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Precise Measurement Technology Based on new Block-type and Rotating Shaft Balances

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Based on several decades of experience in designing and manufacturing strain gauge balances, a new block-type balance family called 7xx was developed with substantial higher stiffness and increased specific load capacities than achieved before. The compact design favours its use within models with limited space or in dynamic environments (shaker testing) where low deformations are required. Extensive tests during the development phase, static load calibrations of complete balances, and the successful usage in numerous test campaigns in different wind tunnels have confirmed the advantages to this new balance design.

RUAG, in close cooperation with its partners, plays a major role in the development and testing of new counter rotating propeller technology for aircrafts. This technology and the space limitations within the nacelle necessitate new measurement technology and substantially higher power than possible with existing propulsion systems. Based on its available know-how RUAG pushed the hydraulic propulsion technology to a new level, especially with regard to specific power output and reliability. Moreover, compact rotating shaft balances for powered tests provide 6 components with good accuracy and high repeatability. Signals from the balances and the blades are transmitted by wireless telemetry systems. In-house developed software for acquiring, processing, and displaying data on- and offline has been adapted to the new systems and customers' needs.

Nomenclature

h = height
l = length
L = rolling moment
M = pitching moment
N = yawing moment
w = width
X = axial force
Y = side force
Z = normal force

I. Introduction

The Aerodynamics Center of RUAG Aviation can look back on many years of experience in designing, manufacturing, and operating strain gauge balances. These balances are primarily used in RUAG's own wind tunnels but have also been well received by customers using wind tunnels and other test facilities around the world for applications as diverse as aerospace, automotive, civil engineering, and education.

The initial plan at RUAG had been the development of sting-type balances for the use in the small transonic wind tunnel and block-type balances for automotive and aerospace applications in both larger wind tunnels of the

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Center, namely the AWTE[4] with a moving ground (2.55 m x 1.55 m x 3.9 m, 60 m/s) and the LWTE[5] (7 m x 5 m x 12 m, 68 m/s), one of the largest tunnels in Europe. However, the development of the sting-type balances was abandoned when the activities in the transonic range diminished and this tunnel was eventually dismantled. In contrast, the block-type balances were continuously improved and a broad family of 13 balances has been established, Fig. 1. About 60 of these balances have been built and sold all over the world, mostly for use in wind tunnels. Generally, these block-type balances have been installed inside the models, but they are equally suitable to serve as external balances, for example when being placed underfloor in combination with a turntable for vehicle applications, or in aerospace applications when a special model support system, such as wire suspension, is preferred.

