Turbomachine Measurements
Paper 5

EXPERIENCE WITH INSTALLING A NEW STEADY STATE MEASUREMENT SYSTEM AT AN EXISTING COLD FLOW ROTATING TURBINE TEST FACILITY

S. Svensdotter, J. Fredriksson, T. Svensson, N. Wei, T.H. Fransson

Chair of Heat and Power Technology
Royal Institute of Technology
S-100 44 Stockholm

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ABSTRACT

Improved understanding of the flow and loss mechanisms in turbomachine passages is leading to better designs with higher efficiency and better performance. Currently used design methods for turbomachines are mostly based on two-dimensional flow calculations for the blading. Three-dimensional codes are being developed, but detailed experimental data from 3D test facilities are still needed in order to validate these codes and to use them routinely in the design process.

The test turbine facility at the Chair of Heat and Power Technology, HPT, is a cold flow, subsonic turbine, driven with air from a 1MW screw compressor in an open circuit.

Small pressure fluctuations (~300Pa) over a period of about 5 minutes in the test turbine facility, probably emerging from the compressor, led to the decision to install a faster steady state measurement system than the previous one, in order to be able to resolve the pressure and temperature data better.

The main gains with the new system are a reduction of the time required for taking the measurements, a reduced standard deviation of the results from 50-170Pa with the previous system (two measurement points per test run, 90 min) to 35-38Pa with the new system (100 measurement points per test run, 20 min), and the capability to increase the 2D measurement from a 10X10 array to an arbitrary mXn measurement. The accuracy of the absolute pressure measurements is improved from ±127Pa to ±, which gives an improvement of the accuracy of the total stage efficiency of about 0.2% [Haghighi, 1996]. Also, with the new measurement system, manual readings of, for example, brake torque and atmospheric pressure are eliminated.

The installation experience showed that the hardware is fairly easy to install. The software took a longer time, mainly due to the decision to develop our own software. The new system is more user-friendly than the old system.

INTRODUCTION, BACKGROUND AND OBJECTIVES

In order to design turbomachines with the aim to achieve higher efficiency and better performance, an improved understanding of the three-dimensional flow and loss mechanisms within the blade passages is essential. Currently used design methods for turbomachines are mostly based ~~on~~ two-dimensional flow calculations for the blading. Three-dimensional codes are being developed, but detailed experimental data from 3D test facilities are still needed in order to validate these codes.

The problems with a rotating test facility lie in interpreting the results and separating various flow behaviours and their sources from each other. Also, even a small machine is expensive to run.

The test turbine facility was installed in 1985 at the Chair of Heat and Power Technology (HPT) as a joint venture between HPT and ABB-STAL. ABB-STAL owns the turbine and HPT owns the surrounding equipment, including the measurement equipment.

Small pressure fluctuations (~300Pa) over a period of about 5 minutes in the test turbine facility, probably emerging from the compressor, led to the decision to install a faster steady state measurement system than the previous one, in order to be able to resolve the global and detailed pressure and temperature data better.

The original measurement system was a Scanivalve pressure scanning system with a CAMAC interface. A measurement system from Pressure Systems Incorporated (PSI) was purchased with the objective of getting a system that is faster, more reliable, better documented than the previously installed system and that gives better control over the calibration and measurement chain.

PRESENTATION OF THE TEST FACILITY

The test turbine facility is a cold flow, subsonic turbine, driven with air from a 1MW screw compressor in an open circuit. Some details of the test facility are presented in Table 1. More detailed information can be found in Södergård et al. [1989].

