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AERODYNAMIC FAST-RESPONSE PROBE MEASUREMENT SYSTEMS: STATE OF DEVELOPMENT, LIMITATIONS AND FUTURE TRENDS

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Aerodynamic Fast-Response Probe Measurement Systems: State of Development, Limitations and Future Trends

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The current development state of the fast-response aerodynamic probe (FRAP) measurement system developed at the Turbomachinery Laboratory of the ETH Zurich is presented. Aspects of probe design, miniature pressure sensors and microfabrication technology are discussed for several in-house built miniature probes. Additionally, new probe designs are presented. The calibration steps for measurements with the FRAP system are discussed. The data acquisition system used and the specially developed data processing software environment are described.

Limitations of present high performance FRAP systems are shown to be due to the probe body (size and geometry), sensors (signal to noise ratio, temperature range and stability), and data processing procedures (computing performance). Potential future development trends are outlined.

INTRODUCTION

A fast-response aerodynamic probe measurement system is under development at the ETH Turbomachinery Laboratory in order to gain a better appreciation of turbulence phenomena and unsteady flow patterns through the rotating components of turbomachines. This permits the improvement in the quality of predictions, enhancements of new machine designs and validation of CFD codes.

One of the main advantages of fast-response aerodynamic probes over hot wires is their robustness and insusceptibility to foreign particle contamination. In contrast to highly sophisticated non intrusive laser techniques (LDA/L2F) fast response probes are easier to use for measurements in turbomachines and provide a higher signal-to-noise ratio. Additionally, not only the time dependent flow vector but also the static and the total pressure of the flow can be determined by using this technique.

With the availability of miniature silicon pressure sensors the development of fast-response probes became possible two decades ago. The sensors of the first multihole probe generation were located in the shaft because of their relatively large size (SENOO et al. 1973, MATSUNAGA et al. 1978). Due to the bandwidth of about 1 kHz the application was limited to water experiments.

With further miniaturisation it became possible to place the sensors closer to the measuring point and thus to enhance the bandwidth of the measurement, making miniature probes available for turbomachines. Shreeve et al (1978 and later) performed measurements with miniature fast-response Pitot tubes (Ø2.4 and 1.6 mm) in high speed compressor flows.

A spherical probe (Ø 5 mm) with 5 sensors was built by Kerrebrock et al (1980), a similar concept was realised by Larguier (1985) and Ng / Poppernack (1987). Epstein (1985) developed a circular cylinder probe with Ø 3.3 mm accommodating 4 sensors. Since 1983, several publications reported on the development of wedge type probes with up to 4 miniature sensors (i.e. Heneka 1983, Ruck 1987, Bubeck 1989, Cook 1989, AINSWORTH et al 1994).

The objective of the research project at the ETHZ Turbomachinery Laboratory - supported by the Swiss National Science Fund - is to investigate the different fields involved in the development of a complete measurement system. This comprises pressure sensor technology, probe aerodynamics, probe design and manufacturing, calibration with corresponding facilities and finally data acquisition and processing systems.

2. PROBE TECHNOLOGY

2.1 DESIGN PROCESS

Important aspects from several fields have to be balanced for the design of new probes:

- *Optimal probe geometry,* dictated by *aerodynamic aspects.* Some characteristics required and their dependence on geometry and size are listed in Table 2.1-1.
- *Probe size reduction.* This aspect is of utmost importance in turbomachine flows (Table 2.1-1). The size of intruded probes must be minimal to enhance both spatial and time resolution. Additionally, dynamic aerodynamic errors and flow disturbances are also significantly reduced. Limitations are mainly set by the *sensor chip's size* and the *microfabrication technology* used.
- *Optimal packaging technique:* an adequate sensor chip encapsulation is crucial to minimise the probe size and the pressure measurement errors. This can be achieved by reducing both thermal and mechanical stresses between the chip and the probe body. Miniature electrical and pneumatic connections must be provided to feed the sensors, as well as the environmental protection of the probe components to achieve a high robustness.

Required Characteristics	*Dependence*	
Static considerations	**Geometry**	**Size**
Measurement of total and static pressure	X	
Angular sensitivity	X	
Angular calibration range	X	
Re dependence	X	X
M dependence	X	
Modeling of calibration data	X	
Reduction of static errors due to...		
• velocity gradients	X	X
• blockage		X
Dynamic considerations	**Geometry**	**Size**
Reduction of dynamic errors due to...		
• circulation (lift)	X	X
• dynamic stall effects	X	(X)
• inertia effects	X	X
• Kármán vortex interactions	X	X
• synchronisation of the Kármán vortices	(X)	X

Table 2.1-1 *Dependence of required probe characteristics on probe size and geometry*

2.2 PROBE AERODYNAMICS

It has been found that the use of fast-response probes designed according to conventional pneumatic probe considerations can lead to significant errors if used in fluctuating flows such as inside turbomachines. Investigations concerning dynamic effects on fast-response measurements have demonstrated the influence of the *probe's size and geometry* (HUMM, GOSSWEILER, GYARMATHY, 1994). The majority of the measurement errors are directly proportional to the probe size. Additionally, the probe geometry plays an important role. Some of the most severe measurement errors are due to dynamic stall effects. These transient phenomena, which cannot be mathematically treated, lead to inevitable errors. This was found to be peculiar for wedge type probes and such the authors postulate that wedge probes are not ideal for measurements in turbomachines. Generally, circular cylinders are best suited for this purpose.