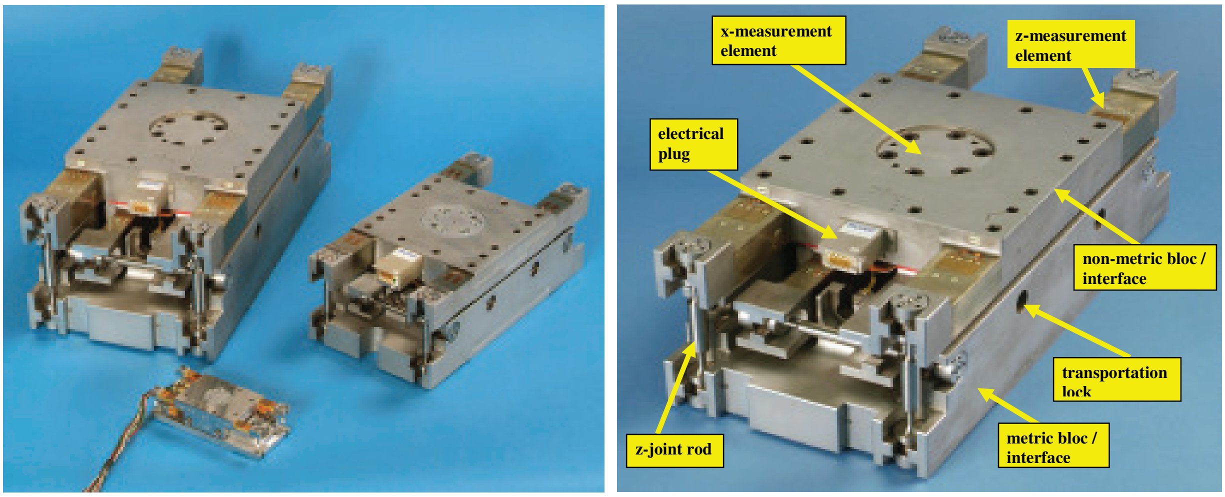

Figure 1. RUAG Balance family 1xx. The load envelopes are ranging from 20 to 12'500 N (axial force) and 10 to 25'000 N (normal force), the dimensions (l x w x h) from 100 mm x 25 mm x 22 mm to 540 mm x 260 mm x 230 mm, and the balance mass from 0.25 to 180 kg. The view to the right shows the main components of the balance and the measurement elements with their parallel beams.

In the past years, the demand for balances carrying higher loads at a given volume that simultaneously produce less deformation has increased. The reasons for this include that more space is needed for diverse measurement instrumentation within the model, more rigid model frames are used and less deformation is accepted, higher aerodynamic loads are acting on the model, and furthermore, models may be actively excited to study unsteady aerodynamic phenomena. RUAG responded to these demands with a new balance family. With the latest technology available the well-known family of block-type balances has now been supplemented by a new generation of balances. Compared to the previous generation with essentially identical external dimensions, the load ranges are now about two to four times higher. Even though the stiffness in both the translational and the rotational directions has been further increased, the new balance family is now more precise and accurate. In contrast to the previous generation of balances that was labeled as 1xx, the new generation is called 7xx. The first prototype of this series, balance type 788, is already in use within our own automotive tunnel as well as at a customer's site. The smaller type 796 is still in the manufacturing process, with four balances to be delivered to customers and used in our own tunnels by mid of 2010. The last and largest so far envisioned, balance 767, has fully been designed but not yet built.

A second area of recent balance activities at RUAG arose from the increasing demand for propeller technology for aircrafts, especially for counter rotating open rotor designs, an application in which RUAG got involved about two years ago. While in the past 2-component spoke-type balances have been used for measuring the propeller loads, full 6-component rotating shaft balances are now increasingly required. Such balances have been developed and presented at previous Balance Symposia by ONERA and NLR (Ref. 1, 2). While the ONERA balance is more cylindrical in shape, NLR has produced spoke-type balances with different number of spokes for almost 20 years. Because of the specific topology within the nacelle and other factors the latter design was favoured by RUAG. But

[4] AWTE … Automotive Wind Tunnel Emmen
[5] LWTE … Large Wind Tunnel Emmen

due to tight space limitations it became quite challenging to manufacture and instrument this sensor. In comparison to other balances, rotor dynamics, dynamic measuring effects, angular position of the balance, sensitivity to temperature drifts, data transmission to the non-rotating system, etc. had to be considered. Moreover, the huge amounts of data require complex and elaborate processing which has to be accomplished online or quasi online, in order to assess safety aspects of operation under rotation in the wind tunnel.

In the following these ongoing activities at RUAG in the field of strain gauge balances will be summarized and presented.

II. Balances 7xx: A New Family of Very Precise Balances Optimized for Stiffness and High Load Range

At the 6th International Symposium on Strain Gauge Balances in 2008, the prototype for family 7xx, balance 788, was presented (Ref. 3). The principal and well-proven design concept of balance 788 was based on the previous balance generation 1xx (specifically balance 188 with which balance 788 shares its geometrical dimensions) but was greatly refined with modern tools for design optimization.

Design components of this balance were extensively tested during the development phase with regard to signal output, interferences, and sensitivity to temperature changes. Also, fatigue stress cycles were performed and the admissible number of load cycles was established.

After completion of the balance, detailed static load and temperature calibration, as well as productive testing in the wind tunnel were performed, ranging from unsteady measurements with excited models up to 20 Hz to highly precise quasi-static measurements with vehicles. The anticipated performance of the balance was confirmed through results during load calibration and by measurements in both in RUAG's and customer's wind tunnels.