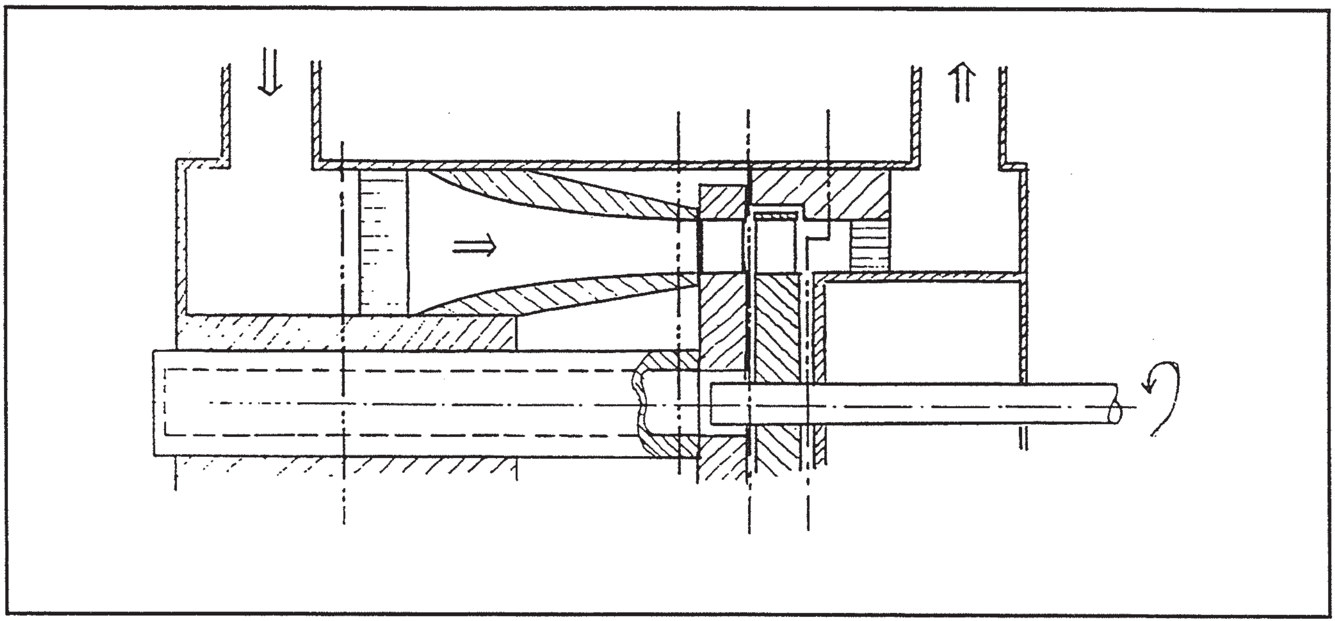

Figure 1: *The test facility [Södergård et al, 1989]*

In Fig. 1, the axial cross-section of the test facility can be seen. The flow enters into a settling chamber before going through the flow straightener. Thereafter is mounted a contraction nozzle in order to adjust the flow channel to the desired span. After the stage follows a restriction plate in order to prevent disturbances from downstream to influence the flow through the stage. The contraction nozzle is a part of the inner housing of the turbine and is exchangeable so that stages with different spans can be tested.

Number of stages	1 - 3
Minimum inner diameter of a disc	280 mm
Maximum outer diameter of a disc	500 mm
Maximum speed	8000 rpm
Type of water brake	Froude FO 209
Accuracy of braking equipment	±0.5%
Type of compressor	Atlas Copco ZA6+6
Maximum compressor working pressure	4 bar
Compressor air massflow	4.7 kg/s
Maximum compressor air outlet temperature	180ºC

Table 1: *Test facility data [Södergård et al, 1989]*

EXPERIMENTAL MEASUREMENT EQUIPMENT

Sensors

The measurement sections in the test turbine can be seen in Fig. 1. The turbine is equipped with static pressure tappings at hub and tip in sections 21, 22 and 50. Stagnation pressure probes are mounted before the stator and after the rotor (sections 21 and 50). Inlet and outlet temperatures are measured with two-thermocouple probes of type K, sections 20 and 60 (see Fig. 1), and the temperature after the rotor is measured with four-thermocouple probes of T-type in section 50. One four-hole traversing probe is positioned after the stator and one after the rotor. The massflow is measured in section 10 with a DIN-standard flow orifice equipped with pressure tappings and a Pt100 temperature sensor. The brake torque and the speed are measured with a Torquetronic device mounted on the turbine axis. The bearing friction torque is measured with strain gauges mounted on the bearings. The exact position of the sensors can be found in Svesndotter and Wei [1995a].

