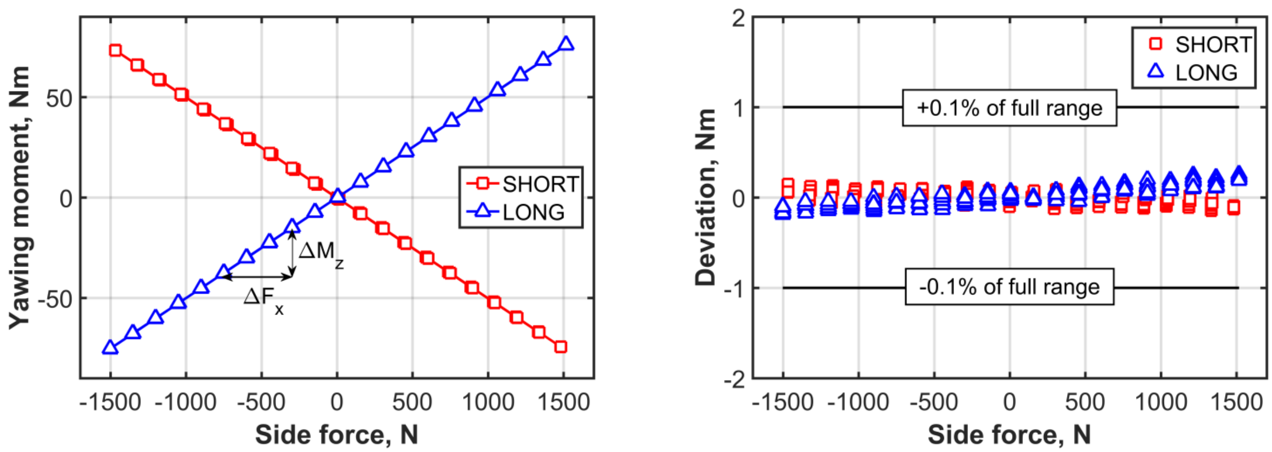
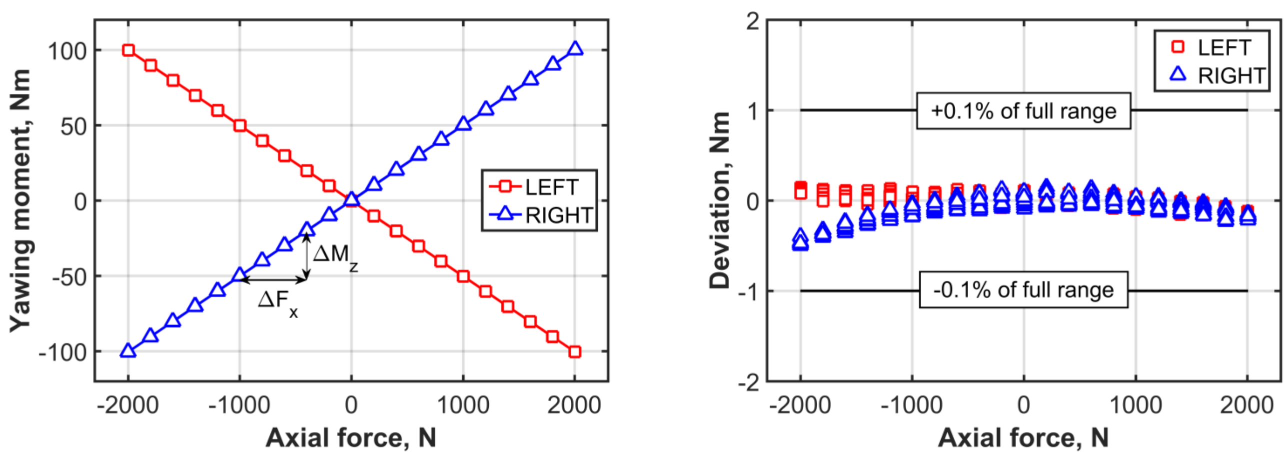


Fig. 14 Results for pitching moment verification



a) SHORT – LONG configuraton



a) LEFT – RIGHT configuraton

Fig. 15 Results for yawing moment verification.

VI. Conclusion

This paper presents a new verification method for ETW's 25 kN fully automatic Balance Calibration Machine. To verify and maintain the BCM's high level of accuracy, a two-step verification method has been introduced, namely the force and moment verification procedure. The results of the first application reveal that the new procedure has significant advantages over the previous master calibration, such as time benefits and risk reductions along with a high level of reliability in the results.

Acknowledgments

The authors would like to thank all ETW colleagues for their permanent assistance during the new calibration verification process.

References

[1] Jansen, U., "Automatic Cryogenic Balance Calibration at ETW – Pushing the Limits", *3rd International Symposium on Strain-Gauge Balances*, Darmstadt, Germany, 2002.
[2] Badet, L. M., "Cryogenic Internal Balance Calibration at ETW", *AGARD FDP Special Course on "Advances in Cryogenic Wind Tunnel Technology"*, Cologne, Germany, 1996, AGARD Report 812.
[3] Semmelmann, J., Quix, H., Strudthoff, W., Jansen, U., and Ernst, F. J., "Modification of the Control & Measurement Software for the Balance Calibration Machine at ETW", *9th International Symposium on Strain-Gauge Balances*, Seattle, WA, 2014.
[4] Polansky, L., Kutney Sr., J. T., "A New and Working Automatic Calibration Machine for Wind Tunnel Internal Force Balances", *AISS/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit*, Monterey, CA, 1993.