These encouraging results provided motivation to extend these novel design features to smaller and larger dimensions. On the one hand, requirements from vehicle applications called for the smaller balance 796, which basically corresponds in its geometry and volume to the previous 196 (Fig. 2). However, purely geometrical downscaling was not possible. Gauges and plugs are of the same size, and other components should have standard sizes and thus, a detailed stress and strain analysis was required according to the design objectives of the new balance. These demands led to discussions and compromises between designers and experts on mechanical manufacture and instrumentation.

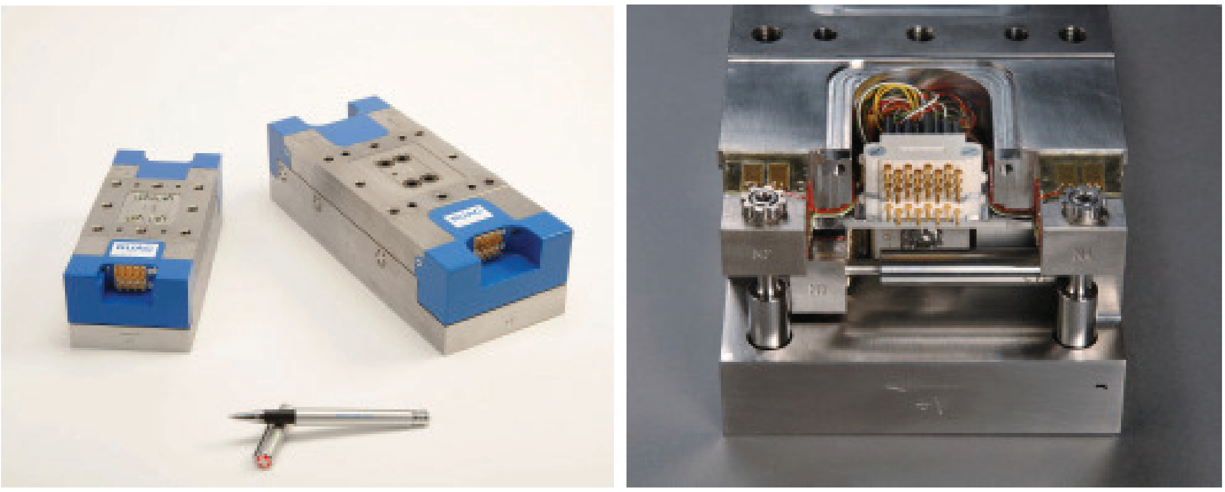

Figure 2. RUAG Balance family 7xx with its characteristic blue protection cover (796 to the left, 788 to the right). The frontal view shows the non-metric part with one lateral and two vertical measurement elements. The forces are transferred by joint-rods from the lower metric end. Between the vertical elements the extremely rigid and reliable electrical plugs are visible.

On the other hand, a scaled-up version of the prototype 788 has been requested. Complex aerospace models are very often tested in different wind tunnels. When maximum wind velocity or static pressure in the tunnels are different, the aerodynamic loading of the model will change, and accordingly, a balance with higher load capacity at the same volume and with compatible interfaces is needed. These considerations led to the development of balance 767. The geometrical size of this balance corresponds to the established balance 167, a «heavy duty balance» for larger aircrafts such as the A400M. With respect to handling and manufacture, upscaling poses less problems than downscaling, but still a detailed analysis of the individual parts as well as of the balance in the whole has to be performed in order to achieve the optimum with regard to desired stress and strain distribution and stiffness.

An overview on the new balance family is given in Table 1.

Table 1. Technical data of the new block-type family 7xx.