Previously installed measurement system (Scanivalve)

The measurement system being replaced is a Scanivalve system consisting of one 32-channel scanner in the range of ±35kPa, relative reference, and one 32-channel true differential scanner in the range of ±35kPa. The scanning is performed by mechanically multiplexing the pressure ports into one pressure sensor. The analogue channels are multiplexed separately and both pressure and analogue signals are measured with a 14-bit voltmeter. Brake torque and speed are measured by the Torquetronic and shown on the manoeuvring panel, where they are read manually and typed into the data acquisition program. The atmospheric pressure is read manually from a barometer and the inlet air humidity is read from a Psychrometric diagram using the atmospheric pressure, relative humidity and temperature. All these values are read from manual instruments and given as input values to the data acquisition program by the user.

Software

The software controls the measurements and traversing motors via a CAMAC interface. The measurement cycle consists of first scanning through all the stationary sensors, then scanning the pressure channels on the traversing probes while stepping through the measurement area, and finally again scanning through all the stationary sensors. For a measurement area of 10X10 points with one probe moving at a time, the total time for one measurement is 1.5h. Before the actual measurement, the probes have been traversed in radial direction in order to find the approximate flow angle. The probes are calibrated for a flow angle of ±10deg relative to the probe and have to be turned in the approximate flow direction. This is defined as the flow angle check.

Accuracy

The accuracies for the various parts of the Scanivalve system and the total measurement accuracy are discussed in the chapter concerning improvements of the measurement quality.

New measurement system (PSI)

