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THE DEVELOPMENT AND OPERATIONAL ASPECTS OF A SIGNAL TRANSFER SYSTEM FOR USE IN WIND TUNNEL PROPELLER MODELS

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ABSTRACT

This paper describes a Signal Transfer System (STS) for use in a Wind Tunnel model propeller. In order to extend the capacity of a conventional mechanical slip ring assembly an electronic Multiplexer has been developed, which is located in the rotating part of a propeller-hub. The amplified transducer signals are multiplexed, digitised and transferred over the slip ring assembly located in the propeller shaft. A Demultiplexer unit processes the signals in order to make them available, in analogue format, for a Wind Tunnel Data Acquisition System.

NLR has developed the Signal Transfer System for use in a specific Wind Tunnel model propeller. Due to space limitations in the model a slip ring assembly had to be applied, which had an insufficient number of slip rings to transfer all signals directly.

Two Signal Transfer Systems have been successfully operated with two Model Propellers, throughout a number of tests in several European wind tunnels. Special attention has been paid to the operational aspects of the system.

A brief overview will furthermore be presented for a future development resulting in a fully contact-less transfer system, replacing mechanical slip ring assemblies.

1 INTRODUCTION

The system conditions and multiplexes 32 transducer signals. The signals are digitised and transferred over the slip ring assembly located in the propeller shaft. In the rotating part a number of strain gauge outputs are amplified and are passed directly via the slip ring assembly without being multiplexed. The supply voltages for the Multiplexer electronics are transferred by the slip ring assembly. All transducer supply voltages are regulated by the Multiplexer electronics.
The high rotational speed (10,000 rpm) of the propeller caused a high static 4,000 g-load on the Multiplexer electronic circuits.

NLR has developed the Signal Transfer System (STS) for use in the APIAN Wind Tunnel model propeller.
APIAN (Advanced Propulsion Integration Aerodynamics and Noise) was a European Union (EC) Fourth Framework programme aimed at developing technology for a new generation of commuter aircraft. Within the APIAN Programme measurements on a model propeller have been performed using different test set-ups in several European wind tunnels. One of the objectives of the tests was to measure the dynamic pressures on the propeller blades at different flow conditions. The propeller blades were equipped with pressure sensors and strain gauges. A Rotating Balance was used to measure in-plane loads and moments. The propeller set-up used for these tests was equipped with a liquid cooled slip ring assembly for the signal transfer from the rotating part to the Data Acquisition System. Due to space limitations in the model a slip ring assembly had to be applied, which had an insufficient number of slip rings to transfer all signals directly.
Multiplexing of a number of channels provided sufficient reduction to transfer the total number of 40 signals over 28 slip rings.

An overall drawing of the propeller, also indicating the position of the Multiplexer, is shown in Figure 1.

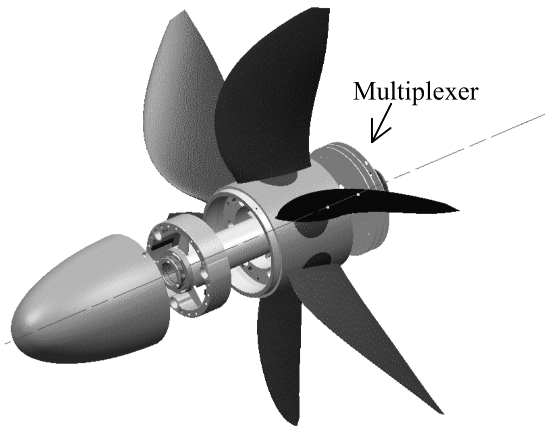

Figure 1. Propeller overall drawing.

This paper describes the development of the Signal Transfer System, highlighting a number of special measures. These measures were taken in order to avoid interference problems related to the noisy operational environment of a wind tunnel. Differential input circuitry, a dedicated digital coupling path and effective shielding and grounding techniques were applied. Furthermore a number of operational aspects will be discussed, including the test and calibration of the system.

Finally a brief pre-view will be presented for future developments. These developments would result in a fully contact-less transfer system, replacing the existing mechanical, liquid cooled, slip ring assemblies. Availability of such a contact-less system would eliminate the cumbersome operational requirements related to the application of this type of slip ring assembly.

