Modification of the Control & Measurement Software for the Balance Calibration Machine at ETW

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The European Transonic Windtunnel (ETW) is a pressurised cryogenic facility adapted for testing cruise or high lift configurations of aircraft models at flight conditions. A high stability of test conditions, excellent repeatability and a wide test envelope of Mach and Reynolds numbers (Figure 1) are some of the main criteria for numerous customers of the worldwide aircraft industry for using ETW. Therefore developments and improvements of new measurement and calibration systems are an important objective of ETW's effort to enhance its capabilities.
To provide information about the model loading, ETW uses strain gauge balances which measure the reacting model behaviour even at flight conditions. Presently, there are 9 full-span strain gauge balances and one half-model balance available. Measuring the occurring loads and moments of the model requires a reliable and precise balance calibration before getting used in test campaigns.
This paper gives an overview on the Balance Calibration Machine of ETW, the modernized setup of the machine, and documents the development and improvement of the BCM Software.

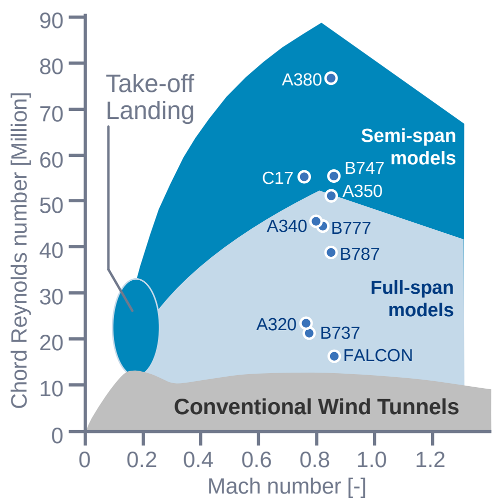

Figure 1: ETW Performance Envelope

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I. Introduction

The European Transonic Windtunnel is a continuous flow windtunnel with a test section of 2.0m x 2.4m and a Mach number range from 0.15 to 1.3. The facility operates within a temperature range of 312K to 110K and a pressure range from 110kPa to 450kPa.

High flow velocities can generate several tons of loads on airfoils. Those loads and moments can be measured with high precision strain-gauged balances for full span models. Before starting relevant measurements in the ETW every balance has to be calibrated over the full temperature range achievable in the facility. Since 1993 strain-gauged balances can be calibrated with a fully automatic 25kN Balance Calibration Machine. In 1988 Professor Ewald developed a concept of the BCM at the technical university of Darmstadt. Within a research project TU Darmstadt, Schenck AG, Airbus and ETW cooperated in the development and provision of a new machine for the calibration of strain-gauge balances. The computer hardware is on a development status of the early 90s, which results in problems of components' replacement. This served as the main driver for starting considerations to update the control and measurement software.

This paper provides a general overview of the Balance Calibration Machine, explains the difference between the installation setup and the upgraded version of the hardware, the current software development, as well as the data reduction and commissioning of the upgraded Balance Calibration Machine.

II. Balance Calibration Machine (BCM)

Reliability plays an important role for customers testing at ETW. Measuring aerodynamic forces and moments of the models which are tested at ETW need an in-depth analysis of the strain-gauged balances for full-span models. The aerodynamic loads are represented by a vector force and a vector moment. Establishing a link between the measured signals and the aerodynamic forces/moments is achieved by a full calibration in the BCM down to cryogenic temperatures. Figure 2 shows schematically the 25kN Balance Calibration Machine of the ETW.