2.3 PRESSURE SENSOR CHIPS

The miniature piezoresistive pressure sensor chips are generally made of monocrystalline silicon manufactured in a planar process. The diaphragm containing a Wheatstone bridge is micromachined by etching or grinding. New types of miniature chips are routinely evaluated and tested in the sensor test facility (described in Section 3.1.a) for several weeks determining whether they are suited for probe applications. Here after, 10 to 70% of the chips (depending on the type) are suited for encapsulation in probes.

Type	Chip size [mm]			Sensitivity	Sensitivity at P_D=5mW	Max. temp. of use	Gauge Resistance
	L	W	H	[mV/Vbar]	[mV/bar]	T_{max}	R_e
Keller 1026	2.0	1.0	0.5	8...30	38...145	120°C	4.7 kΩ
Keller 2927	2.0	1.0	0.5	7...15	30...62	120°C	3.6 kΩ
IMT Kloeck A	2.6	1.1	0.38	15	45	120°C	1.7 kΩ
IMT Kloeck C	2.6	1.1	0.38	20	60	120°C	1.7 kΩ
IMT Polycryst. Silicon	2.8	1.4	0.38	≈ 3	≈ 17	210°C	4...8 kΩ
Ascom CP 731	1.5	1.2	0.38	20	62	120°C	2.0 kΩ
Ascom CP 732	1.46	0.94	0.38	7	30	120°C	4.0 kΩ
Sensym P788	1.68	0.59	0.15	8...19	40...94	120°C	4...6 kΩ

Table 2.3-1 *Comparison of miniature pressure sensor chips (GOSSWEILER 1993)*

Although the excitation power P_D of the Wheatstone bridge is only 5 mW, a high *pressure sensitivity* of 30 ... 145 mV/bar is achieved (Table 2.3-1). For this reason, the self heating of the resistors due to electrical power is negligible and an improvement of the long-term stability of the DC signal improved. Unfortunately, an excitation of the bridge with only 5 mW is not always possible: Compared with a Sensym P788 ($S_{P_D=5\,mW}$ = 40 ... 94 mV/bar), the Kulite CQ-030 sensor (Ø 0.813 mm) used for probes of similar size shows a sensitivity of only $S_{P_D} \approx 2$ mV/bar.

Due to thermal resistor noise effects (p-n junction between resistors and chip diaphragm), the upper *temperature limit* of use for sensor chips made of monocrystalline silicon is 120°C. Operating temperatures up to 210°C are possible with polycrystalline silicon chips by insulating the resistors from the diaphragm with SiO_2 (VAN DER WIEL et al 1989). Such chips with comparable miniature size and sensitivity seem to be not yet commercially available. The thermal noise U_n (RMS) of a resistor R_e shown in Fig. 2.3-2 can be described with $U_n^2 = 4\,k\,T\,R_e\,\Delta f$ [V] (Δf: signal bandwidth; k: Boltzmann constant; T: temperature). The rapid thermal noise increase of monocrystalline silicon illustrates the p-n junction effect in semi-conductor devices.

For flow measurements in turbomachines, higher temperature limits of the order of 400°C are of great interest. This could be attained with the "silicon on sapphire" (SOS) chip technology (ANAGOSTOPOULOS and KELLER, 1988). Some prototypes have been developed, but the size is still too large and the sensitivity too low for an encapsulation in miniature probes.

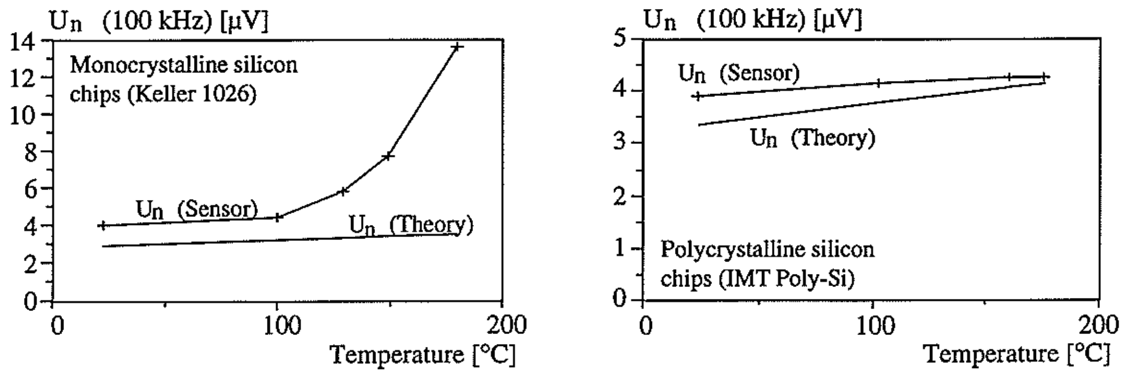


Fig. 2.3-2 *Thermal resistor noise of monocristalline and polycrystalline sensor chips for the bandwidth Δf = 100 kHz compared to a non-semi-conductor resistor (RMS values)*

