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Miniature rotating amplifier system for windtunnel application packs 256 pre-conditioning channels in 187 cubic inch

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ABSTRACT
For a NASA windtunnel model NLR developed a 256-channel pressure sensor signal conditioning and amplifier system. This system was to be mounted within the rotating part of the model in a volume of 7 inch diameter and less than 6 inch long. The development of this system, called Rotating Amplifier System (RAS), required a close cooperation between electrical and mechanical designers to meet all customer requirements.
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ABSTRACT

For a NASA windtunnel model NLR developed a 256-channel pressure sensor signal conditioning and amplifier system. This system was to be mounted within the rotating part of the model in a volume of 7 inch diameter and less than 6 inch long. The development of this system, called Rotating Amplifier System (RAS), required a close cooperation between electrical and mechanical designers to meet all customer requirements.
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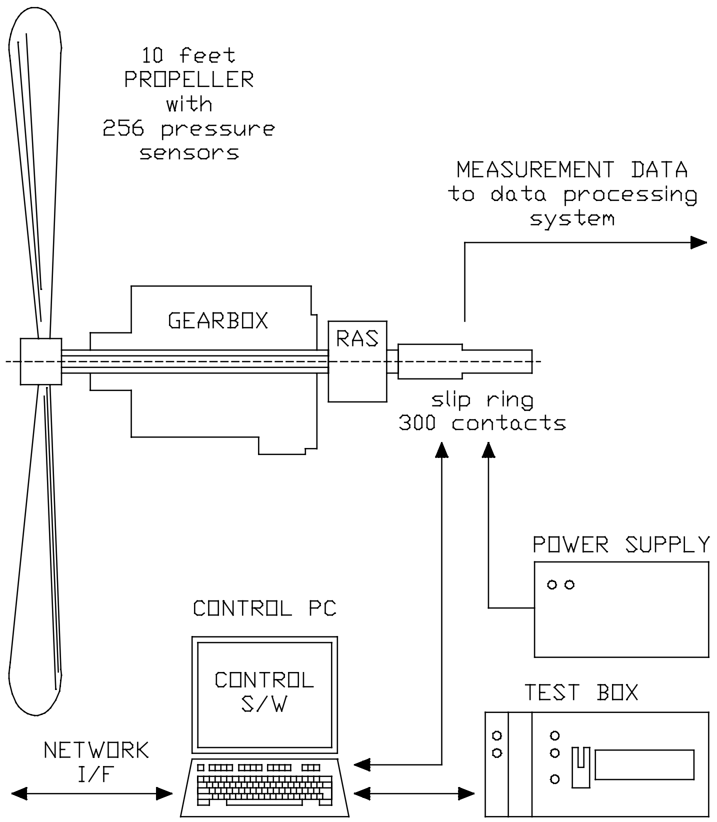
INTRODUCTION

Under contract of NASA NLR performs windtunnel tests in the DNW (German/Dutch Windtunnel) on a scale model of the propulsion part of the V22 - VSTOL Aircraft. The scale model of a single engine nacelle supports a 10 feet propeller. Amongst others, steady and unsteady pressures have to be measured on the rotating propeller.
The measurement setup consists of 256 pressure sensor signals. The scale model was already equipped with a slipring to transfer the propeller borne signals to the rigid world. It was recognized that (due to the environment, the installation and the slipring mechanism) the required signal to noise ratio (s/n) would be too low for direct transfer of the sensor signals. Direct amplification of the signal was not possible as the signal consisted of a large DC component which would overload the amplifier. So the amplification had to take place after offset correction of the sensor signals. Then the signals could pass the sliprings without too much degradation.
As a relatively large (but different for each channel) DC component was present in the signal an offset correction on each separate channel had to be possible. The main signal of interest of the measurements was the low amplitude, high frequency signals measured with the bridge pressure sensors. So it was decided to pre-condition and amplify the signals to an adequate level first, before actual connection to the slipring.
This resulted in a shaft mounted amplifier assembly: "rotating"-amplifier system RAS.
The only remaining free place within the model for this amplifier system was on the shaft between gearbox and sliprings. At this location only a volume the size of a large food can was available for the equipment.
NLR, in close collaboration with Dutch industry HYMEC, won a contract from NASA for the design, test and delivery of this RAS system in addition the windtunnel measurement contract.
A second system which slightly adapted parameters was ordered by a different customer with allowed a shared development cost.