Design Loads[6]	**X* [N]**	**Y* [N]**	**Z* [N]**	**L* [Nm]**	**M* [Nm]**	**N* [Nm]**
796	1’000	800	3’500	350	3’50	3’50
788	4’000	600	8’000	300	1’100	1’000
767	13’000	10’000	30’000	2’300	3’800	3’100
Limit Loads[7]	**X’ [N]**	**Y’ [N]**	**Z’ [N]**	**L’ [Nm]**	**M’ [Nm]**	**N’ [Nm]**
796	1’000	5’500	19’000	550	1’520	385
788	4’000	10’000	25’000	1’000	3’000	1’100
767	13’000	32’000	88’000	6’000	14’000	4’500

Deformations[8]	**δx/δX [m/N]**	**δy/δY [m/N]**	**δz/δZ [m/N]**	**δφ/δL [°/Nm]**	**δα/δM [°/Nm]**	**δβ/δN [°/Nm]**
796	$5.0*10^{-8}$	$1.5*10^{-8}$	$6.3*10^{-9}$	$4.0*10^{-4}$	$8.0*10^{-5}$	$2.0*10^{-4}$
788	$2.0*10^{-8}$	$6.0*10^{-9}$	$5.0*10^{-9}$	$1.4*10^{-4}$	$2.8*10^{-5}$	$3.4*10^{-5}$
767	$1.5*10^{-8}$	$5.0*10^{-9}$	$3.0*10^{-9}$	$3.6*10^{-5}$	$6.5*10^{-6}$	$1.5*10^{-5}$

Geometry / nominal signals	**Length [mm]**	**Width [mm]**	**Height [mm]**	**Weight [kg]**	**Nominal excitation [V]**	**Nominal signal [mV]**
796	180	80	60	5.0	7	14
788	250	100	70	10.3	7	14
767	350	180	120	50.0	7	14

The forces X, Y, Z in axial, lateral, and normal direction and the moments L, M, N are based on a Cartesian right-handed system where all forces are directed towards the positive axis (Fig. 3). All moments are dextrorotatory. The origin of the system and the moment reference center are located in the balance center of gravity.

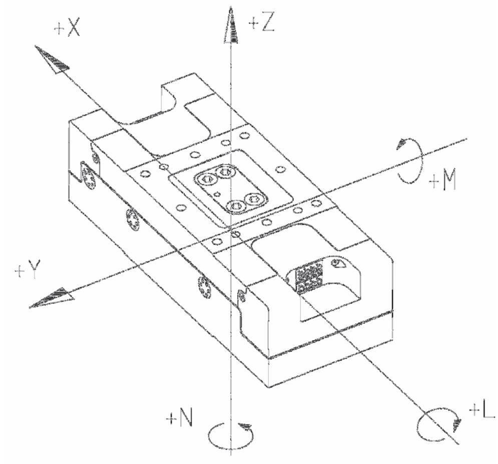

Figure 3. Coordinate system for block-type balances.

[6] Design loads refer to a combined load case, i.e. all components are simultaneously acting on the balance.
[7] Limit loads refer to a load case where only a single load is acting on the balance.
[8] Typical values

A. Main Design Principles

With the required load envelopes, overall dimensions, main design principles, material, and gauges defined, additional, more specific goals were identified, as summarized below:

- Based on the overall requirements, the optimum between scaling factor and limitations from the manufacturing and application process should be aspired. This should help to lower costs and to increase comparability of the different balances.
- Substantial stress should be mainly concentrated and limited to the surface underneath the gauges. In this way, strain mainly occurs where required for the measurements. Since general deformations are so reduced, the stiffness of the balance is substantially increased. As a consequence, the safety margin is mainly dictated by these stress values.
- Underneath the gauges 1'000 microstrain (10^{-3} m/m) are admissible which yield a nominal electrical signal of 2 mV/V with a gauge factor of 2.
- Von Mises reference stress of about 200 N/mm^2 is admissible at the measurement locations which still assures a safety factor of about 6 for the material 17-4PH before irreversible deformations occur.
- Interferences between the different load components shall be minimized. To a large extent this will be achieved by using trapezoidal elements which are insensitive to moments induced by the fixation of the joint rods. Thus, the elements mainly deform in parallel to their dedicated loading, and no disturbing impacts from other directions will be evoked by this deformation.
- Reduction of temperature sensitivity on the x-measuring element by a symmetrical design of the fixation at the metric and non-metric parts.
- Block design with very low deformation and maximum stiffness. In comparison to generation 1xx, this leads to an about 25 to 30 % higher overall mass. Due to much higher loads, special attention has to be put to the interfaces which still should be compatible to the corresponding balance 1xx of the previous family.
- Two covers on either side of the balance should protect the gauges from mechanical damage during installation and from disturbing air flows which might occur during operation.
- Features are needed to protect the balance from disastrous overloading during shipping, installation, and operation.