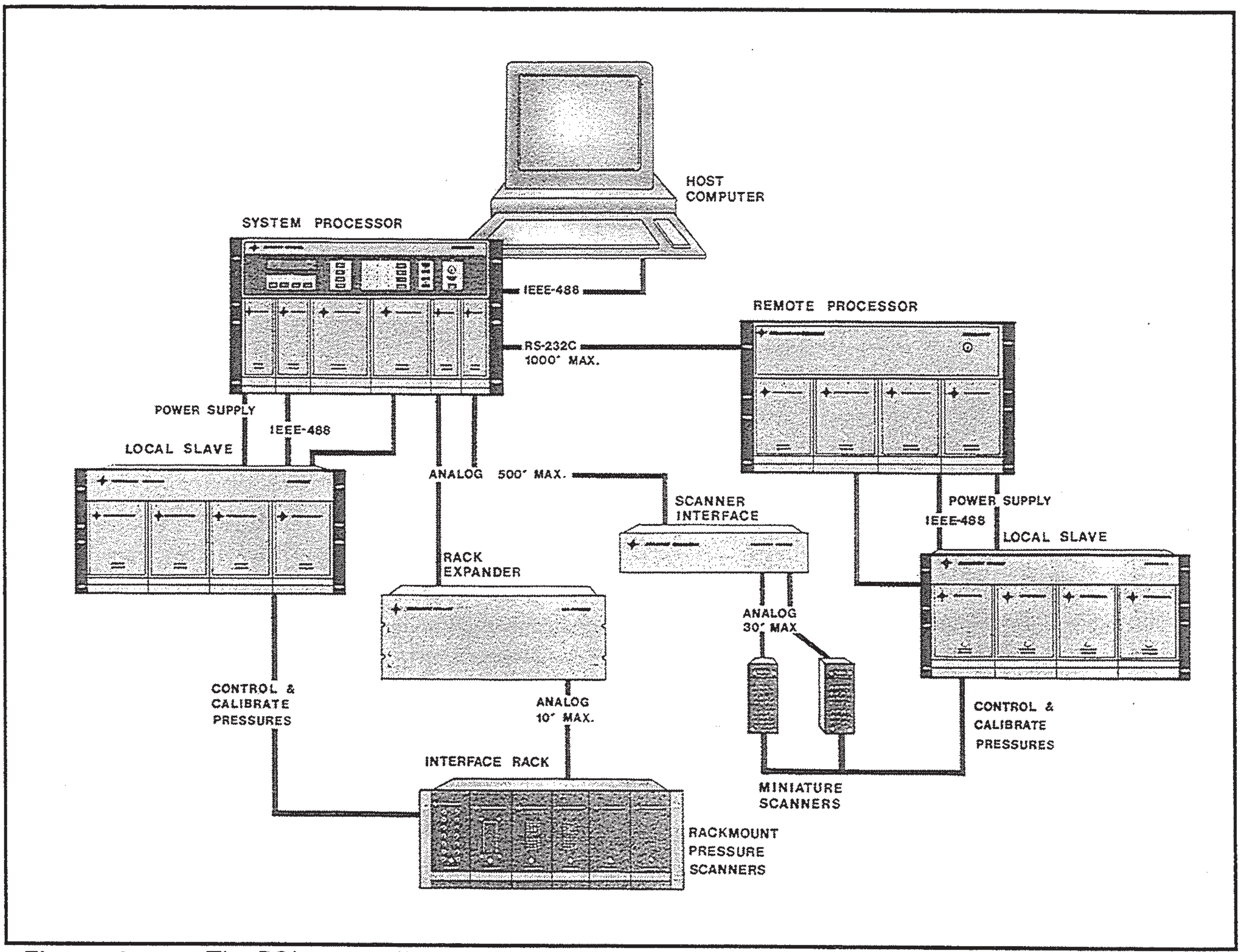

***Figure:* 2** *The PSI system (Pressure Systems Inc., 1994)*

The PSI system is an electronic scanning system with rack mounted modules. It consists of a main rack; the system processor (SP) which runs the communication to the computer, stores the data and where the analogue measurement (AIU), digital measurement (FMU) and calibration (PCU) units are mounted; and one or several scanner racks, where the pressure scanners are mounted. Each scanner rack has room for 8 scanners, each with 16 channels, which allows a total of 128 channels. The SP can be extended with at most 32 scanner racks to control up to 4096 pressure channels (Pressure Systems, 1993). Every pressure channel is equipped with one, relatively simple, pressure sensor which is calibrated from the advanced pressure sensor (a quartz bourdon) in the pressure calibration unit every time the system is started up and at any other time according to the users choice. This calibration procedure takes about 1-2 minutes per pressure range to complete. The calibration of the pressure sensor in the PCU is performed at an authorised laboratory with a reference pressure traceable to international standards.

The system at HPT consists of two 16-channel scanners in the range ±35kPa, relative atmosphere; two 16-channel scanners in the range ±7kPa, relative atmosphere; and one differential 16-channel scanner in the range ±35kPa. The scanning is performed electronically by "sample-and-hold". The scanners are calibrated with a ±35kPa, relative reference, pressure calibration unit (PCU). A ±7kPa PCU was not purchased for economic reasons. One more PCU would have made it necessary to purchase one more rack, which would have increased the price of the system considerably. The gain in total accuracy with a ±7kPa PCU would be only 1.6Pa (see following chapter) and this does not motivate the investment. The time required for the calibration does not decrease with a ±7kPa PCU, since the different pressure ranges are not calibrated at the same time anyway. Using one PCU for each pressure range would make the software easier to develop for the programmer but the user does not notice any difference.

The atmospheric (reference) pressure and the static pressure at the flow orifice, used to determine the air massflow into the turbine, are measured with a 160kPa absolute PCU. Each PCU can measure two pressures by switching an internal valve, controlled from the software. The reason for this is to allow the PCU to be able to measure an accurate reference pressure.

The analogue measurement is performed with two 16-channel 16-bits analogue units (AIU) and the digital measurement is performed with a 4-channel 24-bits frequency unit (FMU). The brake torque is measured in the PSI system by an analogue channel, while the speed measurement is performed by a digital channel. A humidity sensor has been installed at a far distance upstream the flow orifice to measure the humidity of the ingoing air. The output signal of the humidity sensor is measured with an analogue unit.

The pressure scanners are placed in a rack close to the turbine in order to get as short pressure tubings as possible, while the analogue and digital units are placed in the main rack, the so-called System Processor (SP). The SP has a 1MB memory and can be used either with a computer or as a data logger on its own. In the latter case, it can be controlled from the front panel.

The SP has to be connected to clean and dry pressurised air of about 8 bars. If calibration should be performed below atmospheric pressure, a vacuum source is needed as well. At the present, the system at HPT is connected to an ejector to get the vacuum pressure, due to the fact that the turbine application does not require measurements far below atmospheric pressure.