RAS SYSTEM

The complete RAS system not only consists of the RAS amplifier unit but also of supporting equipment. A PC with software is used to perform the control of the RAS unit. This PC is also used as a controller for a special test box that allows for an easy and reproducible test/calibration environment for the RAS modules. The parameters measured using the test box are stored in the software of the control PC and used during operation to set the RAS unit and report the actual settings to the central data acquisition system using a network interface. This data is used by the data acquisition system for the interpretation of the measurement data.



Figuur 1 RAS System Overview

It should be noted that the RAS system does not perform any actual measurements, they are still being performed by the main tunnel data acquisition system. The RAS system does report the active settings of the pre-conditioning and amplifier channels to the data acquisition system so these values can be used during the processing of the measurement data.

RAS UNIT

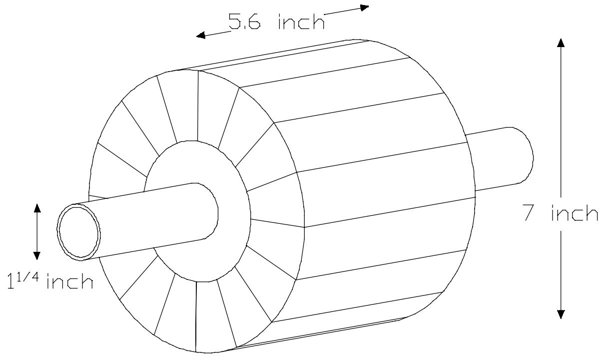
Based on circuitry developed by NLR for a series of successful windtunnel measurement equipment, a pre-conditioning unit was developed for the RAS system. The implementation had to be such that the system would survive and function in the harsh test environment. Operating temperatures ranged from 10 to 80 °C and during operation the system should withstand centripetal accelerations of 325 g (operational speed 1200 rpm but safety margin to 2000 rpm).
The complete amplifier system is split into 16 modules containing 16 amplifier channels each together with the corresponding control circuitry. On each RAS module 16 thick film hybrids are placed that contain the actual amplifier channels. The power supply and control circuitry is implemented on each module in surface mount devices (SMD) on a standard printed circuit board. The thick film hybrids and surface mount devices circuitry will easily withstand the centripetal acceleration during operation. The bonding of the components is good but, more importantly, the mass of the components is very small. The control function is completely implemented in a Xilinx programmable array which also includes digital filters on the serial control lines.

Slipring

In total 300 slipring contacts were available for the connection of the sensor signals to the outside world. For the current measurement setup a set of 166 channels was selected for amplification and 128 lines were required for the experiment safety signals. This means that of the 300 slipring contacts, 166+4 (including 4 ground references) were allocated to the amplified measurement channels. Only single ended outputs could be realized, but this was not a big problem as the signals had sufficient amplitude after pre-conditioning and amplification. The 128 safety sensor signals had to be fed directly over the sliprings as they were part of the safety system for the experiment and no risk could be taken that a malfunctioning amplifier channels would result in the loss of one of these signals. After assigning the minimal required number of power rings only a serial link could be supported for the loading of the configuration data (see table 1).

RAS module

The amplifier system had to be remotely controllable both for offset compensation and amplification setting during operation. This way actual operational offset signals could be compensated for in different tests and different test phases. The amplification can be set in four discrete steps. To allow for a fine adjustment the power supply of the bridge pressure sensors is also adjustable.
In order to reduce effect of slipring noise on the power supply of the sensors the control and stabilisation is performed in the rotating system. The power supply of each pressure sensor is either controllable separately or together with a group of sensors (jumper selectable) in which case one channel assumes control for the whole group. As all the remote control signals are stored digitally on the modules, the settings remain stable over time.