B. Calibration Data for balances 7xx

Up to today two balances of type 788 have been manually calibrated with dead weights and once with an automatic calibration machine. The reproducibility of the manufacturing and instrumentation process is very high, with only small differences occurring between both balances. Also, the long-term stability of the calibrations could be established.

The results of these calibrations validate the design goals described above: small interferences, high linearity, small deviations with maximum errors of less than 0.2 %, and standard deviations of about 0.05 % FS for combined load cases and all components (Table 2).

Table 2. Static load calibration of balance 788 – mean values of the residuals, referred to design loads.

Component	**X**	**Y**	**Z**	**L**	**M**	**N**
Max. deviation %	0.25	0.18	0.12	0.17	0.10	0.17
Std. deviation %	0.06	0.03	0.03	0.04	0.02	0.04

Data are mean values based on about 400 loading points and a purely linear calibration matrix. To a large extent the deviations are very homogeneously distributed for all components. Only small differences between loading and unloading (hysteresis) are observed.

III. Rotating Shaft Balances

In the past, several projects with propeller driven aircrafts have been realized in the LWTE of RUAG. Especially noteworthy are tests with models of Saab 340, Saab 2000, Fiat G222, Pilatus PC-12 and PC-21, Airbus A400M, and a TAI Trainer Aircraft. For all these tests RUAG opted and developed hydraulic engines which are characterized by high power density, extreme speed stability, and outstanding reliability during operation. The aerodynamic loads acting on the blades and the spinner were measured by 2-component spoke-type balances, yielding thrust and torque. In the case of the A400M project, four axis-cylindrical and fully symmetric 6-component balances with a small outer diameter were used. These balances had specifically been designed and manufactured for this application by ONERA. The moment reference center was directly placed in the propeller plane. In all those projects in the past, multi-channel slip rings were used for transferring the signals from the rotating system to the none-rotating system of the nacelle.

When RUAG started a close cooperation with its partners Boeing and Rolls-Royce in the Counter Rotating Open Rotor (CROR) technology in 2008, RUAG put its focus and effort on the development of the inside of the geometrically pre-defined nacelle: New hydraulic engines driving and controlling two propellers fully independent up to 12’500 rpm with an even increased specific power output were required. Directly coupled to either shaft are the two integral units consisting of 6-component rotating shaft balances (RSB), the blade hubs mounted to the metric side of the balance, and the telemetry transmitters connected the non-metric side of the balances for delivering the signals from the rotating system.

A first prototype of this new rotating shaft balance was designed and manufactured in the beginning of 2009. Tests with this balance, intensified analysis of stress and rotor dynamics with Finite Elements Methods, and an iterative approach to the metric and non-metric interfaces consolidated the final design. Subsequently, 6 of these RSB called balance type 320 have been manufactured and calibrated. Figure 4 shows this RSB design together with the telemetry transmitter.

Figure 4. RUAG RSB 320. Fully symmetric spoke-type balance with 2 transversal planes in axial direction each containing 4 spokes. On either side of the inner non-metric part of the balance the transmitter unit of the telemetry system can be attached to.

C. Main characteristics of the new RSB design

- Spatial limitation within the nacelle in radial as well as in axial direction leads to the decision to develop a fully symmetric spoke-type balance with two transversal planes each with 4 spokes. This type of balance – short in axial direction but relatively large in diameter – can only be placed before or behind the propeller planes yielding additional in-plane moments on the balance which are produced by in-plane forces and the distance between the propeller plane and the moment reference center of the balance.
- The load envelope of the balance is listed in Table 3. The coordinate system for this balance is shown in Fig. 5. The load limits are defined by taking into account static and dynamic loading as well as a maximum speed of rotation of 12'500 rpm.

