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DLR ROTOR TESTSTAND MEASURES UNSTEADY ROTOR AERODYNAMIC DATA

by

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DLR ROTOR TESTSTAND MEASURES UNSTEADY ROTOR AERODYNAMIC DATA

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1. ABSTRACT

As a final step in a long period of system development in December 1992 a highly instrumented model rotor has been tested by DLR in the German-Dutch windtunnel (DNW). As a part of a joint program of 4 DLR institutes together with European partners in the BRITE/EURAM project HELINOISE [1], a model rotor (40% scaled BO105 rotor) with 124 absolute pressure sensors, 32 strain gauge sensors and further sensors on one blade was developed. The subject of this joint program is to investigate the aerodynamic, aeroelastic and the acoustic behaviour of a rotor system at various flight conditions by measuring the surface pressure, the flapwise, lagwise and torsional motions of one blade and in addition the acoustic field below the rotor.

For these investigations the DLR rotor test setup was modified to allocate wires and the specially developed preamplifiers of extremely small size for each sensor in the rotating part of the rig.

The high number of channels, a sampling rate of 35.84 kHz/channel (2048 samples/rev) and the required upgrade capability to even more channels yield in a complete new concept for the measuring system. A highly parallel architecture based on transputers allows a virtually unlimited number of channels combined with high sampling rates. In addition the computing power of the system scales with the number of channels and thus allows the measuring system to process additionally the sampled data at high speed. The type of ADC has changed compared to traditional systems: Delta Sigma ADC's which are normally used for audio purposes seem to be the best solution for avoiding analog preprocessing (antialiasing filters) but gaining high resolution (16 Bit) and low harmonic distortion (-90 dB).

Starting with an overview of the entire measuring system the paper continues with a discussion of all relevant aspects of the system. Finally some results and a conclusion are given.

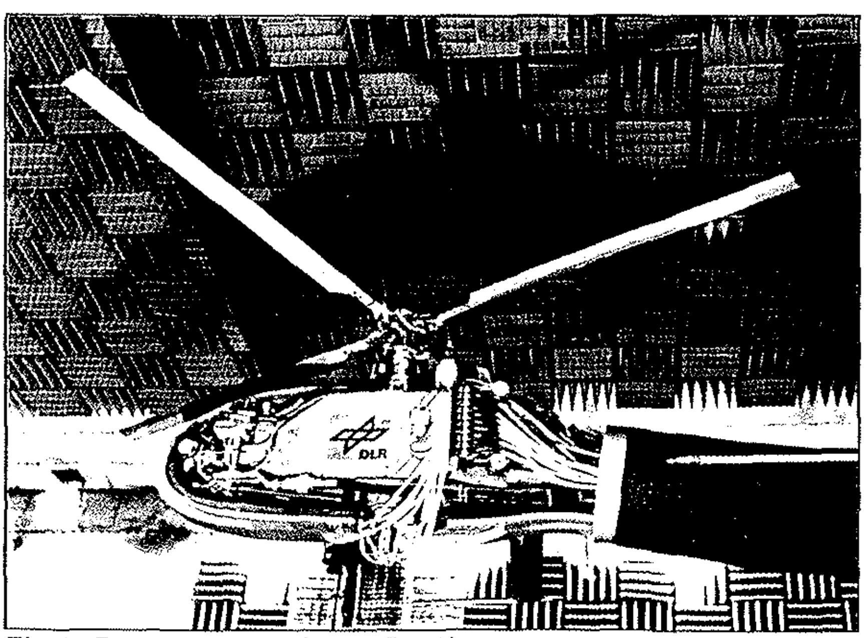

Fig.1: Rotor teststand in the DNW

2. Overview

As a forerunner to the projects CP-ROT/Helinoise, the DLR Institute of Aeroelasticity in Göttingen agreed to carry out the data acquisition of the signals from the rotating system during the planned windtunnel tests with the rotor teststand. The Institute of Aeroelasticity has long term experience with acquisition and processing of multichanneled unsteady signals, and thus it was obvious that this experience would be contributed to the project. However the requirements of the planned measurement task were so high, that the institutes data acquisition system AMIS I ("Anlage zur Messung Instationärer Vorgänge") was unsufficient. Therefore it was decided to modernize the system, naming it AMIS II. New ideas arose during the conception phase, especially when the New Technologies Group of the DLR Institute of Flight Mechanics became involved, adding its know-how in transputer technology.
Instead of using conventional ADC acquisition system technology an intelligent recording system using transputers was conceived, which is also able to preprocess and thus reduce the enormous amount of data besides data acquisition. Furthermore, since transputers are especially suited for parallel applications, the system was constructed in parallel technology, i. e. each signal channel has its own ADC and 8 channels together have their own transputer for the management and preprocessing of the data.
Further the Institute of Aeroelasticity developed suitable preamplifiers for the signal conditioning fitting into the rotating part of the system. For this purpose well tried amplifiers were miniaturized from the size of an eurocard to the size of an sugar cube, allowing to place 240 of them in a housing on the rotor shaft. All these amplifiers are parameterizable from outside the rotating part during measurement.

2.1. The Rotor Teststand

For these tests the MWM (Modular Windtunnel Modell) rotor teststand was used. The rotor was a 40% scaled BO 105 hingeless rotor system (airfoil NACA 23012 mod) with 124 absolute pressure sensors and 32 strain gauges on one blade. The advantage of this test facility are the small dimensions of the test rig casing and the possibility to attach an additional amplifier and slipring system at the end of the hollow rotormast.
The rotor teststand was covered with an acoustic fairing to reduce engine noise and reflections. The contour of the fairing is similar to the fuselage of the BO 105. Thus the interference between rotor and fuselage are similar to the original. Only on the bottom side the fairing has to be scaled up to cover the additional amplifier and slipring system.
The test facility is driven by a hydraulic engine with a maximum rotor power of about 130 kW. The rotor balance to measure the forces and moments of the rotor are six dynamic and static measuring force cells between the casing and the gear box. The 124 installed pressure sensors (Fig.3) are developed by KULITE. One sensor with a size of about 10 mm in length and 1.5 mm in height and width has an ortify of 0.5 mm. The distance to the sensor membrane is about 0.8 mm. The temperature compensation is inside the sensor.
On the pressure instrumented blade additional 32 strain gauges for measuring the flap-, chord- and torsion modes of the blade are installed. On the other blades only 7 strain gauges are mounted for validation. On one blade at three radial positions with the most chordwise distributed pressure sensors, temperature sensors are mounted to get information about temperature effects for additional compensation. To reduce slipring noise all the signals are amplified before