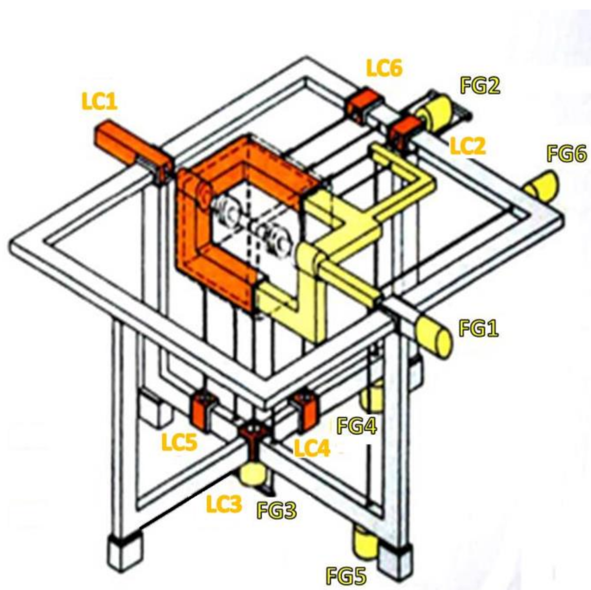

Figure 2: Balance Calibration Machine Schematic

A. Installation setup of the machine

The selected design strategy for the BCM was primarily set on controlled force generators. Every force generator, coloured yellow in Figure 2, is set up as a pneumatic actuator and finally connected to a switching valve. Opening and closing of the valves in a feedback loop is controlled by the external balance. The measuring frame, coloured orange in Figure 2, is described as the external balance which is built up on 6 Master load cells and measuring the real acting load on the internal balance to a higher degree of accuracy. Hence, the operator sets up the load schedule and the switching valves of the force generators are opened until the external balance displays the desired load. The internal balance represents the strain-gauged balance which has to be calibrated within the machine. Contrary to the installation of the balance in an aircraft model, all strain-gauged balances in the BCM are clamped fixed on the model side and the sting side is loaded (see Figure 3).

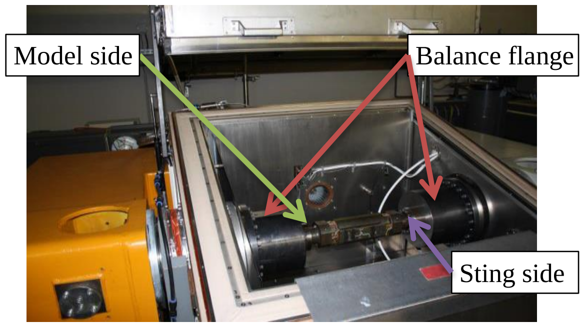

Figure 3: Balance installation in the cryo chamber

A fixed connection of the sting side results in different axes systems during a calibration. Clamping the model side of the calibration balance results in a single axis system and finally in a single calibration matrix for the whole load cycles. The internal balance represents the softest part of the complete assembly and is connected between the external balance (left side, orange coloured) and the loading tree (right side).

Regarding the modernization of the BCM the basic installation hardware has not been changed. The external balance (measuring frame) and the force generator setup are kept in their original configuration. The main difference of the machine software setup is controlling the force generators by the pressure generator units as opposed to a feedback loop controlled by switching valves in the old BCM. The machine upgrade results in the implementation of 12 Pressure Generator Units (PGUs). Every force generator owns 2 pressure generators for a positive or negative force direction. Elimination of the feedback loop has been based on experiences during the past decades. In this case opening the switching valves and increasing the load of the internal and external balance could result in a contact between the earth fixed frame of the BCM and the external balance. This would lead to a force closure and could result in a damage of the whole BCM. Using the 12 PGUs there is no overshoot possible and therefor no force closure can be generated.

Presently in the upgraded version of the BCM an operator selects a load case. Afterwards the external- and internal balance have to measure the same applied load level. Measuring the signals from the complete BCM is achieved by 2 amplifiers supplied by Hottinger HBM. In the past 2 decades ETW had no severe problems with the measurement equipment from Hottinger which is a positive argument for using modernized amplifiers of the same company again in the future.

B. Software

Before starting the upgrade of the software the whole system was divided into 5 subsystems. Every subsystem had its own computer and control unit which monitored each load case of the currently used subsystem[1]:

1. Supervisor
2. External Balance
3. Internal Balance
4. Force Generators
5. Cryo Chamber

While the old system was already structured in 5 individual hardware computers (see above), the new system relies on a single PC which runs five software classes. Every software class has its different methods (functions) which can be called by the operator.

Getting an idea of the current load cases mean reading the measurement signals of both amplifiers and converting those into physical, true loads. Each conversion from signals measured by the load cells is realized with a constant factor given by the Carl Schenck, but each constant factor can just be seen as a specifically applied conversion factor. Regarding the whole machine it has to be taken into account that each force generator has a small and in some cases even a high influence, on another force/load component.