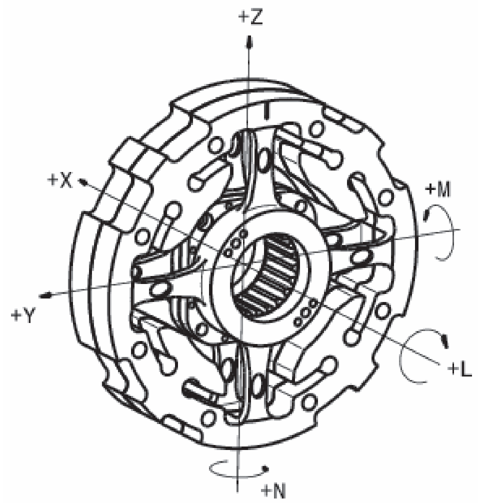

Figure 5. Coordinate system for rotating shaft balances.

Table 3. Load envelope of rotating shaft balance 320.

Component	**X**	**Y**	**Z**	**L**	**M**	**N**
	N	N	N	Nm	Nm	Nm
Load	1300	450	450	90	50	50

- A fully symmetric design is desired to reduce static out of balance. It also eases to reduce the sensitivity of the measurement locations on the spokes to centrifugal effects by a specific and an appropriate mass distribution along the outer ring of the balance. Carefully designed radii and local weakening of the spokes produce small interferences between the bridge signals and a concentration of measurable strain underneath the dedicated gauges.
- Regarding rotor dynamics the natural frequencies of the rotating units must be outside the rotational frequencies where the propellers are operated and which are of main interest during the measurements in the wind tunnel.
- High stiffness of the balance is required and unavoidable for dynamic reasons as there are unbalance, vibrations, and flutter. This is in sharp contrast to the desire of having sufficient strain to resolve all load components and therefore cannot be fully achieved. Especially the output of the in-plane forces is very limited and – in comparison to thrust and torque – only about 10 %. Therefore, the accuracy for these components will also be substantially reduced.
- The design of the new rotating shaft balances also takes into consideration the complexity of mechanical manufacture and instrumentation, the efficient mounting of the complete unit inclusive an efficient blade angle adjustment within the wind tunnel, and finally their exchangeability in order to simplify the entire process and reduce excessive costs for spare parts.
- The compact design of the balances leads to a very demanding instrumentation and wiring of the gauges. In total 64 gauges are applied and carefully wired to 6 bridges, one for each component. The symmetry of 4 spokes in two transversal planes also complies best with the characteristics of a full strain gauge bridge which requires a multiple of four active gauges being simultaneously sensitive to positive and negative strain. Table 4 lists the gauge arrangement and the corresponding loading case of the measuring elements. All bridges are temperature compensated and the temperature characteristics are determined within a range of 5 to 70 °C. As for block-type balances, resistance thermometers are installed on the metric and non-metric part of the balance (outer and inner ring) each with 2 sensors. Possible heat flows across the spokes (measuring elements) can be monitored and corrections applied. Feeding voltage for all bridges is 5 VDC. The nominal signal for thrust and torque is 1 mV/V corresponding to 500 microstrain ($5*10^{-4}$ m/m).

Table 4. Instrumentation of RSB 320 with strain gauges from Vishay Micro Measurement.

Component	**X axial**	**Y and Z in-plane**	**L axial**	**M and N in-plane**
No of gauges	16	8 each	16	8 each
Stress	bending	tension/compression	bending	bending

- Load calibration: As for other balances the static load calibration of the RSB is manually performed with dead weights. About 300 precisely defined and distributed load points with up to three load components are simultaneously applied to the balance, both in negative and positive directions. The signals of the gauges are measured with an HBM high precision data acquisition system. Table 5 presents the residuals of the back calculated loads (in % of full scale load range) based on a purely linear calibration matrix. Smallest deviations are found for the most important components thrust and torque, larger deviations are seen in the in-plane components as already described above. Only small differences (hysteresis) are observed between loading and loading.