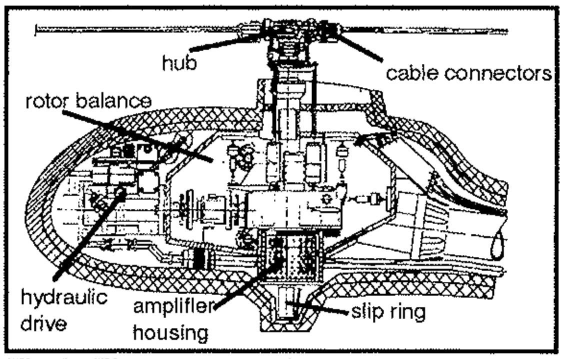

Fig.2: *The rotor test rig*

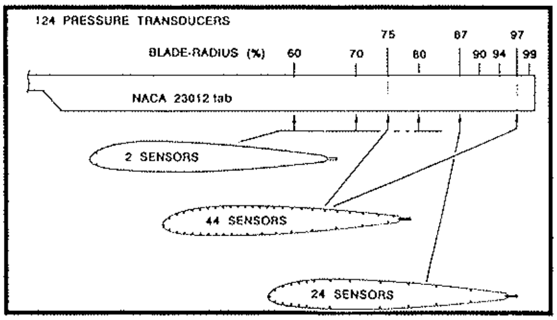

Fig.3: *Pressure transducer distribution*

transmission via the slipring. For further investigations the amplifier and slipring system is designed to transmit 240 signals.

2.2. The data acquisition system

Fig.4 is a schematic overview of the complete rotor data acquisition system (without the acoustic set-up). One of the four blades is equipped with 124 Kulite pressure sensors. 53 further strain gauges, four force transducers, four moment transducers, two angle transducers and three temperature pick-ups are distributed on the other three blades, the blade hub and the rotormast. The signals of all these channels are conveyed to the preamplifiers. After preamplification the signals are fed by the slip ring to the outer system via 60m long cables. As Fig. 4 shows, 190 signals are conveyed to the Transputerbased Expandable Data Acquisition System (TEDAS) and 70 channels lead to the control unit of the rotor test stand. TEDAS subsystem is controlled by the AMIS II measuring system.

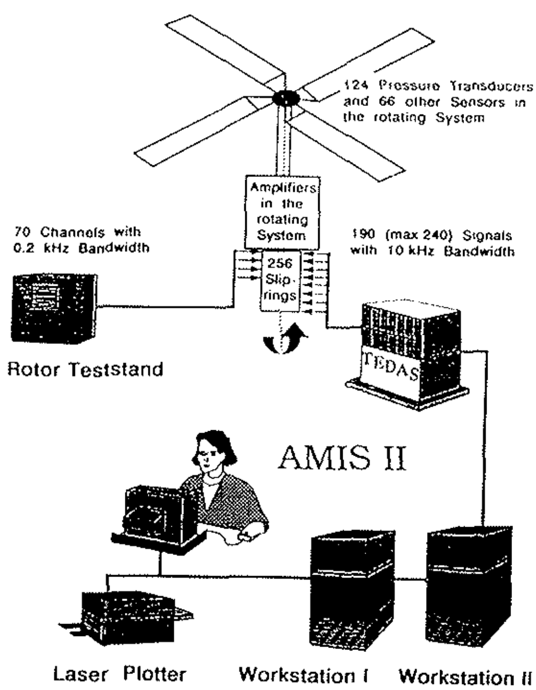

Fig.4: The rotor data acquisition system

3. Description of the AMIS II Measuring system

The AMIS II measuring system is based on the idea to connect the enomous graphic capabilities of modern workstations with a multi channel, operationally efficient digital acquisition system for analog time-changing signals. This connection is of increasing importance, since nowadays in many experiments the number of channels can reach several hundred, and the absolutely necessary on-line controls of the measured data are only possible with fast, distinct graphics.
The workstations also offer the possibility to connect several machines through networks (Ethernet) thus enabling task division. In this measurement the work was divided on three machines. The first controlled the experiment, the second was used for quicklook graphic presentation and the third printed the graphics.

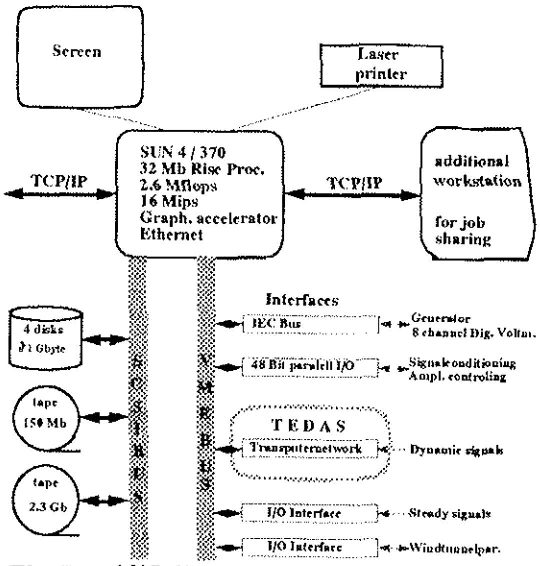

Fig.5: AMIS II components

To obtain a connection from the external data acquisition system with a workstation, the VME bus which allows fast data connection with up to nine external devices was chosen. It should be noted, however, that meanwhile the S-bus offers the same or better characteristics. Fig. 5 shows a scheme of the hardware of the AMIS II system. A 48-bit parallel I/O serves to parameterize by program the pick up preamplifiers. In order to store the large amount of data a four Gigabyte harddisk is provided. For portable data storage an Exabyte tape machine with a capacitiy of 2.3 Gigabytes and a Sun tape recorder with 150 Megabytes is installed.
One substantial component of the measuring system is the bind of the TEDAS data acquisition system to the VME bus of the sun through a special transputer interface.