2 ELECTRICAL DESIGN

2.1 Design approach

The Signal Transfer System (STS) consists of two major building blocks; a Multiplexer, which is located in the rotating propeller part, and a Demultiplexer, located outside the Wind Tunnel test section. Both building blocks are connected by a slip ring assembly, which has 28 single mechanical slip rings. A total number of 40 signals had to be transferred over this slip ring assembly. Besides the signals from transducers located in the Rotating Balance and the Propeller Blades, a number of excitation voltages had to be applied to the bridge-type transducers for temperature, strain and pressure. The excitation voltages for the transducers are regulated in the Multiplexer, providing high accuracy and stability.

A choice was made to multiplex a number of 30 blade pressure transducer signals and 2 temperature transducer signals from the Rotating Balance. In total 14 slip rings are used to transfer these signals after digital multiplexing. The remaining 8 strain transducer signals are only amplified to improve the signal-to-noise ratio and passed directly over the slip ring assembly to the Demultiplexer. The Demultiplexer unit restores the multiplexed transducer signals into analogue format and makes all signals available for the Data Acquisition System.

A total number of 32 transducer signals are multiplexed. This multiplexing is accomplished by means of a digital method to overcome problems with noise and distortion of the analogue signals due to fast switching.
The 32 input channels are split up into 4 conversion blocks, each processing 8 analogue input channels, in order to limit the bit rate of the digital signal of each conversion block.

Figure 2 shows the Functional Blockdiagram of the STS.

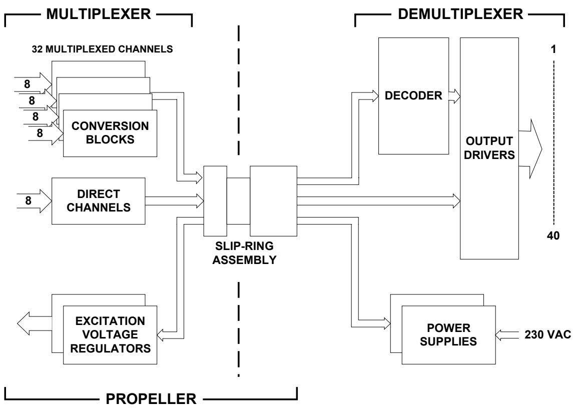

Figure 2. Functional Blockdiagram STS.

Special care has been taken in the design of the system bandwidth and sampling rate. The maximum rotating frequency of a propeller blade at a speed of 10,000 rpm is 160Hz. The maximum frequency of interest was the 6^{th} harmonic or about 1 kHz. Therefore a –3 dB cut-off frequency for the anti-aliasing filter was chosen at 2 kHz. To limit the number of components, a second order filter was applied. NLR data acquisition specialists normally like to see an aliasing suppression of at least 40 dB. In order to achieve this objective, it was necessary to use a 17 kHz sampling rate of the analogue to digital conversion for each channel.

Both the direct and multiplexed channels have identical analogue filters to equalize signal delay differences. During test and calibration of the system, the actual channel phase shift was measured to enable compensation by the data processing software of the Data Acquisition System. Before multiplexing, all signals are captured simultaneously by a sample and hold circuit. In this way the additional delay, caused by multiplexing and digital transfer, is a fixed value for each multiplexed channel. The data processing software can also easily compensate this delay.

Table 1 shows the major specifications for the multiplexed channels.

Table 1. **STS Specifications multiplexed channels**	
Bandwidth, @-3 dB	DC- 2 kHz
Overall Gain	100
Gain Stability	0.02%/°C
Offset Drift,	< ± 10μV/°C
Aliasing Suppression	> 40 dB
Conversion Sample Frequency	17 kHz
ADC Resolution	14 bit
Cross-talk, DC-2 kHz	> 45 dB
Noise Level	< 60 dB
Output	0-10Volt

It should be noted that the name Multiplexer is used for all the circuitry located in the rotary part and the name Demultiplexer is used for all circuitry located in the stationary part.