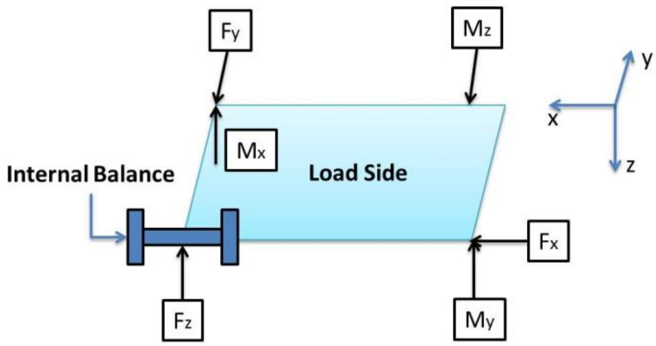

Figure 4: BCM – force generators Setup

The different aspects of algebraic signs and force directions (see Figure 4) have to be taken into account for each load which finally results in a 6x6 force generator matrix.[2] This matrix converts the desired load case into the necessary forces for each force generator.

The resultant forces have to be converted into pressures for setting the PGUs. The conversion of forces into the necessary pressures is a modernized aspect of the machine. Afterwards the whole loop can be repeated by calculating the measured forces and transforming it back to a pressure. A detailed description of the transformation is given in Chapter IV.1

After transmitting the setpoint to the pressure generators the software starts monitoring until the setpoint is reached and the measurement results are stored into the data files. The control loop checks for overloading of the internal balance. If any setpoint is above the maximum allowed load limit of the internal or external balance all pressure generators are set to 0 kPa and the operator has to decide either stopping the calibration or going on with the next setpoint.

1 External Balance

In the beginning of the modernization all necessary data files (e.g. Forces to Loads Matrix, Internal Balance Matrix, Master Calibration Matrix) were collected and analysed. One example of those data files represents the Master Calibration Matrix. This data file gives the opportunity for converting the measured signals of the load cells into the true measured loads. Using it in combination with the measured signals and subtracting all zero-values did not lead to an acceptable solution.

The internal balance calibration matrix is the only link between the old and the upgraded version of the Balance Calibration Machine. A negative aspect is the hardware change of the amplifiers. So in the first upgraded setup of the BCM the internal balance measures the true loads and adaptation of the external balance, force generators and pressure generators could be started.

Regarding the external balance, deviations between the external and internal balances became visible for a single load case. After analysing the gathered data of X, Y and Mz a constant deviation factor of 2 remained between the internal and external balance. This factor led to the different load cells which are installed in the BCM. On the one hand a single-ring-torsion load cell type and on the other hand a double-ring-torsion load cell configuration. The torsion ring of those cell types tends to turn down, which means the load cells measures around zero with a small degree of non-linearity. For vertically mounted load cells (Mx, My, Z) this area of imperfect linearity is avoided by preloading those load cells. The preloading can be achieved by the weight of the loading tree itself. The horizontal force generators can’t be preloaded with a dead weight. In this case avoiding zero-crossing 2 load cells are uptight against each other. In the end 2 signals are combined and the summation is proportional to the upcoming force.

Regarding a master calibration the resulting matrix is calculated for single ring-torsion load cells. Measuring the resistors of double-ring-torsion load cells at the amplifier (X, Y, Mz) those are double the normal single load cell resistors. Which means the voltage drop is twice as much for a double load cell in comparison to a single one. The constant factor has to be implemented into the signals (signals are multiplied by a factor of 2), which finally results in a perfect match between the internal- and external balance.

2 Force Generators

As previously mentioned the calculated forces deviate significantly from the external- and internal balance forces. Within the old BCM the force generator signals were stored into the data files but not used. In the modernized software the signals of the force generator load cells are stored into the data file and can now be analysed for the first time.

For a successful adaptation of all components a new Force Generator Matrix has been calibrated. The calculated matrix results in a smaller deviation between the External Balance and the Force Generator Loads. A detailed description of the gradient is given in the Data Reduction (Chapter IV.2).

3 Internal Balance

Measuring the signals of the internal balance and converting those into the loads represent the easiest part of the upgraded BCM. In this case the calibration matrix exists and a control function is given of the true applied loads. In the beginning of the modernization the internal balance represents the single system, which measures the true loads. The internal balance has been calibrated with the old software and represents a connection between old and upgraded BCM. The measured signals of the internal balance just have to be converted with the calibration matrix of the old BCM into the “true” measured loads. All other systems have to be analysed in detail.