2.4 MICROFABRICATION TECHNOLOGY

The ultimate goal of probe design - the probe miniaturisation - is not only limited by the size of the sensor chip but also by the technologies available to manufacture the probe components. The accuracy of conventional machining sets a limit for fabricating smallest parts both from the economical and from the technical point of view; the relative accuracy of the machine compared to the component's size decreases rapidly. For instance, an accurate positioning of pressure taps on probe bodies or a sealed fit of parts becomes very difficult with further miniaturisation. The four sensor probe with outer diameter of 2.5 mm shown in Section 2.6 is probably at the lower size limit for such conventional machining processes.

To surpass these limitations and make smaller probes available not only as prototypes, a few ideas from watch industry have been adopted, such as wirecut and diesinking electro discharge machining. Benefits from these techniques are a high precision even for complex geometries and the ability to produce small series at constant high accuracy.

2.5 PACKAGING TECHNIQUE

In the majority of publications, the results gained from FRAP measurements are confined to the AC part of the flow signal. Inevitable sensor drift of the pressure signal results in inaccurate DC measurement. A goal of both pressure sensor technology and packaging technique was to improve the long-term stability of the signal and thus enable direct *DC measurements with fast-response probes* even at low Mach numbers.

The final properties of the probe, especially the temperature behaviour of the chip/body ensemble, are strongly affected by the packaging technique. To avoid thermal induced stress on the silicon sensor chip, the bodies of the probes are made of nickel alloy to match the thermal expansion coefficient of silicon. Two bonding concepts are possible:

- *Soft bonding:* The sensors are bonded to the probe body with soft silastomers to ensure a mechanical decoupling by yielding between chip and probe body. As a disadvantage, this method induces *creep* of the pressure signal zero (decreasing towards zero) under pressure influence due to the silicone adhesive (below 0.05% FS). This can be corrected by pre-applying pressure before measurement. Temperature hysteresis effects (shown in Fig. 2.5-1 for 2 temperature cycles) due to the adhesive used are typically of the order of 1.5 mbar (0.15% FS) over a temperature range of 40°C. They may not influence the measurements if the probe is heated up to the temperature of use.
- *Hard bonding:* Used sometimes. Unfortunately, epoxy adhesives were found to be too sensitive to air humidity and show dramatic changes of their properties beyond the glass transition temperature T_g around 100°C (Fig. 2.5-3) for most epoxies (-90°C for silicone adhesives).

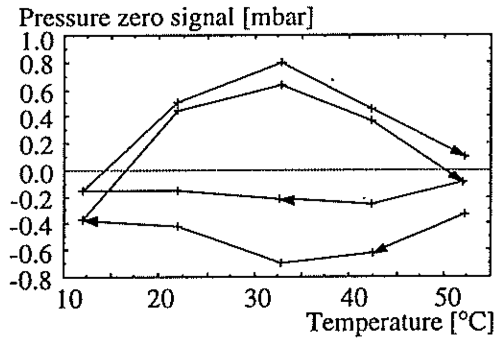


Fig. 2.5-1 *Typical temperature hysteresis of the pressure signal after 2 temperature cycles*

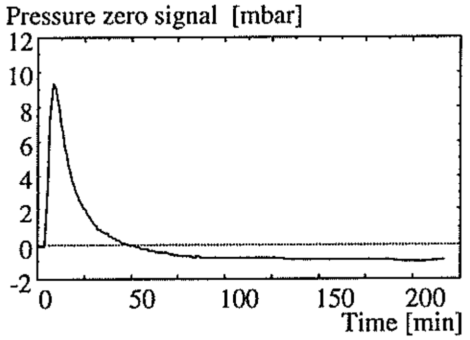


Fig. 2.5-2 *Thermal induced dynamic error of the pressure signal zero (with* $T_S \approx 30°C$ *)*

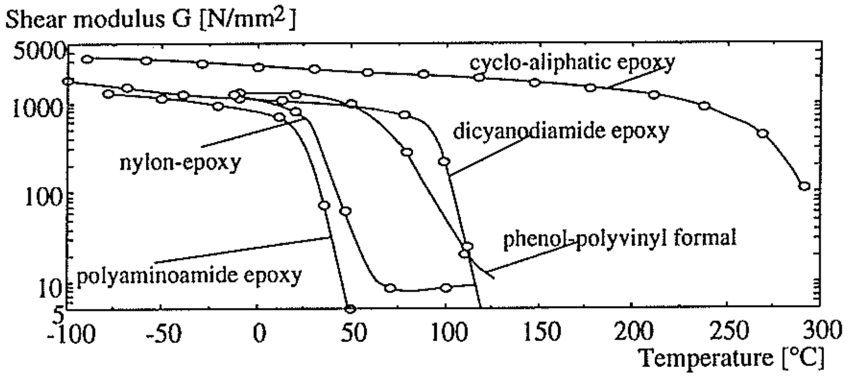


Fig. 2.5-3 *Mechanical properties of epoxy adhesives (HABENICHT 1986)*

Thermal transient effects may cause severe measurement errors (Fig. 2.5-2, for a temperature step T_S of 30°C). Soft-bonded pressure sensors show smaller maximum deviations of the indicated pressure signal, which decays towards zero within one hour.