Figuur 2 RAS Unit with 16 modules

power	16 rings
166 signals (+4 references)	170 rings
108 safety signals	108 rings
control	6 rings
total	300 rings

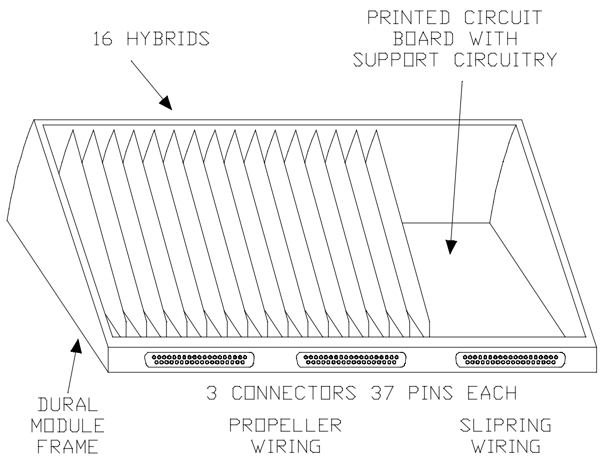
Table 1 Slipring use

Mechanical

For the mechanical design of the RAS system a close cooperation was needed between NLR's mechanic and electronics departments.
The mechanical construction consists of 16 pie shaped aluminium modules that connect via three 37 pin connectors to the central axle which also contains all the wiring for the channels. For each module the two connectors on the propeller side carry the sensor wiring and one connector carries the wiring to the slipring assembly. The pie shaped modules connect the two parts of the central axle, one end is connected to the slipring assembly and the other part is connected to the drive and propeller section. This separation made construction and easier maintenance of the amplifier modules possible. The 16 modules are balanced but fabrication tolerances are tight enough to allow for field replacement of any of the modules with a spare module.
The mechanical construction of the modules consists of an eloxated aluminium frame in which the connectors and the module printed circuit board is mounted. The inner long edge of this frame carries the 3 connectors while the thick edge forms the outside of the cylinder. The mating parts for all 3 connectors of all 16 modules are mounted on the central shaft. The printed circuit board almost forms the bottom of this small box.

Electrical

NLR's design is based on its well proven windtunnel



Figuur 3 RAS module with 16 hybrids

signal conditioning unit. Due to the very limited space available (cylinder 7 inch diameter, 5.6 inch length around a $1^1/_4$ inch shaft) a very high degree of miniaturisation had to be realized. Hybrid technology was selected, as it both offers a possibility for a high degree of integration, good thermal properties and enough strength. The Dutch company HYMEC was selected as a sub-contractor as it has a high degree of expertise in this manufacturing process.
In total 256 conditioning channels were realized in the cylindrical unit. All are remotely controlled and consist of the following parts: instrumentation amplifier with 4 gain settings, excitation with 0 — 10 Volt range, DC-offset compensation and R-CAL function with 3 resistor values (see table 2).

Thermal

Thermal stability of the circuit was a main driver for the development of the electronics, as small (but stable) deviations could be removed in post processing whereas any variations would make it impossible to reconstruct the actual data. The temperature stability of the complete system had to be good over the operating temperature

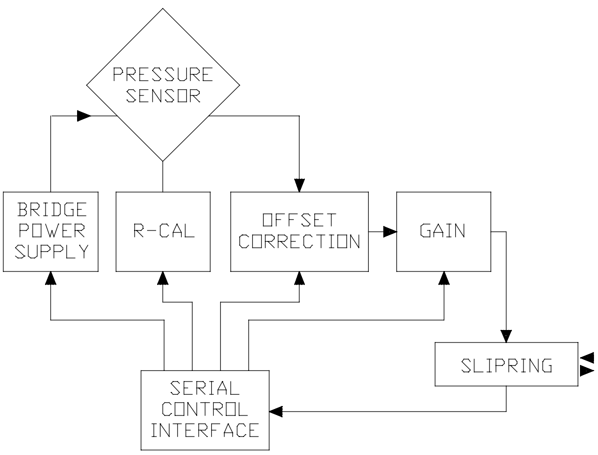
range (10-80 degrees celsius). The thick film hybrid circuits are built on a silicon oxide carrier which is a good thermal conductor. The thermal and mechanical support of the hybrids were improved by filling the slits in which the hybrids are mounted (in the inside of the outer module wall) with a thermal conducting and mechanical damping epoxy compound.
This together with a routing of the wiring and components on the hybrids that made the coupling between bridge pairs as close as possible resulted in a stable system.