2.2 Multiplexer

Figure 3 shows the Schematic Diagram of the Multiplexer.
Each input signal is amplified by a factor 100 and has a differential input amplifier. Each analogue input channel is filtered in order to prevent aliasing. The signals of all channels are captured simultaneously by the Sample and Hold circuit. The resulting 8 signals are selected one after each other by the Analogue Switch and converted into digital format by a 14-bit ADC and serialised by the Shift Register. The resulting signal has a bit rate of approximately 0.2 microseconds and is fed to an output driver which drives an opto-coupler located in the stationary Demultiplexer. The differential output driver is configured in such a way that the load of the opto-coupler approximately matches with the characteristic impedance of the applied cable. The resulting driver configuration assures a reliable transfer mechanism for long cable lengths and also reduces RF emissions with respect to a single ended driver configuration. Furthermore applying an opto-coupler makes each conversion block fully floating, which is important for avoiding ground-loops and reducing noise.
The whole conversion process is controlled by the Address Generator, which drives the Analogue Switch, the ADC and the Shift Register. In order to be able to decode the digital signal, a synchronisation (sync) and a clock signal are also sent to the Demultiplexer. To conclude, the 32 analogue input channels are transmitted by the Multiplexer over 4 serial digital bit streams, a clock and a sync signal.

The supply voltages for the Multiplexer electronics are transferred from the Demultiplexer by the slip ring assembly. The transducer supply voltages are derived from this supply and regulated by the Multiplexer electronics.

The Rotating Balance signals (4 strain gauge bridges) and the Blade strain signals (4 strain gauge bridges on two propeller blades) are amplified up to 1000 times to reduce the noise of the long distance signal path and passed directly to the slip ring assembly.

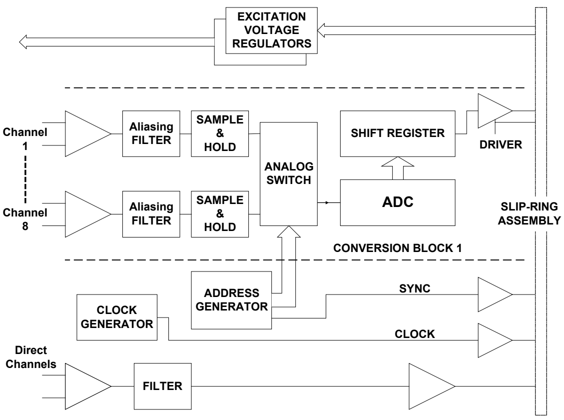

Figure 3. Schematic Diagram of the Multiplexer.

2.3 Demultiplexer

Figure 4 shows the Schematic Diagram of the Demultiplexer.

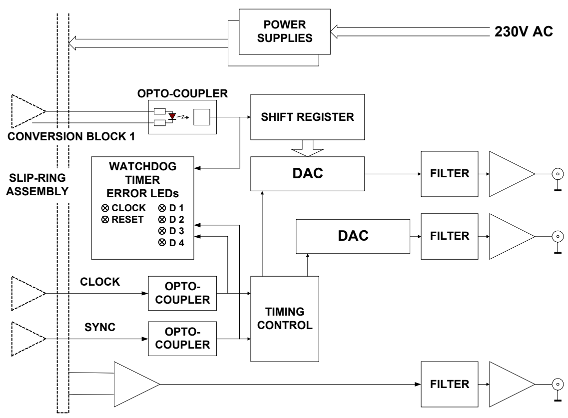

Figure 4. Schematic Diagram of the Demultiplexer.

The Demultiplexer may be located outside the test section of the wind tunnel, at a maximum distance of 40 metres from the Propeller. The incoming serial bit stream of conversion block 1 represents 8 analogue input channels of the Multiplexer. The clock and the sync signals from the Multiplexer are fed to a timing control circuit, which controls the restoration of the incoming serial bit stream. The Timing controller selects the correct Digital to Analogue Converter (DAC) at the moment that the data for this DAC is present in the Shift Register and updates all channels at the same time. In this way the digitally multiplexed data for 8 analogue input channels is restored into 8 analogue output signals. After conversion the resulting analogue signals are fed to a smoothing filter to remove switching transients. Finally a buffer amplifier is used as a line driver to enable connection to the wind tunnel Data Acquisition System over a maximum distance of 100 metres.

A so-called Watchdog Timer is used in order to check the correct timing of the incoming digital data. This circuit acts as a built-in test circuit, signalling errors in the serial data and the sync and clock signals. The Light Emitting Diodes (LEDs) at the Demultiplexer front panel indicate to the Operator if there is a failure in one or more specific digital circuits or the cable.