3.1. The TEDAS Subsystem

For this measuring task the system was developed based on the following 7 thesis:

1. The number of channels has to be expandable to an unknown number in future, thus ensuring a long life cycle of the system.
2. As quicklook is necessary and wind tunnel time is very expensive, the computing power for signal postprocessing has to be scaled with the number of channels.
3. For measurements related to rotor rotation, the measurement is made not in time but in angle domain, thus all parameters have to be scaled with the rotational speed.
4. High resolution and low harmonic distortion is required to observe all dynamic effects without errors.
5. Absolute or DC accuracy is dominated by the sensors and their fitting, not by the acquisition system.
6. At high resolution the antialiasing filters become the dominant cost factor of traditional systems.
7. An absolutely synchronism between the channels is necessary, independant of the number of channels.

Thesis 1. leads to a modular design of equal components resulting in intelligent data acquisition modules (IDAM).

Thesis 2. forces these modules of which the system is composed to have their own processor.

Thesis 3. to 7. say something about the ADC principle to be choosed. Traditional systems use successive approximation converters which consider the Nyquist sampling theorem, have a high order antialiasing filter, provide a DC accuracy which is equal to their resolution, are combined with analog multiplexers and sample and hold circuits and are controlled by one CPU (Fig. 6). The effect is, that most of the effort is spent into the analog components in front of the ADC. Nevertheless the analog filters are not able to be scaled with the rotor speed and add pulse distortion because analog filters can not maintain d /d = constant. Using switched capacitor filters changes the scaling feature against a poor signal to noise ratio < 12 bit). Finally, antialiasing filters for 16 Bit ADC with a sharp cut off behaviour are extremely expensive.

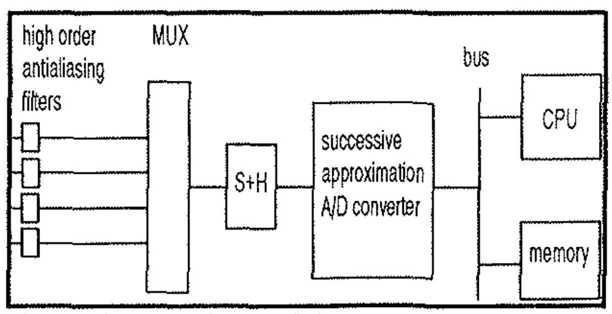

Fig.6: *ConventionalADC*

The solution choosed is the combination of three principles which are seperately known since decades of years, but now are available integrated in one cheap chip:

- Oversampling
- Noise sahping
- Digital filtering
- Decimation

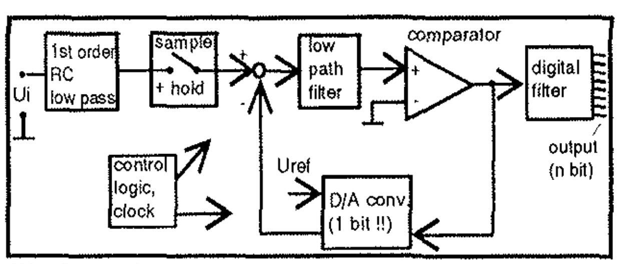

Fig.7: *Delta Sigma ADC*

3.2. Delta Sigma Converters

The delta sigma ADC (Fig.7) is a highly oversampling device which operates at an analog sample rate which is 64 times higher than the required output wordrate. The part of the ADC doing the conversion is called the modulator and performs a one bit conversion. Fig.7 shows that the D/A converter in the feed back loop has only one bit resolution. The advantage of the 1 bit quantizer is that errors in the 1 bit feedback loop do not produce any distortion but only gain and offset errors [2]. As a one bit converter produces a very bad signal to noise ratio [3], the noise inside the spectrum of interest is transformed to an area outside the spectrum of interest. This is called noise shaping.

Noise shaping does not eliminate the noise energy but only transforms the energy into a frequency range where it can be rejected by further digital filtering . In Fig.8 , a simplified analog modulator model, the quantization noise is substituted by the noise source **p.** The transfer function for Din=0 shows the noise distribution at the output. Fig. 9 shows the output of a real modulator in frequency domain.

The sampled and noise shaped signal is then filtered by a FIR (finite impulse response) filter (Fig.11), which has an extremely sharp cutoff (Fig.13) and a very high stopband attenuation (-90dB), while the pass band (Fig.12) is very flat (ripple=+-0.0005dB). By choosing the FIR filter it is possible, to force $d\varphi/d\omega$ = constant thus adding no additional pulse distortion. The filter rejects all components of the sampled signal which are higher than half of the desired word rate. If these components are no longer existent it is allowed to decimate the signal. Decimation describes the fact of taking not all filter outputs but only every n_{th} output and thus reducing the high sampling rate to a handable value for further calculations. The decimation does not violate the Nyquist criterion, because of the previous digital filtering (Fig. 10). In this figure **fs** is the oversampling frequency, **fs´** is the output word frequency an **fb** is the bandwidth of the band of interest. Delta sigma ADC´s are known since several years as components for audio purposes. They appeared because the chip technology now allows to combine analog components (the modulator) and high speed digital components (the FIR filter) on one monolithic chip. The analog part of the chips is only 10% of the die size [4]. The use of these chips in the consumer electronics industry made them very cheap (about 200 DM for a dual ADC). When DLR 3 years ago decided to use delta sigma ADC´s this was one of the first applications to integrate these devices into scientific measurement systems. Meanwhile they appear in several industrial measurement systems. The device chosen by DLR is the CS5329 a 16/18 bit 50 kHz dual ADC from Crystal. This device is currently one with the best performance, it includes auto offset calibration. Fig. 14,15,16 show some important characteristics of this ADC. The DC accuracy is about 12 bit and therefore more than sufficient for this type of application.