Sensor supply	±0 — ±5 Volt	256 steps
Offset compensation	-100 — + 100 mVolt	4096 steps
Gain	50, 200, 400 and 550 times	
R-Cal	83, 125 and 250 kohm	

Table 2 Channel specifications

Cabling

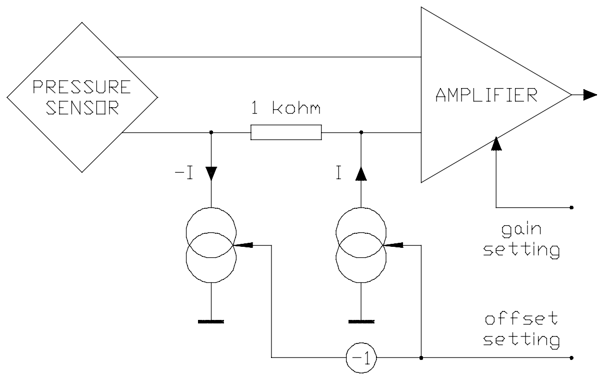
A further challenge was the internal cabling, slipring to RAS and RAS to sensors (up to propeller nose cone). This has been manufactured by specialised NLR technicians. To give an idea of the difficulties related to the internal cabling, on the RAS transducer-side about 800 signal wires have been fed through a hollow axle with an inner diameter of 1 inch and a length of 5 feet. This includes some spare wires, as it is expected that the wire bundle can no longer be removed from the axle once the RAS module has been operated. This due to the setting of the wires in the axle. On the RAS slipring side 300 wires were connected to 16 RAS connectors in a very small space.



Figuur 4 Basic amplifier circuit

RAS hybrid

For the RAS amplifier circuits a thick film hybrid implementation was selected because of small available volume and good thermal characteristics. The hybrids were designed and manufactured by the Dutch company Hymec based on a proven NLR design and according to NLR specification. Thick firm hybrids consist of a ceramic substrate (SiO_2) on which the electronic circuitry and sometimes resistors are created using a silk-screen printing process. During the design, special attention was paid to the lay-out of the hybrid and the pairing of resistors to obtain optimal thermal stability of the amplifier channels. The offset compensation circuitry uses two controllable current sources. The two current sources are controlled with a signal of opposite magnitude and the result is that an adjustable offset is added to the sensor output without changing the balance of the sensor bridge (figure 5). The adjustment of this circuitry is delicate as any unbalance between the two current sources will result in a disturbance of the sensor bridge by injecting a current into it.



Figuur 5 Offset compensation

Trimming

After initial burn-in of the hybrids and a functional test, a functional trim of some resistors in the circuit was performed. Functional trim means here that during the trimming process of a resistor one of the functional parameters of the amplifier was measured. These trim operations were performed in steps with thermal relaxation of the hybrids in between.
The trimming is preformed by means of a laser that burns traces in the thick film resistors. So resistors can only be trimmed to a higher value. For voltage dividers this has an extra effect, as voltage dividers can only be trimmed by increasing one of the two resistors, the total resistance will increase. This made the trimming process quite different from the trimming process of the proven circuit and

resulted in some difficulties getting all the hybrids trimmed to the required specifications.
After these trim operations the hybrids were again heated to simulate the first part of the aging process in which the thick film resistors show most of the change in value.

CONTROL PC

The remote control unit consists of a standard portable PC that transfers the settings of the amplifier system via a single serial link to the amplifier unit. This remote control unit was also used during channel calibration when it was used to store the actual amplification and offset values. During operation the amplifier channels are set to the selected values and the actual values are transferred via either a serial link or a local area network to the main data acquisition system to be used during processing of experiment measurement data.
The remote control unit also doubles as control unit for the checkout/verification equipment. Single modules can be automatically tested and their operational parameters can be verified against the requirements and against previous measurements. The external test unit contains a power supply, a dummy sensor bridge (both balanced and unbalanced, relays and some amplifiers and is completely controlled from the PC which also contains the measurement card used during the checks.
The DC parameters of the 16 amplifier channels of each module (gain, offset range, power range and R-cal) including some amplifier errors (offset etc.) can be determined in an automatic way. No extra equipment is needed to perform these measurements.