Experiments of GOSSWEILER 1993 with soft and hard bonding of sensor chips revealed that the use of epoxy adhesives leads to dramatic offsets of the chip's pressure signal zero due to residual thermal stresses caused by hard bonding at higher curing temperatures (up to 280 mbar). In oppostion, the signal zero of soft bonded chips remains almost constant (deviation: -1 ... 8 mbar) due to yield typical for silastomer adhesives.

Most of the effects described above may be corrected by applying an adequate strategy when the measurements are taken (i.e. pre-heating of the probe, in-situ adjustments of signal offsets and gains). Thermal stress can also be reduced by manufacturing the probes from material with a thermal expansion coefficient similar to the sensor's (i.e. borosilicate glass such as Pyrex 7740 or silicon).

The chips are not used as absolute pressure sensors but in the differential mode only. Such the probe interior can be kept on an accurately known reference pressure level, controlled with a external pneumatic regulator valve. The advantages of this method are:

- the pressure difference on the chip diaphragm can be hold in a small range, enabling the use of chips with low FS range with best sensitivity and accuracy even for high absolute pressure applications
- to improve the accuracy the reference pressure is chosen in order to achieve chip diaphragm deflections in one direction only
- in-situ sensor offset adjustments are easy to perform.

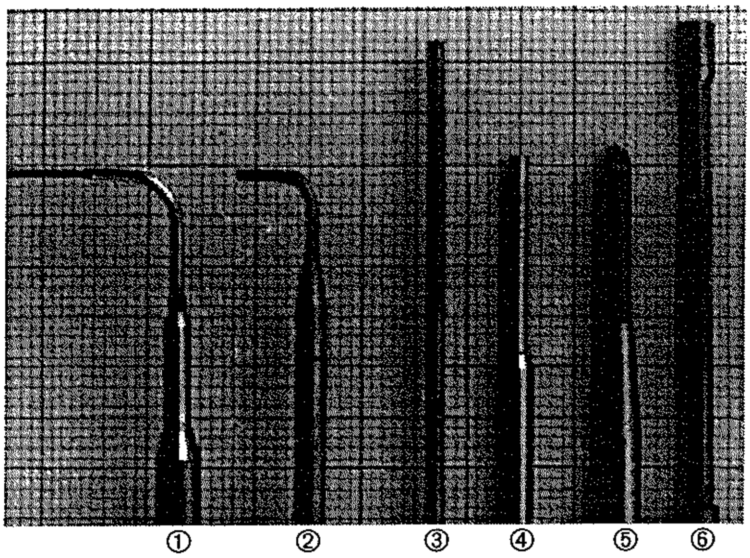
2.6 PROBES

All the probes shown in Figure 2.6-1 have been manufactured in-house in order to test and improve each fabrication step. The probe designs, ranging from small Pitot tubes with 1 sensor up to cylindrical probes with 4 sensors, are listed in Table 2.6-2.

A prototype Pitot-type probe with a tip diameter of 0.84 mm (Fig. 2.6-3) has been newly developed to investigate microtechnologies such as body parts fabrication, electric connections and packaging concepts - beside all aerodynamic benefits of such a size. The sensor chip is located at 0.4 mm from the probe tip. The resonance frequency of 46 kHz of the open tip cavity was determined experimentally and theoretically. Despite the miniature size of the probe and the chip, a high pressure-sensitivity of 90 mV/bar at 5 mW excitation power is achieved.

Contrary to wedge probe designs where the sensors are surface-mounted, all cylindrical probes shown accommodate the sensors inside the body to enhance the probe robustness (sensor connection bonds and active diaphragm protected from particle impact) as well as the accuracy of the pressure tap locations. This is a wedge probe's disadvantage, since the positioning of the pressure sensor chips in the side faces of the probe has a dominating influence on the aerodynamic behaviour. Silastomer coatings or screens on the sensor's surface are necessary to prevent the active diaphragm and the bonds from damages and to maintain the aerodynamic shape of the probe. More information about the 1-sensor probe (Ø 1.80 mm) and the 4-sensor probe (Ø 2.50 mm) is given in GOSSWEILER, HUMM and KUPFERSCHMIED 1990.

A new cylindrical 3-sensor probe generation, with a diameter of only Ø 1.80 mm, is under construction. The design is dedicated to flow measurements in configurations where 2-D flow effects dominate. Measurements are planned to study thoroughly the diffuser region of the research impeller formerly investigated with 1-sensor fast-response probes (see HUNZIKER et al, 1990 and GYARMATHY et al, 1991).