The five scanners are equipped with purge options. The purge valves also have to be connected to clean and dry pressurised air but with higher pressure and massflow than the calibration units. The exact amount of the required massflow for the purge depends on the number of scanners installed and on the pressure drop in the tubings. It is clear however, that the requirements must be different than for the pressurised air used for the calibration. The purge valves needs a pressure of 10bars to open and the maximum allowed pressure for the calibration valves is 9bars.

Software

The software controls the measurements via a GPIB interface, and the traversing motors via a serial port. The measurement cycle consists of first scanning all the channels, moving the probes and thereafter scanning all the channels again, and again moving the probes until the entire measurement area has been covered. For a measurement area of 10X10 points with both probes moving at the same time, the total time for one measurement is 20 minutes, including the flow angle check, which for the PSI system is performed on-line.

The software for the data acquisition was written at HPT for a general purpose, i.e. not only for the PSI system but for other GPIB instruments as well. It is operated under a menu format, where the different menus contain links to data acquisition and post-processing programs, editors, compilers and an internal help system. During measurements an on-line data evaluation function shows up to 24 pre-chosen data on the screen.

The data can be transferred to the host computer in several modes ranging from raw AD data (HEX format) to engineering units in ASCII format. The raw data transfer is faster and can give a data throughput of up to 50 000 ch/s or 350Hz, whichever limit is reached first. When measuring only pressure channels without conversion, HPT has managed to measure with 280Hz. With 80 pressure channels, 32 analogue channels and one digital channel, measured with engineering units in ASCII format, the data throughput was 20Hz.

If the PSI system were to be used as a data logger without on-line data transfer to a host computer, the maximum sample frequency might be higher, but this option has not been studied.

The PSI system is designed in such a way that all commands concerning initialisation, calibration and measurements are sent to the system at the start up. Therefor, the rest of the software is set up in the same way, i.e. traversing steps, on-line data etc. are chosen from the start and can not be changed during test runs. They can however be changed without leaving the menu environment.

Accuracy

The accuracies for the various parts of the PSI system and the total measurement accuracy are discussed in the chapter concerning improvements of the measurement quality.

Traversing system

The traversing system for the test turbine consists of five controller units, each one driving a stepper motor. One unit is used for turning the stator, two for the radial movement of the probes and two for the angular movement of the probes. Two probes are controlled presently. The controller units had to be changed for the new data acquisition system, due to the GPIB communication. The commands for the probe and stator movements are preloaded into the controller units, which means that the only communication needed during measurements is a trigger pulse. The intention again is to speed up the measurements.

A trigger pulse is sent by the traversing units to the PSI system when the probes are in correct position. The measurement is performed according to the initialisation (see below). Thereafter, a trigger pulse is sent to the stepper motors to start them moving. While the probes are moving, data is transferred from the SP to the computer and written on disk.

IMPROVEMENTS OF THE MEASUREMENT QUALITY WITH THE PSI SYSTEM

The main improvements with the PSI system, compared to the Scanivalve system, are the speed of the measurements, the decreased standard deviation and the elimination of possible error sources due to manual reading.

The speed of the measurement is improved, from 90 minutes to 20 minutes for a typical case, due to the fact that the electronic scanning of the PSI system scans all channels in about the same amount of time as required for the mechanical scanning of the Scanivalve system to scan one channel. Also, the new measurement software moves the two probes at the same time while the old software moves only one probe at a time.

The decrease in standard deviation is due to the fact that the PSI system scans all the channels during the entire measurement cycle, while the Scanivalve system first scans the stationary sensors, thenr traverses the probes and scans ONLY the probe channels, then finished by scanning the stationary sensors again. The PSI system gives a better average because it uses more measurement points. As an example, the standard deviation for stagnation pressure measurements, with the stationary probes after the stator, decreased from 170Pa (Scanivalve, two measurement points per test run) to 38Pa (PSI, 100 measurement points per test run) [Svensdotter and Wei, 1995b].

For the PSI system, calibration of all sensors relative to the calibration units (PCU) is performed automatically each time the system is started up. The calibration units are calibrated at authorised laboratories with traceable references once per year. The sensors in the Scanivalve system are also calibrated at authorised laboratories.

The PSI system was calibrated at its delivery in October 1993 and again in October 1995. During this period the drift of the 160kPa absolute PCU was 0.04% of full scale and the drift of the ±35kPa relative PCU was 0.2% of full scale. Guaranteed drift over 6 months is 0.03% of full scale for the 160kPa absolute PCU and 0.02% of full scale for the ±35kPa relative PCU.