- The reproducibility of the manufacturing and instrumentation process is very high. Looking at the data from the 6 balances manufactured so far, only very small differences could be observed for all components.

Table 5. Static load calibration of RSB 320 – mean values of the residuals of 6 balances, referred to design load.

Component	**X**	**Y**	**Z**	**L**	**M**	**N**
Max. deviation %	0.04	1.57	1.49	0.11	1.10	1.04
Std. deviation %	0.01	0.34	0.36	0.02	0.28	0.27

- A reference signal is needed to detect the angular position of a rotating balance. This information then is used to resolve the in-plane components of the balance in the none-rotating system. At RUAG an optical solution has been realized with a laser emitted in the stationary part and a photo sensor in the rotating part of the telemetry. The signal is transmitted together with the gauge and temperature signals of the balance. By placing a second system in circumferential direction the sense of rotation can be detected as well.
- A new digital telemetry system with a high package density and 20 channels for each rotor was selected for data transmission. The system is capable for simultaneous transmission of static and dynamic gauge and temperature signals from the balance as well as from the blades. In addition, two digital signals from the reference sensor (angular position and sense of rotation) are included into the data stream.
- Software: With rotating balances, multiple, huge sets of data are acquired and have to be processed and displayed. Of interest are not only time-averaged data in different coordinate systems but also time-resolved and angular-resolved data (averaged over time and interpolated to a number of angular positions) of all load components. Furthermore, dedicated processor hardware, sufficient storage media, and efficient storage and backup strategies have to be developed and implemented into the existing in-house code.
- In addition to the standard static load calibration with dead weights diverse test setups serve to evaluate and validate the dynamic behaviour of the balance and the entire measurement chain.

  First setup in the laboratory: The non-metric part of the balance with the telemetry unit is connected to a gearbox and a stepper motor and can be rotated up to maximal speed. By installing a dummy hub without blades the effects of centrifugal forces and incomplete balancing on the gauge signals are studied. In addition, a special tool for loading under rotation has been designed in order to use dead weights and to apply pure loads and also load combinations with the exemption of torque.

Second setup in the laboratory: It consists of the hydraulic motor, the rotor shaft with balance and telemetry unit, a calibrated torque meter, and a water brake. This arrangement allows to validate the static calibration of the torque while rotating at high speed.

Third setup in the wind tunnel: An isolated propeller test is performed in the wind tunnel. The complete nacelle with two hydraulic engines, rotor shaft balances, telemetry systems, and a support strut are mounted to a block-type balance (main balance) which is also kept inside the tunnel. This arrangement allows the commissioning of an entire and complete system. Assembly, handling and operation procedures, safety functions, measurement chains, and the software code can be validated. From the aerodynamic point of view the isolated characteristics of the propeller can be determined and analyzed without the influence of any other disturbing aircraft component part. Also variations over pitch and yaw angle, engine speed, thrust coefficient, and blade angle can be studied.

IV. Conclusion

With the new block-type balance family 7xx RUAG now provides three 6-component sensors which are characterized by high specific load ranges, extreme stiffness, and excellent linear accuracy with standard deviations of about 0.05 % FS for combined load cases and all components. The quality of the first prototype balance could be confirmed by the second balance.

All three balance sizes of the new family are designed according to the same novel design features and are scaled to each other as much as possible. A ratio of about 1:2:10 results for load components and balance weight, while for the geometrical dimensions length, width, and height the ratio is approximately 1:1.25:2.

Within a very tight time schedule new hydraulic propulsion systems and rotating shaft balances were specifically developed and manufactured for counter rotating open rotors. The signals from the rotating systems are digitalized, transmitted by telemetry systems, and further processed by the Master Computer Programme (MCP) of the RUAG wind tunnels. Various tests and checks with individual components and subunits have been performed on test rigs outside the wind tunnel. Followed up by an isolated propeller test in the tunnel the complete nacelle unit was successfully operated and aerodynamically analyzed.

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