III. Internal Balance – B005

The B005 is a full model strain-gauged balance, which has been fabricated from copper beryllium. The balance has 7 strain-gauged bridges and 10 PT100 for temperature measurement (see Figure 5). The material was chosen for high thermal conductivity which should result in a uniform temperature distribution. Changing the setpoint temperature during a measurement at the ETW is time consuming and part of this is reserved for the balance conditioning. Copper beryllium has a higher thermal conductivity, which means the balance achieves in a shorter time period a necessary setpoint temperature.[3]

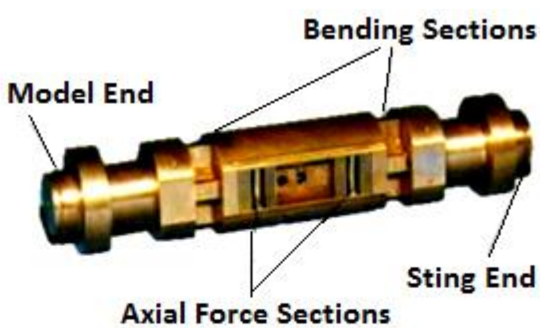

Figure 5: B005 – Copper Beryllium Balance

IV. Data Reduction

The post-processing of the measured data set is the final step of the calibration and can be separated in two steps. The first step is analysing the force generator data, while the second step is the final comparison between the internal and external balance measurement data.

1 Force Generator

As previously mentioned the force generator signals were not used in the old BCM. Processing these signals is an update of the BCM.

Firstly the gradient of the true external balance loads for the pressure setpoints have to be calculated. The final deviations between the external balance loads and the force generator load cells can be reduced with a new calibration matrix of the force generator matrix.

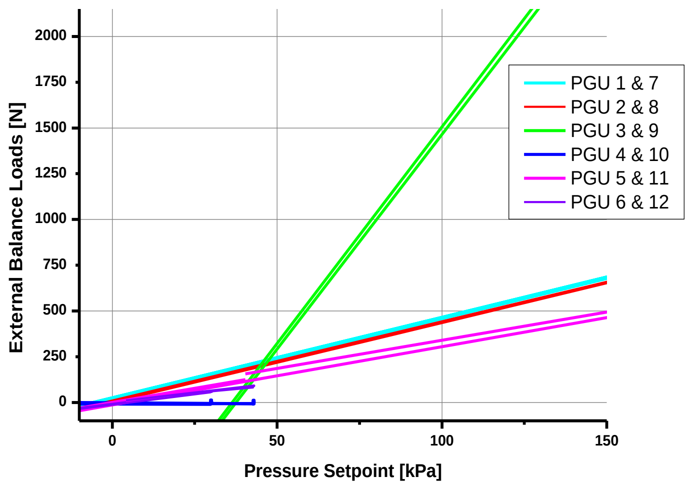

Figure 6: Linear Performance between Pressure Generators and External Balance

Figure 6 shows a linear behaviour between setpoint generation and the measured loads for the external balance. This relationship can be used to calculate the correct area of each force generator cylinder resulting in a gradient unit of [N/kPa]. This Unit can be converted into m² and finally the correct diameter of the force generator cylinder can be used within later calibrations to calculate the necessary pressure setpoints.

2 External Balance vs. Internal Balance

In the first step all measurement data for the data points are plotted and analysed. Within the measurement data the zero values of the external and internal balance are subtracted.