2.4 System Cabling

Careful design of the system cabling was very important, for two reasons:

- The relatively long distance between the Multiplexer and the Demultiplexer.
- The high switching frequency of the digital signals.

The digital signals are each placed in a twisted and shielded cable in order to minimise distortion of the signal. An overall shield was applied to the 7-pair cable bundle in order to prevent excessive RF emission.

The analogue output drivers of the Demultiplexer can be adapted either to a differential or single ended configuration of the Data Acquisition System inputs. The cabling concept and the specific cable types have been mandatory specified for all the wind tunnels in which the system should operate. This was considered an important topic, because the specific cabling between the Multiplexer and the Demultiplexer could not be a system deliverable, but had to be produced by the instrumentation team of each wind tunnel involved.

3 MECHANICAL DESIGN

3.1 Multiplexer

The Multiplexer is located just behind the blade roots in the most downstream section of the Propeller hub. This is a section in which extra weight will only have a minor effect on the dynamics of the rotating system. Figure 5 shows the assembled Multiplexer, the visible plastic tube is only to support some of the wiring.

The propeller hub has a fairly large 100 mm diameter, but due to the large number of components (about 640), the Multiplexer had to be packaged onto two printed circuit boards (PCBs) using both sides for components. Almost all components are Surface Mounted Device (SMD) types. Besides the number of components, a total number of 98 input connections to the transducers and 30 output connections had to be accommodated on the PCB. All the input and output connections are located in a 50 mm diameter circle on the first Multiplexer PCB. The input and output wires are located in the hub in such a way that all wires are fully supported over their entire length in order to be able to withstand the applied g-force.
The lesser number of connections to the second Multiplexer PCB are located within a smaller circle diameter, using board-to-board type PCB-connectors. This approach gives the opportunity to easily disconnect both PCBs for maintenance.

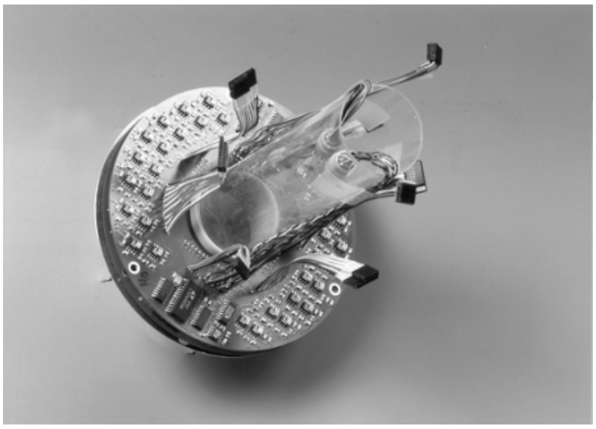

Figure 5. Assembled Multiplexer.

During the development it appeared necessary to incorporate a heatsink, because the total dissipated power of all on-board voltage regulators could not be locally dissipated. In order to solve this problem the voltage regulators were mounted to a separate aluminium back-plate, near the second PCB. The voltage regulator leads are directly soldered into the second PCB. This back-plate is the final downstream rotating part of the propeller hub and has a pressure settling function between the rotating part and the stationary part. The heatsink capacity is high, due to the fact that the back-plate has a perfect fit into the aluminium propeller hub. The back-plate also acts as a mechanical protection for the Multiplexer when it is removed for test and installation.

3.2 Demultiplexer

Figure 6 shows a picture of the assembled Demultiplexer with the Multiplexer on top.

The space available for the Demultiplexer was not a limiting factor, as it was for the Multiplexer. Therefore a standard 19” cabinet was applied. All

circuitry was packaged onto standard size PCBs. To prevent excessive amounts of wiring, all input and output connectors are directly located on the PCBs.
Due to stringent regulations in Europe, it is a NLR strategy to use only off-the-shelf certified power supplies. All power supplies are procured as standard modules and are located in the rear section of the instrument.