① Pitot tube, Ø0.84 (P1LS08)

② Pitot tube, Ø1.20 (P1LS12)

③ Circular cylinder, Ø1.8 (Z1LS18)

④ Circular cylinder, Ø1.8 (C3LS18)

⑤ Circular cylinder, Ø 2.5 (Z4LS25)

⑥ Wedge, apex angle 55° (W2LS31)

Fig. 2.6-1 *Overview of in-house built fast-response probe types*

Type	Shape	Sensors	Size [mm]	Estimated techn. limit (Chapter 2.7)	Typical sensitivity at $P_D = 5$ mW	f_{Res} (tested)
P1LS08	Pitot type	1	Ø 0.84	Ø 0.8 mm	80..90 mV/bar	46 kHz
P1LS12	Pitot type	1	Ø 1.20	see above	50..60 mV/bar	43 kHz
Z1LS18	Circular cylinder	1	Ø 1.80	Ø1.0 mm	50..60 mV/bar	70..80
C3LS18	Circular cylinder (under develop.)	3	Ø 1.80	Ø 1.6 mm	80..90 mV/bar	>80 kHz
Z4LS25	Circular cylinder	4	Ø 2.50	Ø 1.8 mm	50..60 mV/bar	70..80
W2LS31	Wedge (apex angle 55°)	2	3.10	1.8 mm	50..60 mV/bar	

Table 2.6-2 *Characteristics of different in-house built probe types*

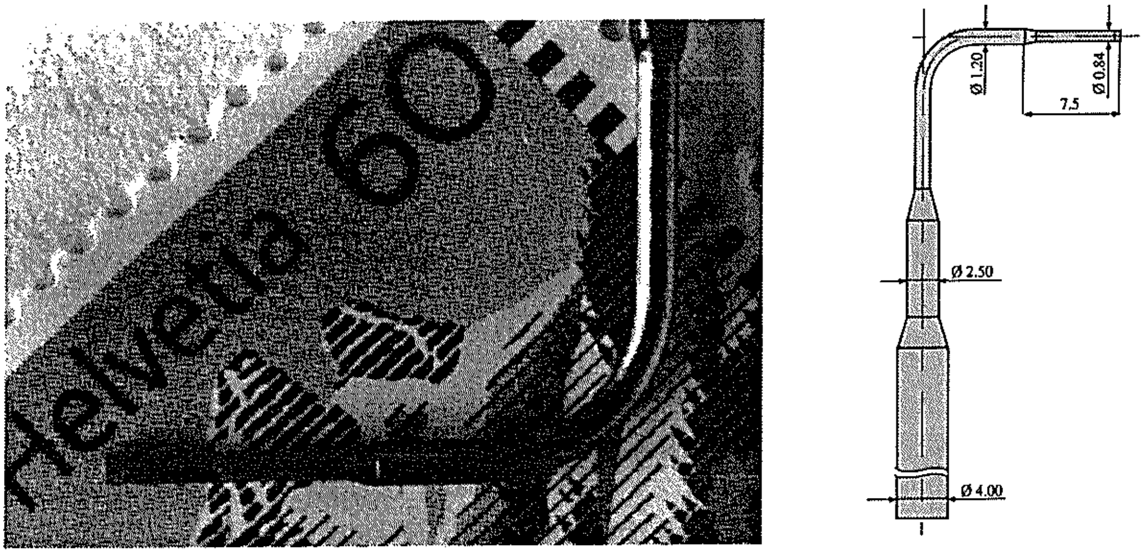


Fig. 2.6-3 *Miniature fast-response Pitot tube (Ø 0.84 mm)*

2.7 LIMITS OF MINIATURISATION

The availability of sensor chips featuring good qualities with smallest size sets a first limit to the probe miniaturisation. A chip cross section of about 0.70 ... 0.60 mm x 0.15 ... 0.20 mm is currently a rigid design parameter. The machine tools available, the mechanical precision and the related costs of the ensemble is the second limit to further miniaturisation. A third limit is set by the technology used to connect the chips electrically from their bonding wires (Ø20 ... 25 μm) through the probe shaft to the amplifiers and power supplies. Since the probe design philosophy is to use the sensors in the differential pressure mode, a reference pressure feed must also be provided. The application of the new technical solutions developed for the Pitot type probe (tip Ø 0.84 mm) to future probe generations would allow the lower size limits listed in table 2.6-2.

Finally, static and dynamic probe strength considerations play a role with decreasing probe size. A Ø 0.84 mm Pitot probe was used to determine the total pressure fluctuation profile of a circular jet (nozzle diameter D_N = 100 mm) at a nozzle exit distance x/D_N of 1.0. Spectral densities recorded in a traverse from the jet border region towards the jet axis revealed several peaks when the probe was in the centre area (Fig. 2.7-1), which are in good accordance with the natural frequency and higher harmonics of the thin probe shaft (Ø1.2, 2.5 up to 4.0 mm, see Fig. 2.6-3). The 3rd peak at 3750 Hz corresponds to a Kármán's vortex excitation. For these reasons, a careful shaft design is also required with decreasing probe dimensions to avoid perturbations due to probe vibrations.