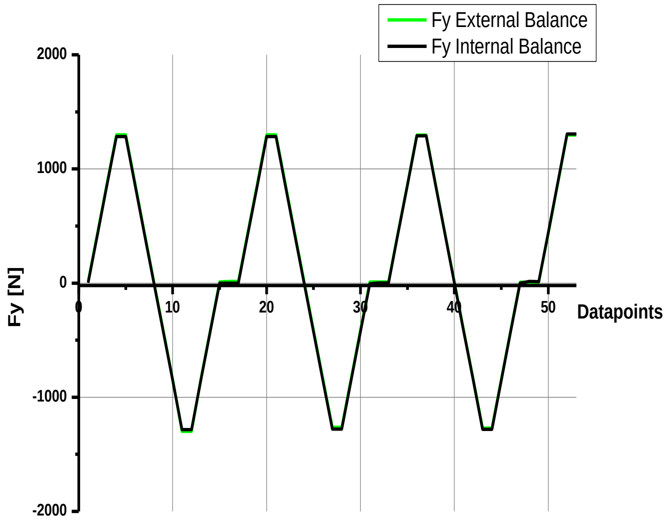

Figure 7: Side Force Comparison Ex. /Int. Balance

Figure 7 and 8 show examples of all measured setpoints. In the left picture the side force is compared between the internal and external balance. The residuals are smaller than 10N. On the right picture the nominal signals between the external and internal balance are plotted versus data points. In this case the external loads are the measured loads but not the true loads which are affected on the internal balance. A model adapter is connected for a correct force initiation from the loading tree and finally ends up into the external balance. Those weights and resulting forces/moments have to be included into the external balance measurement signals. Afterwards a deviation of smaller than 10N remains between the external and internal balance.

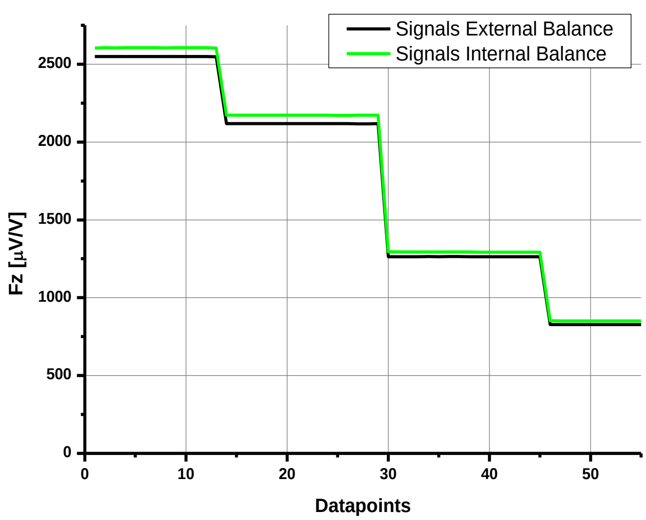

Figure 8: Signals Comparison Ex./Int. Balance

A further aspect is the calculation of the internal and external balance zero signals. Before starting a calibration the zero signals are measured for the internal and external balance. After the calibration the calculated loads can be plotted versus the measured signals. In Figure 9 the calculated signals of F_y=0 can be determined to a value of -29 µV/V. In opposite the measurement signals are determined to a value of F_y=-25 µV/V. The deviation of 4 µV/V is equal to a load of F_y=15.5N. Regarding the difference between measured and calculated loads this can be validated in the way of measuring the zero signals. All zero measurements are taken at the Balance Turntable Device (see Figure 10).

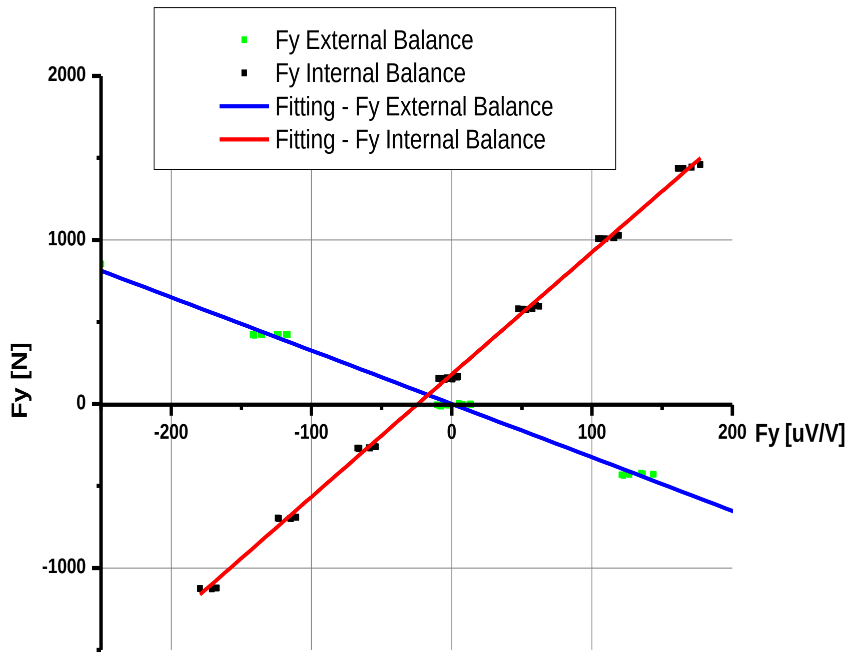

Figure 9: Balance Signals in side force (Fy)