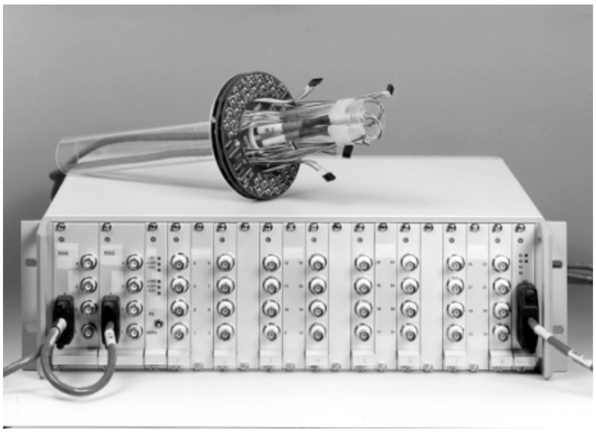

Figure 6. Assembled Demultiplexer.

4 OPERATIONAL ASPECTS

During the design phase it is extremely important to consider the operational environment in which a system must be used. This is a statement clear to anybody, but frequently overlooked in practice. The Signal Transfer System, particular the Multiplexer, is a delicate piece of electronics and had to be handled in a rough industrial environment. Additional mechanical protection is not considered because that would have cost extra space, weight and cost.
In this chapter a number of measures will be summarised which have been applied in the development of the Signal Transfer System.

4.1 Ruggedised product(ion).

Mainly three measures have been taken in order to ruggedise the Multiplexer:

- All components have been placed in such a way that the mass of the components is evenly distributed over the PCB surface in order to prevent mechanical unbalance. Relatively heavy components have been placed opposite of each other with respect to the PCB centre.
- Conformal coating has been applied after production and test on both sides of each PCB. This measure is important in an industrial environment where small metal particles possibly can cause a short circuit on a PCB.
- Finally the highest available production quality standards have been applied in order to assure high product reliability. This type of quality standard is normally used for space qualified production. It provides visual pre-production inspection, soldering techniques and post-production inspections.

Figure 7 shows a detail of the Multiplexer

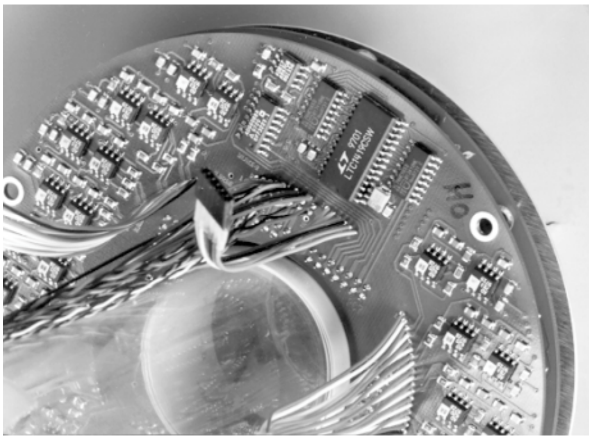

Figure 7.Multiplexer detail

4.2 Test tools.

It is an engineer's nightmare if a product fails after extensive building-in of a test specimen. Therefore it is important to be able to test a component during several stages of assembly. A number of test tools have been designed in order to:

- Simulate transducers.
- To measure the transfer of the system without transducers.
- To check the functions of the complete assembled system.

4.3 User documentation.

It is good engineering practice (and a legal requirement!) to provide sufficient user documentation for each delivered product. A rather extensive User Manual has been written in order to communicate correct and safe handling procedures to the user.

5 TEST and CALIBRATION

The Signal Transfer System was subjected to a severe testing process before it could be released to operational service. After development and production a standard functional test has been performed. Following the functional test a more severe non-rotating performance test has been performed, covering the following parameters:

- Overall noise
- Cross talk
- Aliasing suppression
- Excitation voltage accuracy

- Channel DC offset and gain
- Channel frequency and phase characteristics

These tests have been performed in a wind tunnel with cabling and a slip ring assembly installed. All measured results have been recorded for calibration purposes. During both the functional and the performance tests the system fulfilled all requirements and specifications.
Finally an acceptance test has been performed in order to prove performance of the system in an operational environment, both static and rotating. This was considered important, because it is not easy to troubleshoot an instrumented propeller. Confidence in a correctly functioning system was of paramount importance. The acceptance test was carried out without blades, but with dummy blade transducers installed. These dummies simulated nominal DC blade pressure and blade strain signals, so in absence of the transducer signal, the operational performance of the channel could be measured. All signals have been recorded during rotating propeller runs up to 10,000 rpm. During the acceptance test the system proved to comply with the specifications, also during rotating tests in a real wind tunnel environment.
Figure 8 shows a picture of the propeller during the acceptance testing.