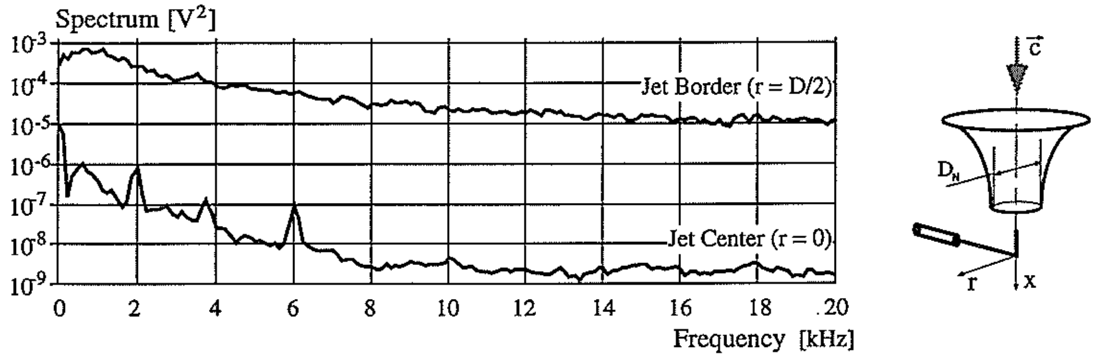


Fig. 2.7-1 Spectra of total pressure fluctuations in a circular jet (D_N = 100 mm, M = 0.2)

3. CALIBRATION PROCEDURES

3.1 CALIBRATION AND CALIBRATION FACILITIES

Prior to the measurements the completed probes are calibrated in four steps :

a. Electrical calibration of the sensors in an closed chamber at a temperature and a pressure range matching the application conditions. An automatic test facility (Fig. 3.1-1) has been developed for this purpose and runs calibration programs without assistance for weeks. The probes are placed into an industry oven in which the temperature is kept stepwise constant within ±0.02°C. According to the calibration parameters and time schedule chosen at the beginning of the calibration run, several pressure levels are regularly applied on the probes with a computer controlled reference pressure device. The electrical signals of the sensors and the test parameters (i.e. temperature, pressure and air humidity) are collected by computer via a scanner voltmeter (20 bit resolution) and a reference pressure sensor (ParoScientific "Digiquartz"). A typical calibration cycle takes several days - each temperature step lasting 12 ... 48 hours.

The sensor characteristics recorded as functions of excitation and output signals are modelled with polynomials to enable the conversion of the sensor signals into pressure and temperature for later data processing. The high accuracy achieved with this numerical approach makes any electric compensation circuitry for temperature effects obsolete and takes non-linearities of the pressure signal into account (GOSSWEILER, HUMM and KUPFERSCHMIED 1990).

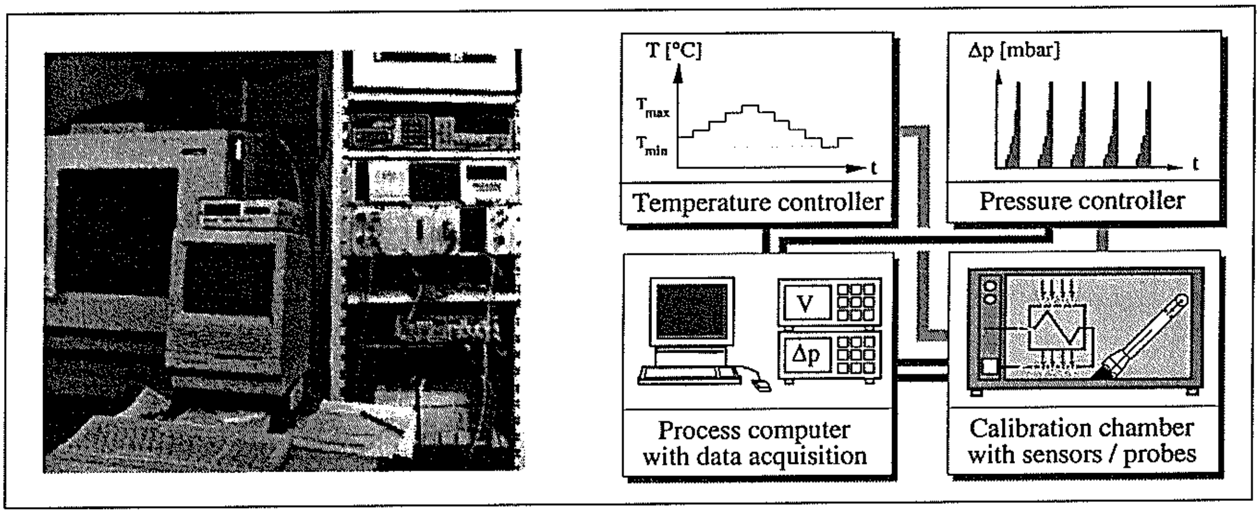


Fig. 3.1-1 *Test and calibration facility for sensor chips and completed probes*

b. Dynamic response calibration of the probes, depending on the type of sensors used and the chosen packaging configuration (chip flush mounted or mounted inside the probe; see GOSSWEILER et al 1990). This step is necessary only for new sensor types or after significant changes in the packaging configuration. The typical eigenfrequency of the pneumatic cavity is of the order of 45 ... 80 kHz (design specific, see Table 2.6-2); the sensor chip diaphragm eigenfrequency is of the order of 500 ... 600 kHz.