Accuracy

The total system accuracy of the measurement systems is not trivial to analyse. It consists of a mix of guaranteed accuracies from manufacturers of certain parts of the system, and assumptions concerning other parts of the system where, for example, field calibrations and system-specific solutions have been applied. One of the advantages of the PSI system over the Scanivalve system is that more parts of the system have a manufacturer guaranteed accuracy, and thus some error assumptions have been eliminated.

The individual sensor accuracies can be found in Table 2. The pressure transducers and the voltmeters for both measurement systems have a manufacturer guaranteed accuracy. For the Scanivalve system, certain values are read manually and typed into the data acquisition program, for example: the atmospheric pressure, the brake torque, the rotational speed and the humidity of the inlet air. When discussing the accuracy of these values, it has been assumed that no errors are introduced from the manual reading. This is most likely not a correct assumption.

	Scanivalve	**PSI**
Scanivalve transducer, relative to atmosphere (Druck)	±42Pa	---
Scanivalve transducer, differential (Druck)	±21Pa	---
Barometer (Paulin)	±120Pa	---
160 kPa PCU	---	±32Pa
±35 kPa scanners	---	±17.5Pa
±7 kPa scanners with ±35 kPa PCU	---	±12.6Pa
±7 kPa scanners with ±7 kPa PCU	---	±7Pa
Solartron 7055 10mV range	±(0.01%rdg + 4μV)	---
Solartron 7055 100mV range	±(0.01%rdg + 4μV)	---
Solartron 7055 10V range	±(0.01%rdg + 2mV)	---
AIU 10mV range	---	±12μV
AIU 10V range	---	±4mV
PT100 sensor incl. voltmeter accuracy	+0.30±0.11°C	---
Thermocouple type K	±0.4°C	±0.4°C
Thermocouple type T	±0.2°C	±0.2°C
Torquetronic	±0.2%rdg	---
FMU	---	±1 count
Friction torque sensor	0.09μV	0.09μV (±0.045μV)
Hygrometer	±2.5%r.h.	---
Humidity probe (Hylog)	---	±2%r.h.

Table: 2: *Sensor accuracy [Svensdotter, Wei, 1995a].*

When calculating the total system accuracy for absolute pressure, the accuracies for the atmospheric pressure and the scanner relative pressure have been combined as a root-sum square [Doebelin, 1990]. It can be seen that the large difference in total pressure accuracy between the Scanivalve and the PSI systems [Table 3] comes from the accuracy of the atmospheric pressure.

When calculating the total temperature accuracy, the voltmeter input accuracy, the sensor gradient and the sensor accuracy all have to be taken into account [Pentronic, 1994].

	Scanivalve	PSI
Absolute pressure		
±35 kPa range	±127.5Pa	±36.5 Pa
±7 kPa range	±127.4Pa	±34.4 Pa
±7 kPa range[1]	---	±32.8 Pa
Differential pressure		
±35 kPa range	±18.2Pa	±17.5 Pa
Atmosphere	±120Pa	±32 Pa
Temperature		
T-thermocouple	±0.22°C	±0.36°C
K-thermocouple	±0.41°C	±0.50°C
Friction torque	±1.1*10^{-3}Nm	±2.5*10^{-3}Nm
Brake torque	±0.4Nm	±0.4Nm
Speed	±0rpm	±0.5rpm
Humidity	±0.09gwater/kgair	±0.51gwater/kgair
Mass flow	±0.67%rdg	±0.67%rdg

Table 3: *Total system accuracies for the measured data [Svensdotter, Wei, 1995a]*

The accuracy of the absolute pressure measurements is improved from ±127Pa to ±36Pa [Table 3]. This gives an improvement in turbine efficiency of about 0.2 percentage units [Haghighi, 1996].

Also evident in table 3, the accuracy for the analogue measurements is not improved with the PSI system. This is due to the fact that the AIU:s are not as accurate as the voltmeter used for the Scanivalve system. HPT is also working on improving the analogue measuring part. This will probably result in using a different system for analogue measurements than the PSI system.