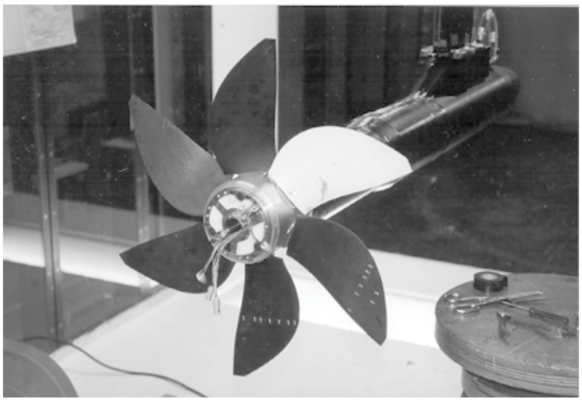

Figure 8. Acceptance testing of the Propeller.

6 RESULTS

Both Signal Transfer Systems passed all test sessions and have been successfully operated with two Model Propellers throughout a number of tests in the following European wind tunnels:

German-Dutch Wind Tunnels (DNW):
- High Speed Transonic Tunnel (HST)
- Low Speed Tunnel (LST)
- Large Low-speed Facility (LLF)

The French Office National D'Etudes et de Recherches Aérospatiales (ONERA):
- S1

The STS Multiplexers withstood all operational stress applied during the tests. The frequent installation and removal of the Multiplexers had no detrimental effect on the system reliability and performance.

7 CONCLUDING REMARKS

It can be concluded that the measures which have been taken during the development, together with the extensive testing, resulted in a first-time-right operation of the system.
This success actually triggered within NLR a series of new developments, which could result in a fully contact-less signal transfer system. Such a system, briefly described below, should replace existing mechanical slip ring assemblies. A fully contact-less system would eliminate the cumbersome operational constraints related to the application of liquid cooled slip ring assemblies.

The most challenging part of the development of such a contact-less system is a coupling device. This device must provide power from the stationary part to the rotating part, at the same time providing a reverse data-path. The mechanical outline of the coupling device should more or less have the same dimension as a mechanical slip ring assembly, offering a direct replacement.

A number of coupling mechanisms can be considered for the coupling device:
- Optical
- Inductive
- Capacitive
- Radio-Frequency

At present a study has been started in which an inductive coupling mechanism is investigated. The power for the rotating electronic circuits and the excitation circuits will be transferred in the low-frequency range. The data to the stationary part will be transferred using the same inductive mechanism in the high frequency range. The data will be transferred by a digital modulation technique.
The circuit of the rotating part will consist of a similar design as the STS Multiplexer. The digital data will be decoded by the stationary part, however it will not be demultiplexed into an analogue format, like STS. The data will be translated into a standard high-speed digital interface format. The reason is that most Data Acquisition Systems are able to receive data in a standard digital format. This approach will result in an

efficient and high-performance contact-less transfer system for wind tunnel model application. Figure 9 shows the Functional diagram of the system.

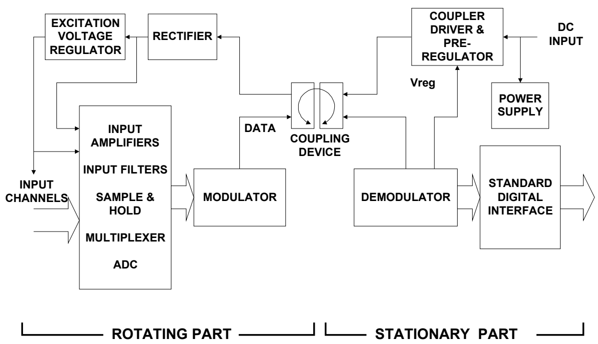

Figure 9. Functional Diagram contact-less signal transfer system

8 ACKNOWLEDGEMENTS

The authors wish to thank all NLR, DNW and ONERA employees involved in the development and test of the STS. Their support was essential for the successful operation of the system.