c. Aerodynamic calibration of the probes under static conditions in a reference flow are carried out in a jet calibration facility with a nozzle exit diameter of 100 mm. For this purpose a computer controlled traversing system with acquisition of flow conditions and probe data has been developed. The electric signals from the probe sensors and from the test facilitity gauges - reference pressure and temperature - are measured with 20 bit resolution.

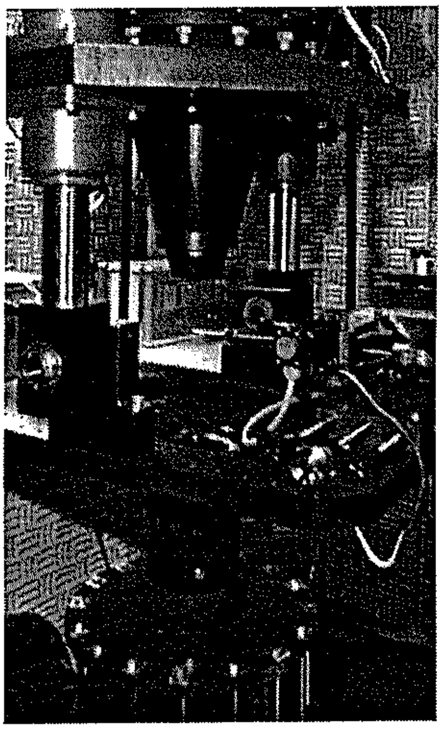


Fig. 3.1-2 *Aerodynamic calibration facility (jet nozzle)*

Both pneumatic and sensor-equipped probes can be calibrated in the facility. For this reason, the steadiness of the flow field is very important in terms of total pressure and flow temperature. A long term variation of the flow velocity of ±1‰ and of better than ±0.02°C for temperature could be achieved (measured over 100 minutes at a Mach number of 0.4).

The calibration of a fast-response probe equipped with 4 sensors takes 24 minutes for 330 angular positions (at a Mach number of 0.3); this illustrates how long steady flow conditions are required. The typical mean drift of the 4 sensor's pressure zero during this time period was 0.7 mbar (1.1% of dynamic head at $M = 0.3$). This drift can easily be corrected by interpolation after the calibration. Later, the calibration data are transformed into non-dimensional calibration coefficients and fitted with polynomial equations with high accuracy in the interesting angular range for further measurement data processing (KUPFERSCHMIED, GOSSWEILER, 1992).

d. Aerodynamic calibration of the probes for fluctuating flow conditions is very important for measurements in turbomachines. In model experiments in a water towing channel the dynamic response of probes in dynamic flows was determined (HUMM, VERDEGAAL 1992). These experiments enable establishment of basic compensation procedures to be implemented in the near future.

4. DATA ACQUISITION AND DATA PROCESSING

For data acquisition, an 8 channel system with 200 kHz sampling frequency per channel providing 40 kHz of analogue bandwidth has been developed. The resolution of 12 bit A/D converters sets a limitation on measurement accuracy if both AC and DC parts of the signal are of interest. An improved resolution of such high speed converters is desirable.

The processing of the large data sets is performed off-line with a specially developed software ("AW-System") currently running on a DEC-VAX 9000-420 mainframe computer. Flexible data processing and statistics capabilities, signal processing and graphic output are features of this software, described by HERTER et al, 1992.

To avoid the practical limitation set by the requirement of large and expensive mainframe computers, the software package is currently being ported on DEC AXP workstations equipped with high-performance Alpha-processors. Thus, it will be possible to perform number crunching for data processing with a handy and transportable machine (Fig. 4.1-1). For typical processing of data points, the AXP workstations showed generally a higher overall performance in comparison to the VAX 9000 with vector processor. The availability of expensive mainframe computers is no longer required to use the FRAP measurement system.