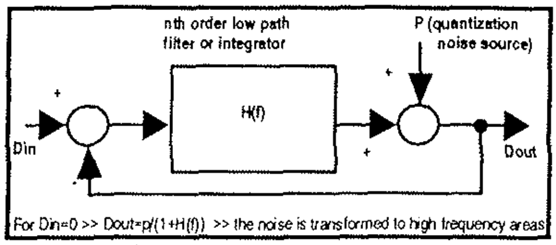

Fig.8: Noise shaping

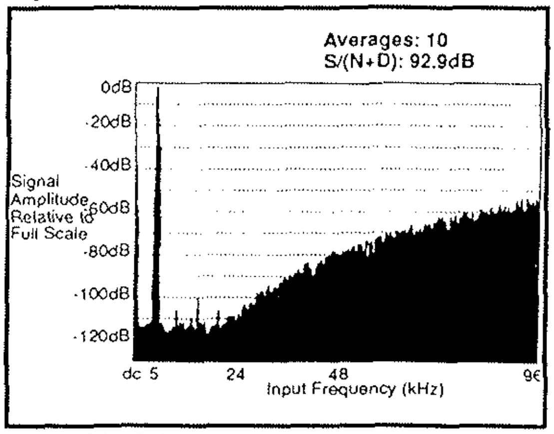

Fig.9: Modulator output

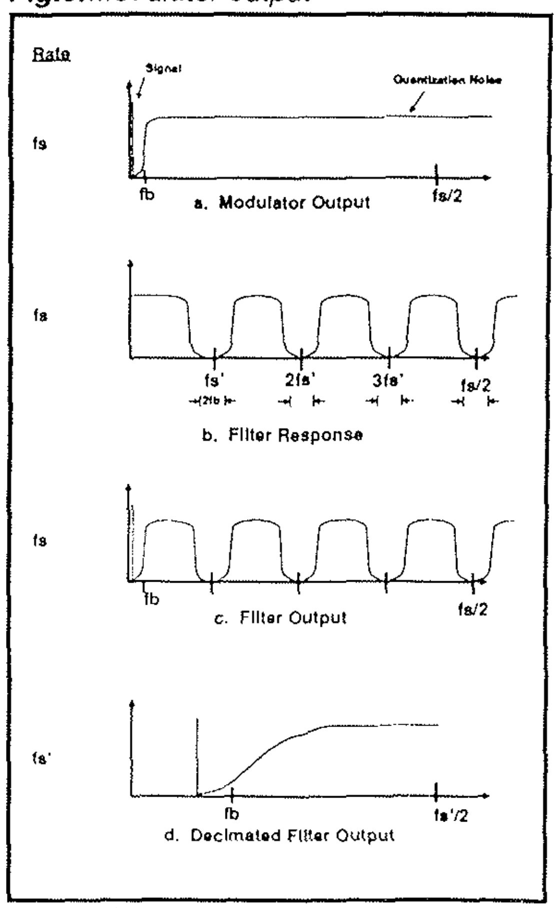

Fig.10: Filter strategy

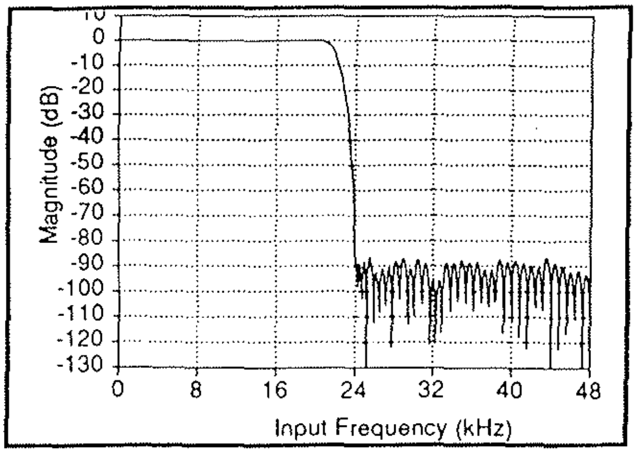

Fig.11: *Filter response*

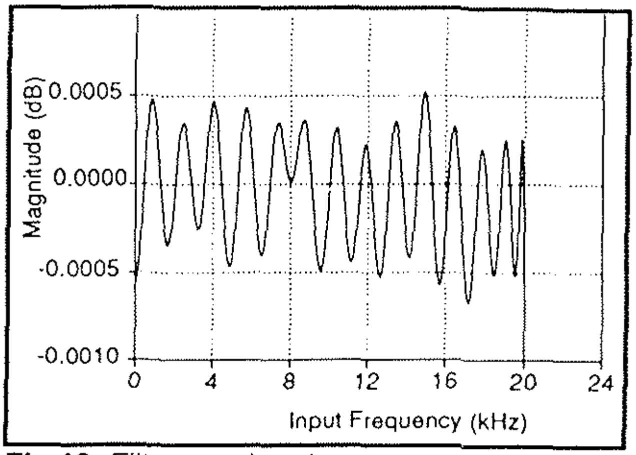

Fig.12: *Filter passband*

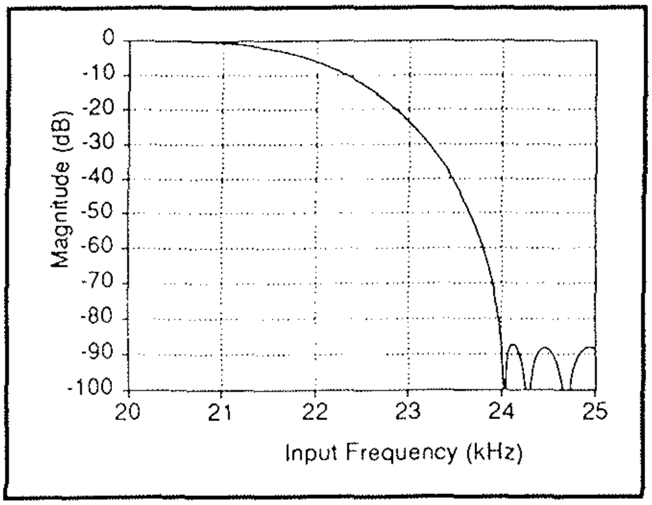

Fig.13: *Transitionband*

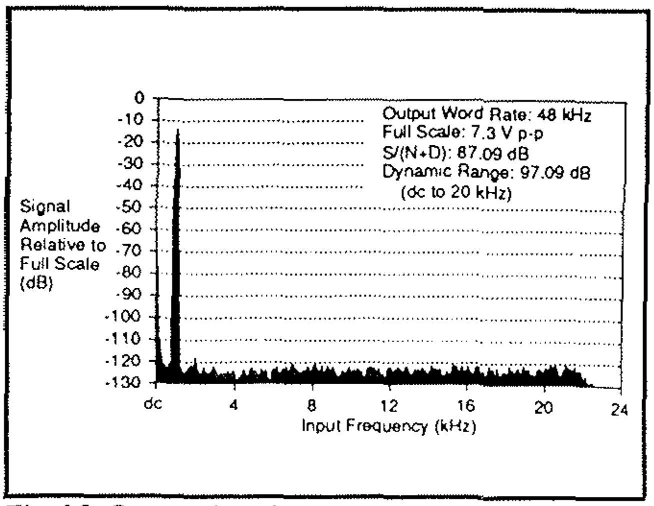

Fig.14: *Spectral purity*

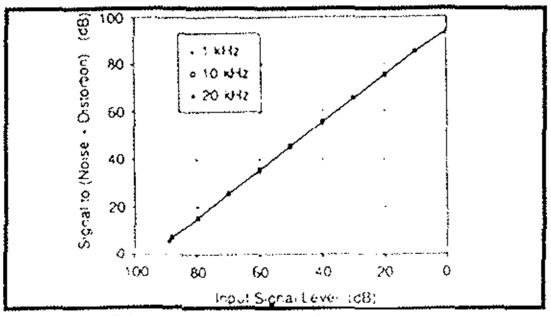

Fig.15: *Signal/noise ratio*

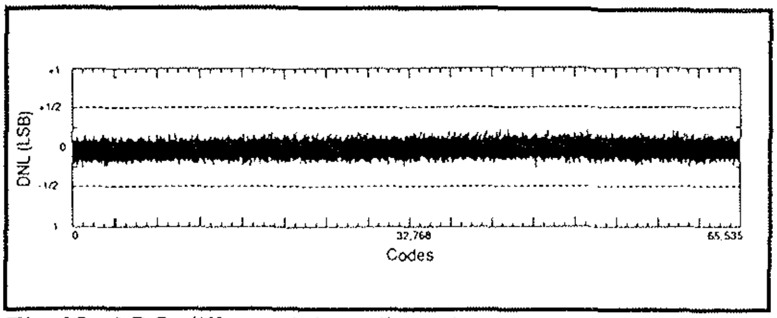

Fig.16: *ADC differential nonlinearity*

3.3. Transputers

As noted, the computational power of the data acquisition system has to scale with the number of channels for fast quicklook, data postprocessing and therefore enforces an economical use of wind tunnel time. This requirement leads to a multiprocessor system without a bottleneck limiting the acquisition bandwidth. Transputers as easy to implement microprocessors support the distribution of programs on a large number of processors by firmware (on chip scheduler, built in link engines for communication), and the corresponding language OCCAM supports an easy abstract description of such normally very complex systems [5,6]. Fig. 17 shows the system layout. The modules are arranged in a pipeline structure which can be expanded unlimited. The transputer communicate via 20 Mbit/s serial full duplex links. Each IDAM contains the same program, which is booted via the serial links by pushing a key on the host. The data is stored in 4 Mbyte on board RAM. As each transputer serves 8 channels, each channel can store about 250 k samples, which corresponds to more than 100 rotor revolutions with 2048 samples/rev. At nominal rotor speed each channel is sampled with 35 kHz.