Another gain with the PSI system was a reduced standard deviation of the results from 50-170Pa with the Scanivalve system (two measurement points per test run, 90 min) to 35-38Pa with the PSI system (100 measurement points per test run, 20 min) [Svensdotter and Wei, 1995b].

EXPERIENCE WITH THE PSI SYSTEM INSTALLATION

Traversing speed, hysteresis in the angular movement:

The speed of the traversing measurement has been improved considerably with the PSI system, due to the facts that both probes move at the same time and that the speed of each motor has been increased. One problem that has occurred, however, is that occasional pulses from the new traversing controller units were lost, causing the motors to get a large hysteresis, especially for the angular movement. This is being solved by adjusting the stepper motor controllers.

Vacuum air:

The use of an ejector to create the vacuum is quite sufficient for calibration pressures just below atmospheric conditions (as needed for the turbine at HPT). However, the adjustment of the ejector is very sensitive and the calibration pressures have to be monitored. If the vacuum pressure is far from the wanted

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[1] If a ±7kPa PCU had been purchased

vacuum pressure, the PSI front panel will give the message “Pressure not reached”, but if the vacuum is just barely outside wanted vacuum, the PSI system will get a time-out and the data acquisition program will be stuck. The level of desired vacuum for the system depends on what pressure ranges are being calibrated. Better control of the vacuum pressure has to be installed in order to correct this.

Purge air:

The purge air, taken from a pressurised air source, needs to be of higher pressure and larger massflow than the air used for calibration. This means that two sources of pressurised air or a reduction of the calibration air are needed. The exact amount of needed purge airflow depends heavily on how many scanners are used and the losses in the pressure tubings, and thus can not be determined until the system has been completely assembled with all pressure tubings installed.

Computer communication:

Using a different computer than the one presently connected to the PSI system might cause problems with the communication, due to the fact that even computers with the same clock frequency have slightly different speed when communicating with the PSI system through the GPIB card. A change of computer might make it necessary to do minor changes in the program.

Also, occasionally, when the acquisition program has crashed, the PSI SP and the computer get out of phase. This results in the trigging of the traversing probes not working properly. This is solved by rebooting the computer and the PSI system.

Longer installation time than expected:

The data acquisition software provided with the PSI system was specific for the PSI system only. HPT wanted a flexible software which would allow the possibility of combining various other GPIB interface instruments. A lot of time was thus spent on the development of this software.

Another reason for the long installation time was the fact that none of the graduate students working with the installation had any experience with such work and, therefore, the work with the equipment was performed as a part of their education.

Good technical support from USA but slow delivery of extra parts and manuals:

When the system was delivered in 1993, HPT ordered a more detailed "Engineering Manual" for the system. It is still being revised by PSI and has not been delivered. Spare parts sent from the USA are slow to arrive due to transport and customs procedures. This problem has increased since Sweden joined the CEE. Problems with, and questions about, the system behaviour are, however, always answered very quickly and reliably.

User-friendliness:

The PSI system and the new data acquisition system are easier to use than the Scanivalve system in the sense that manual reading is not needed and that the calibration of each sensor is performed automatically. It can not, however, be considered as very user-friendly. The PSI system has been designed to be flexible and to allow the user to use the system to the limits of the technical specifications. Thus, the user can modify a large number of parameters, but the behaviour of the system is not always trivial to predict. However, it does allow the user to optimise the system with regard to the measurement situation.

CONCLUSIONS

- The PSI system is very flexible and has a high capacity and accuracy for pressure measurements.
- The accuracy of the analogue measurements is not sufficient for the turbine application. Improvement of the temperature measurements will have to be achieved with another system.
- The PSI system provides better control over the calibration chain from the authorised calibration laboratories to the measurements than does the Scanivalve system.
- The main gain with the system are the reduction of the time required for the measurements and a decreased standard deviation of the results [Svensdotter, Wei, 1995b]. The accuracy of the absolute pressure measurements is improved from ±127Pa to ±36Pa, which gives an accuracy improvement of the total stage efficiency of about 0.2 percentage units [Haghighi, 1996].
- The work with the installation took a long time due to the decision to develop our own, flexible data acquisition software, and due to the inexperience with such systems at HPT.

ACKNOWLEDGEMENTS

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