Serial link

A low rate serial link is used to transfer the configuration data (amplifier, offset and power settings) from the control PC to the RAS unit. The total amount of configuration data is 16 * 16 * 24 = 6144 bits. To reduce noise problems a very low bit rate with extensive filtering (both analog and digital) was selected. The 1 kHz clock rate means that the complete configuration process takes over 6 seconds. A serial data return line is used to verify that the correct data has been received by the modules.
An addressing scheme was implemented that splits the total data in 16 separate addressable groups. This limits the amount of data that needs to be transferred in case of single channel changes. Also, a broadcast address was introduced that makes it possible to set all channels of a single module to the same setting. For instance this can be used for the fast switch off of all the channels. This allows for the use of a low data rate which in turn makes it possible to filter the digital signals heavily to obtain reliable transfers over the noisy slipring contacts.

Network link

Using an Ethernet interface the control PC is connected to the main data acquisition system, this link allows for the transfer of current configuration settings and calibration data from the Control PC to the main data acquisition system, to allow for the interpretation of the acquired measurement data.

TEST AND CALIBRATION

To support the test and calibration process of the RAS system a tool had to be built to set the configuration of the RAS hybrid/module under test. This had to be an automated process because configuring the units by hand is not a practical approach.
A test box was defined that could first be used to verify correct operation of the hybrids after production but before they were placed on the module printed circuit board. These measurements would also provide initial values for the operational parameters.
In the following phase the test box was used during module tests. Extensive module tests were performed after production of the modules but these tests will also be repeated to verify that the modules are operating before measurement campaigns. On module level the determination of the operational parameters is very important because besides an indication whether the modules are functional this also gives parameters that are used during the measurements for the interpretation of the measurement data.
A separate operating mode of the PC software was defined which allowed the same PC with software to be used during all these tests. An extra interface board is added to the PC for analog input which allows the PC to perform the DC parameters measurements in an automated (reproducible) way. This software also allows manual setting of the different operating modes of the modules so it can also be used during manual measurements of more extensive operational parameters.

Test-box

For the acceptance testing of the hybrids and for verification and calibration tests of the modules a test box has been made. This test box provides power and a way to control the test setup for the system components. Amongst others it can connect a simulated sensor bridge to the amplifier channel under test either in a balanced or a defined un-balanced mode.
The complete test box is PC controlled. This automated measurement results in a well defined calibration setup and reproducible measurements of the module parameters.

The test-box provides facilities to measure all important DC operating parameters of the amplifiers. It also provides support to perform AC measurements but these also require external equipment.

Calibration

The calibration function of the test box allows for a reliable and convenient way to measure the actual DC parameters of the module. The Control PC stores these data and allows for comparison with previous measurements of the same module. Correct functioning of a module can easily be verified.
These values are also used during operation of the sys-tem. When the data acquisition system requests the actual setting of the RAS unit these calibration values are forwarded. The main data acquisition system uses these values in the interpretation of the measurement data.

CONCLUSION

The close cooperation between electronic and mechanical designers resulted in a compact and elegant design for the RAS unit, which fulfils the requirements of the customer. Integration aspects like wiring could be solved and even the task of connecting about 1100 wires to 48 connectors within a volume of roughly 10 cubic inch was completed successfully.
The RAS system has been delivered to NASA and has been extensively used during experiments, in which it proved to function reliably. In the actual experiment setup (RAS mounted on propeller shaft inside nacelle) with the gear-box producing more heat than expected some thermal problems appeared but these could be solved by an improved air-cooling of the unit.
The Hybrid modules proved to be a good way to obtain the required miniaturisation and thermal system stability. The trimming process of the hybrids though was quite different from ’normal’ electronics and proved to be more difficult than expected from similar circuits realized in more conventional technology.
A second RAS system has been made for another customer with slightly adjusted ranges and settings but basically the same as the NASA system.
The large scale windtunnel experiments for which the RAS system was designed and developed are foreseen to take place in the near future.

Abbreviations

AC	Alternating Current
DC	Direct Current
DNW	German/Dutch Windtunnel
NASA	National Aerospace and Space Administration
NLR	(Dutch) National Aerospace Laboratory
PC	Personal Computer
RAS	Rotating Amplifier System
rpm	revolutions per second
s/n	signal to noise ratio
SMD	Surface Mount Devices

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