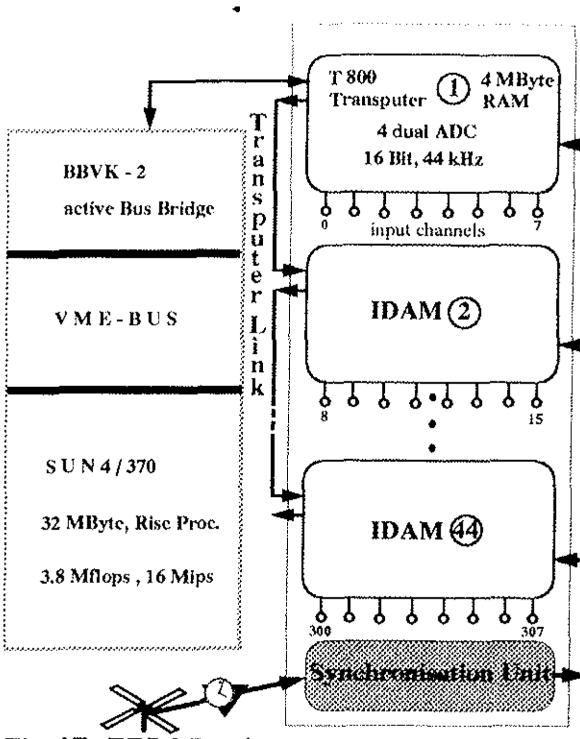

Fig.17: *TEDAS subsystem*

The link of the first transputer is connected to a host adaptor which transformes the serial link protocol to the bus of the connected machine. This can be VME bus Sun, S bus Sun, PC, or VAX. A well defined protocol allows the host to set up a command (like Start Conversion, Compute FFT, Compute Mean Value, Send Raw data, Send FFT Data etc.). Then the subsytem reacts according to the command. The internal structure of the subsystem is completely invisible to the host which only has knowledge of the number of channels and the number of transputers.

3.4. Data precalculation inside the transputers

The transputers are not only used for controlling the ADC's and storage in local memory but also for data precalculation. As each eight channels are served by one transputer, the calculations can be done on several tranputers in parallel. The most intensive calculations are the FFT's. For a 100 rev. measurement one FFT of 2048 points has to be calculated for each revolution. For 240 channels the system has to compute 24000 FFT's of 2048 points each. This takes about 3 minutes. Other calculations which are not so intensive are averaging the FFT's, cross correlation, RMS, mean value, average of several revolutions and other. All calculations inside TEDAS are controlled by host commands. Finally raw data and calculated data can be transfered to the host.