On this device the balance is fixed on one side and turned clockwise in steps of 90°. Afterwards the 4 measurements are averaged and the resulted signals are the measured zero signals of the internal balance. In contrast the calculated zero signals in the BCM (see Figure 9) are measured differently. First in the BCM the balance is fixed on the model side and loaded on the sting side. Second the balance zero signals are calculated with a linear fitting. Therefor the deviation of 4 µV/V can be attributed to the clamping of the balance.

Figure 10: B005 fixed on the Balance Turntable Device

Finally the hysteresis of the internal balance has to be determined. The deviation to the real loading results in a horizontal loop-kind behaviour (see Figure 11). Experiences during the past calibrations of different balances show a maximum Amplitude of ±1 N which can be seen coloured blue in Figure 11. The larger discrepancies for Normal force (red in Figure 11) can be attributed to the referenced internal balance matrix. During the recalibration of the B005 within the upgraded BCM a 5 years old balance calibration matrix was taken to get a first idea of the measured loads. In conclusion after successful upgrading of the BCM this balance matrix has to be recalculated with the gathered signals. Afterwards the angle of the hysteresis will largely be eliminated with a final error bandwidth of ±1 N.

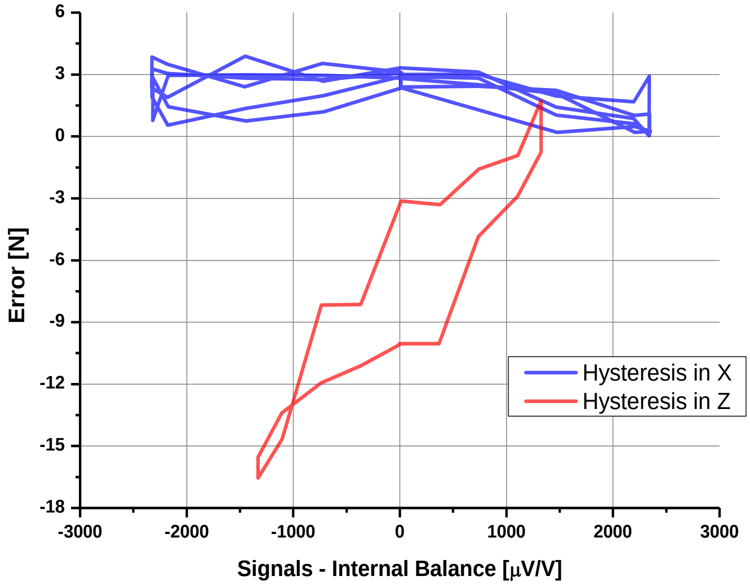

Figure 11: Balance Hysteresis

V. Conclusion

The European Transonic Windtunnel has the capability to separate Reynolds number, Mach number and dynamic pressure (load) effects by varying the tunnel conditions. Hence the model loadings are primary client data but also an important variable for the understanding of test results. Measuring the loading of so called full-span models can be done with internal strain-gauged balances. Before using an internal balance at ETW every strain-gauged balance has to be calibrated in the 25kN Balance Calibration Machine.

The paper gives an overview of the modernized and upgraded Balance Calibration Machine. The measurement principle, the hardware setup and the usage of the software are described in detail. During the past decades Computer hardware spare parts were no longer available. Upgrading the BCM is justified based on the clients' requirements for reliable calibration hardware at ETW.

Upgrading the BCM led to a more detailed understanding of the whole machine and improved data quality analysing by the signals. Until now the measurement signals generated by the force generators could not be analysed after calibration of an internal balance. Upgrading the machine now allows for inclusion of those measurement signals into the data files and finally achieving a minimal deviation between force generator signals, external- and internal balance signals. Hence, ETW is now in the position to cover clients' requirements on the data with improved quality.

Acknowledgments

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