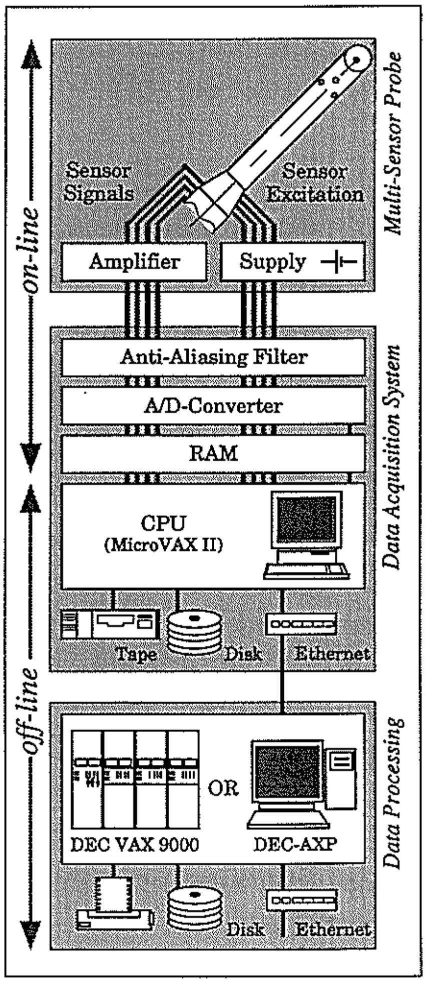


Fig. 4.1-1 *Data acquisition hardware and data processing system*

5. PERFORMANCE AND KNOWN LIMITATIONS

5.1 SELECTION OF ADEQUATE PROBES

Naturally, the success of FRAP measurements is strongly dependent on the type of probe chosen for the application. On one hand, operational aspects such as physical accessibility to the blading and aerodynamic aspects concerning the shape of the probe (see Chapter 2.2) have to be considered. On the other hand, the maximum probe size is determined by the dynamic aerodynamic parameters of the experiment: the reduced frequency $k = f_{\mathrm{Blade\ passing}} D_{\mathrm{Probe}} / c$ must not exceed a value of 0.15. Applications or experimental set-ups often require a specific fabrication of the probe instead of using standard types. Generally, the probe tip (representing the main part of the design work) can be adapted on a probe stem redesigned according to the application.

The probes have been developed for gases and tested in air. They could be used in other media after a compatibility check of all components. The characteristics of the adhesives used for the fabrication can be a limiting factor in conjunction with some Freon qualities used in research turbomachines. Applications in liquid flows require special attention (i.e. probe stiffness, vibrations) due to the much higher specific density of the flow and to other effects such as corrosion or electric isolation.

5.2 SYSTEM PERFORMANCE AND LIMITATIONS

Environmental capabilities	Range	Comments
Media compatibility	tested in air	preliminary tests with other media
Differential pressure range (max.)	typ. 500 mbar	eased by selection of reference pressure
Common mode pressure (maximum)	several bar	probe design specific
Probe exposition temperature (max.)	>200 °C	tested without harmful effects
Probe Types		
In-house built miniature probes		available probe types listed in Table 2.6.2
Probe lifetime	not reached yet	high robustness confirmed (several 100 h operat. time)
Data Acquisition System		
Sampling rate (per channel)	200 kHz	8 channels used simultaneously
A/D converter resolution	12 bit	Accuracy: ≈ 11 bit
Analogue bandwidth	40 kHz	
RAM capacity (total)	16 MWord	
Data sample length (typical)	262'000 points	
Typical Performance		
Pressure sensor sensitivity	40 ... 90 mV/bar	normalised to the low excitation power of 5 mW
Stagnation pressure (minimum)	12 mbar	(restriction, accuracy 2%, S/N ratio ≈ 40 dB)
Pressure signal offset drift (typical)	1.5 mbar/h	correctable by in-situ offset adjustments
Operating temperature (maximum)	120 °C	limitation for monocrystalline silicon sensors
Resonance frequency of the cavity	46 ... 80 kHz	Ø0.84 Pitot type ... cylindrical types
Signal to noise ratio at $M = 0.3$	65 dB	limited by electrical sensor noise
Signal to noise ratio at $M \geq 0.4$	72 dB	limited by the A/C converter used (Chapter 4)
Temperature measurement accuracy	0.1°C	in-situ zero adjustment (excl. radiation errors)

Table 5.1-1 Performance and known limitations of the ETH FRAP measurement system

Some typical FRAP measurement system specifications are shown in Table 5.1-1. Note that many parameters are given as a illustration and can be optimised for the planned application.

The strategy used during measurements helps minimise errors of the pressure measurement (Chapter 2). For instance, in-situ offset and gain adjustments reduce such errors significantly. The free selection of the reference pressure facilitates this operation. Temperature hysteresis and thermally induced errors can be reduced by pre-heating the probe to the temperature of the flow.

6. CONCLUSIONS

In order to define the challenges for future improvements of the FRAP measurement technique, the limitations of present high-performance FRAP systems are analysed and shown to be due to:

- *probes:* the size of probes dedicated to dynamic flow conditions must be minimum. A further miniaturisation is made possible by new micromachining technologies and microtechnic processes.
- *sensors:* chips of smaller size and chips with a higher temperature range are technically feasible but commercially not yet available. Further efforts are necessary in this field. The sensor stability can be significantly improved by an adequate measurement strategy.
- *inevitable measurement errors* are due to aerodynamic effects for inappropriate probe designs.
- *data acquisition system:* the resolution of present high-speed A/D converters sets a limit to the signal to noise ratio and the resolution of the measurement of the AC *and* DC components.
- *data processing:* the huge amount of data requires very efficient processing procedures and computer hardware.

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