3.5. Synchronization

All transputers and ADC's are synchronized by a synchronisation unit. An incremental encoder mounted on the rotor shaft deliveres two outputs: 1 pulse/rev and 32768 pulses/rev. The first is the zero angle pulse the second is multiplied by 32 using a PLL. With the resulting frequency of 13.7 MHz at nominal rotor speed the ADC's are clocked.
It should be noted, that all mechanisms (conversion, digital filtering etc.) inside the ADC are exactly scale with the current rotor speed unlike high order analog antialiasing filters in front of conventional systems. These filters, used in traditional systems work strictly in time domain which is in opposite to the sampling process and to further calculations which per definitione work in angle domain. If there are variations of the rotor speed during one revolution, which is the normal

case, all parts of a measurement system which are not able to scale with the actual speed produce errors.
As in this oversampling system the only part not able to scale is a simple 1st oder RC low pass filter in front of the ADC such errors are minimized.
A more detailed discussion about the ADC principle and the use of transputers can be found in [7,8].

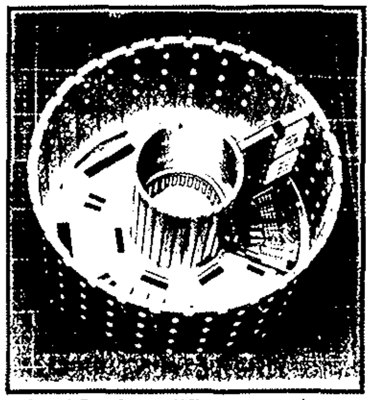

Fig.18: Amplifier housing

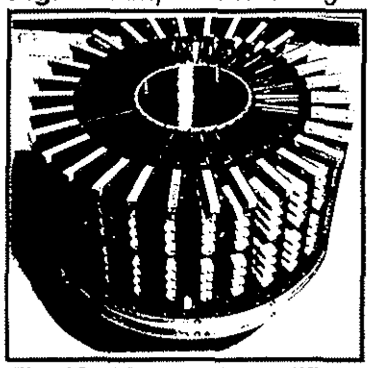

Fig.19: Mounted amplifiers

3.6. The Amplifier Subsystem

As the signals from the rotating system have a small amplitude, they are amplified before they are fed through the slip ring to the inertial part of the system. The amplifiers have been developed from the Institute of Aeroelasticity in Göttingen. Based on a conventional design they have been redesigned with the goal to miniaturize them. The result is a hybrid amplifier in a 24 pin DIP (Fig.21) which was originally built on a eurocard (100x120 mm) (Fig.20). The technical data of this bridge amplifier are:

Size:	35mm x 12.6mm x 5mm
Power:	+-15V, 6mA;
Bridge Supply:	5V or 10 V,20mA
Amplifier factors:	programmable, 50,125,250,500
Output:	50mA for 50 Ohm loads
Bandwidth:	0 to 20kHz
Offset:	programmable auto zero

Error detection:

No mass present on Bridge	ouput ca. +15 V
+Input to the amplifier defective	output ca. +15V
- Input to the amplifier defective	output ca. -15V

Overload protection: up to 100V

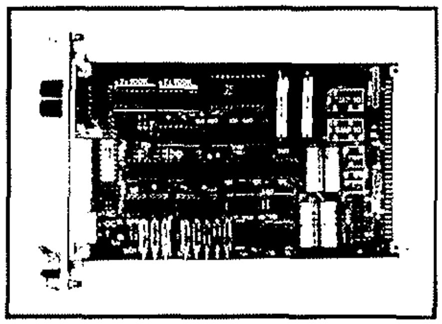

Fig.20: Old amplifier design

The parameters of the amplifiers are programmed from the SUN hostcomputer via a parallel output interface. Each amplifier is separately programmable.
The housing of the amplifier is a cylinder of 250mm diameter and 150mm height (Fig.18,19). The cylinder contains the amplifiers for up to 240 channels.

3.7. The Slip Ring Subsystem

The mounted slipring (Typ RU 4561) is a serial product of Poly Scientific. The slipring has 256 circuits (rings), a lenght of 10.5 inch and a diameter of 2.5 inch.
At a speed of about 1050 rpm there are no problems with handling. In periods of 15 minutes a volume of about 6 ccm cleaning and lubrication fluid is sprayed by air pressure over the sliprings. By online signal observation the status of the slipring is controlled.
The slipring was only used for the transmission of the sensor signals and signals for the amplifier control. The power for the sensors and the amplifier was transmitted by an additional solid slipring unit.

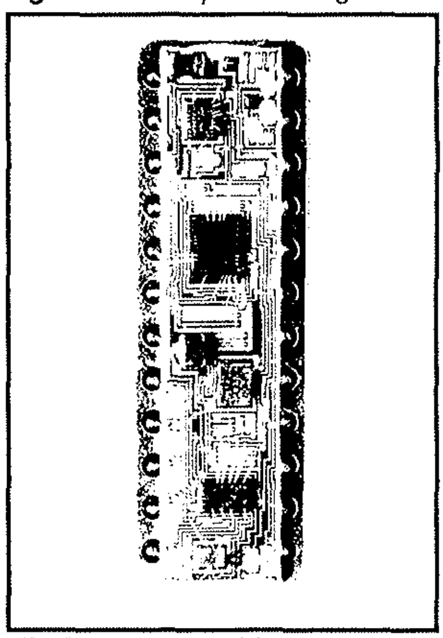

Fig.21: New hybrid amplifier

4. The Measurements

Fig. 22 shows a flowchart of the windtunnel measuring cycle. Measurement begins with the manual start of the main program.
After that, using an RS232 cable and the communications program KERMIT, the parameters of the wind tunnel and of the rotor conditions are read from the computer of the rotor test stand. This includes the actual measurement point number which then designates the measurement data. Next, the transputer subsystem TEDAS is initialized, which means that the corresponding transputer programs and parameters are down loaded. TEDAS is now ready to measure. After a manual start command, the system waits for the next zero passage of the rotor angle and then starts to simultaneously sample all channels. After all data are sampled and stored in RAM the desired precalculations are initialized by host commands (FFT, mean values, time mean, etc.). When all calculations are done, the mesasured data and the calulated data can be transfered to the host via a link cable by appropriate commands to be stored on host disk files.
On the host the data is prepared for the quicklock presentation of the lists and plots. As mentioned earlier, these tasks are distributed on three workstations to save time. After examination of the quicklook results by the operators the system is ready for the next measurement cycle.

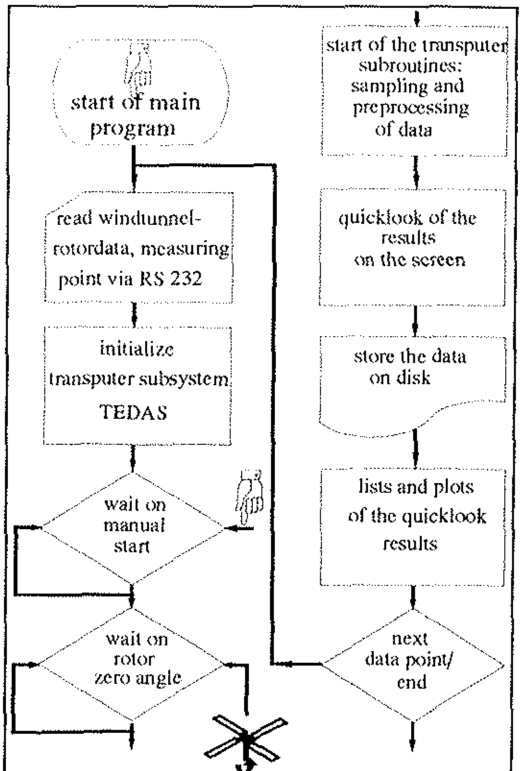

Fig.22: AMIS II measurement cycle

4.1. AMIS II System Software

An essential part of the measuring system is the operational software (Fig. 23). The software can be divided into three main parts:

- device software,
- evaluation software,
- visualization programs.

Device software: This group contains the programs for experiment definition and execution. The experimentally specific definitions of the model, the pick-ups, the wind tunnel and the measurement parameters are entered here. The actual measurement program carries out the measuring procedure in single steps. As a

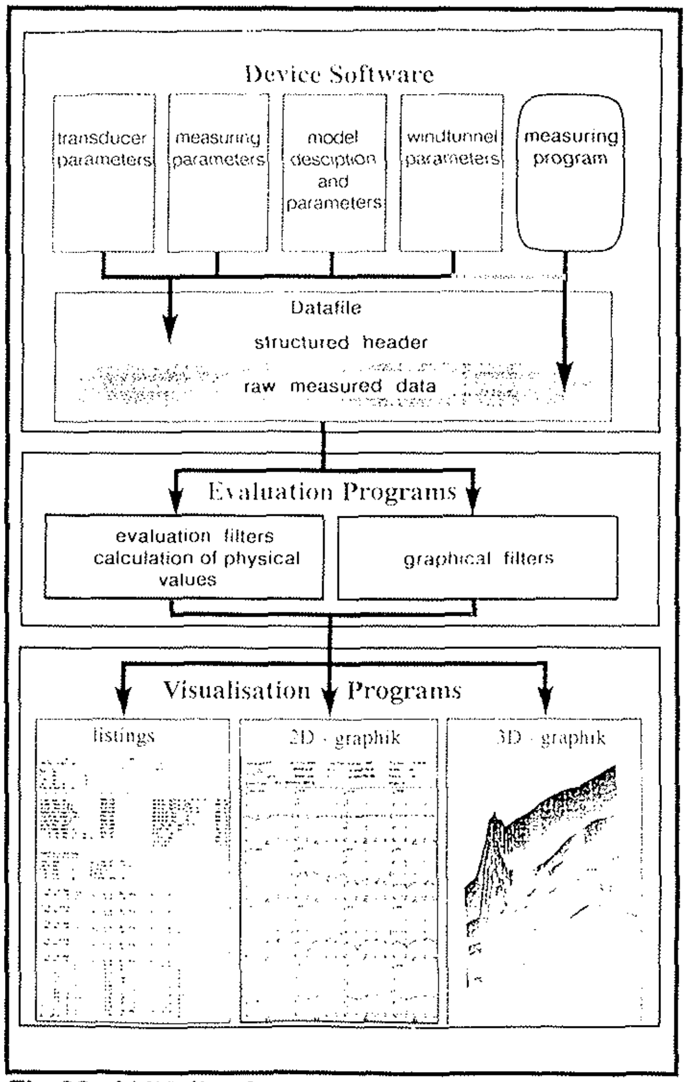

Fig.23: AMIS II software

result, a data file whose structure is made of a data header and a data field of the raw measurement data is built. The header contains all of the entered or measured values which are relevant for the measurement and for further analysis and presentation (scaling factors, time stamp etc.).

Evaluation programs: This group includes the programs that can read the raw data files and transform them into a suitable form according to the intended purpose. These are for example, filterprograms for measurement list preparation or filter programs that bring the data structure into a form readable by graphic programs, as well as programs that calculate the corrected physical dimensions from the raw data.

Visualization programs: This group comprises the programs for the visualization and output of the measurement results. The result can be given in list form, where either plots or computer screen presentations can be chosen. A very fast program based on XGL is used as the 2D graphic for the quicklook of the data. In addition, the public domain program XVGR with specially manufactured layouts is utilized. Its graphic presentations can be printed as postscript files with high quality using a laser printer. For 3D graphics the program AVS is used, also containig layouts manufacured specially for the specific measurement requirements.

4.2. The Data Presentation

Fig. 24 and Fig. 25 show the leading edge pressure time history of one sensor as single revolution and as average of 60 revolutions. The average time history is very close to the single revolution except in the rear of the disk where the hub turbulences interact with the blades. Fig. 25 gives an impression of the leading edge pressure distribution (first 10 harmonics sustracted) and BVI locations in the rotor disk on the upper side.

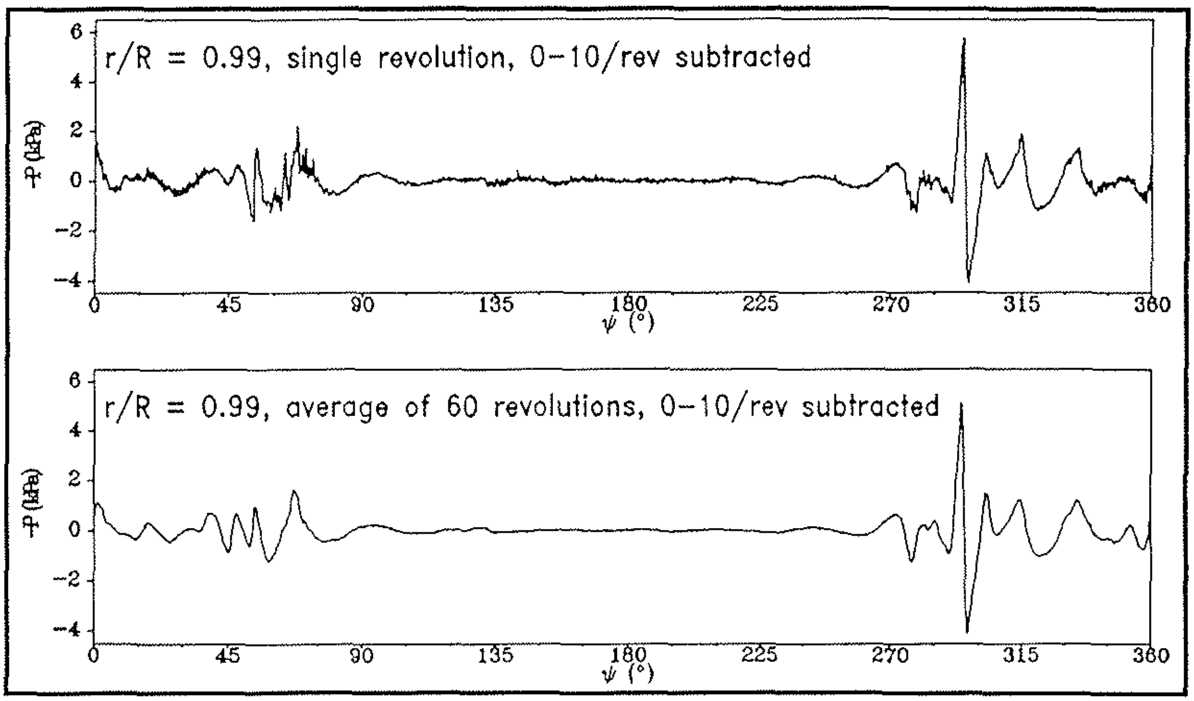

Fig.24: *Leading edge pressure time history*

As this paper focusses more the aspects of data acquisition methodologies a detailed presentation of the results will be given in [9] and [10].

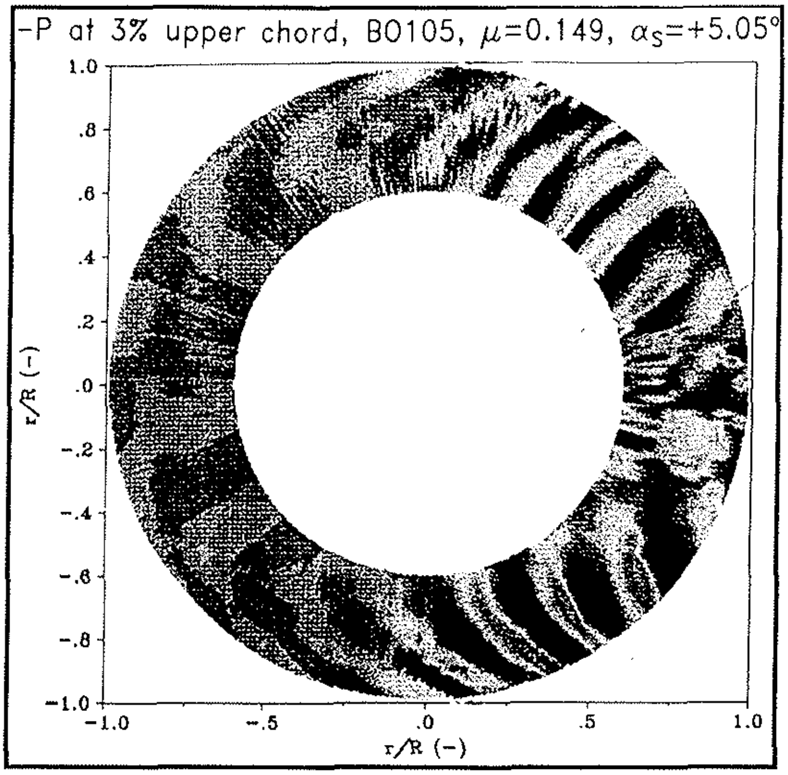

Fig.25: *Leading edge pressure distribution with BVI effects*

5. Results and Conclusion

Presently rotoracoustics and unsteady rotor aerodynamics play an increasing role in the area of helicopter research. This leads to requirements adressed to the data acquisition which can not be matched using traditional systems. While until now channel counts of 64 or 128 with sample rates up to several harmonics of the rotor speed were sufficient, now the channel count increases by an order of ten and the sample rate required is some thousand per rev. . This results in sum data rates of several 10 Mbytes per second. A complete new system architecture resulted in a modular multiprocessor system based on transputers. Because of the virtual unlimited number of channels this design should also match future requirements. The shift of data reduction and preprocessing into the frontend processors helps to get fast quicklook data and thus saves expensive windtunnel time. The combination of such an intelligent ADC frontend with the power of modern workstations of any type gives a strict separation from operative tasks like the pure data acquisition and precalculation against dispositive tasks like the data evaluation and the measurement concept.
A further advantage of the described system is the analysis of the type of A/D converter and the selection of that type giving the best results at lowest costs. Using delta sigma converters most of the analog processing of previous systems could be shifted into digital domain and at the same time allows nearly all of the system to scale with the actual rotor speed. This assures better reproducabilty by shifting from time domain into angle domain.
The development of very small preamplifiers sitting inside the rotating part allowed to avoid slip ring transmission errors.
Overall the first measurement campaign using this system delivered highly reproducable data with high resolution. Thus the number of averages over lots of revolutions can be reduced which again results in save of windtunnel time.
Currently 4 ADC subsytems of TEDAS have been built for different DLR internal users. These also include sample rates per channel up to 80 kHz and local memory per IDAM of 16 Mbyte.

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