Computer controlled calibration of high precision pressure transducers

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Department of Aerospace Engineering
ACKNOWLEDGEMENT

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SUMMARY

At the Laboratory of High-Speed Aerodynamics of the Department of Aerospace Engineering of the Delft University of Technology an automatic pressure transducer calibration system has been developed (and successfully used for several years). Using an HP-1000 computersystem and a high precision quartz bourdon tube manometer, a 20-point calibration of one or more pressure transducers mounted in or near a wind tunnel is performed in about 20 minutes. An overall accuracy of 0.02% Full Scale for Druck Limited PDCR-22 pressure transducers in the obtained Signal conditioner-Amplifier-Scanner-A/D converter chain is regularly acquired. Several pressure transducers with similar pressure ranges may be calibrated simultaneously so that in a few hours a complete test set-up is provided with high quality calibrations. The last module of the computerprogram provides the user with a set of polynomial calibration coefficients and a graph representing the residual errors of the calibrated pressures when using these coefficients for each of the calibrated transducers.

The HP-RTE operating system allows the calibration process to proceed concurrently with other tasks like editing and compiling of programs under development.

Pressure measuring devices that are not connected to the data acquisition system (i.e. mechanical instruments) may be calibrated easily as well.
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1. INTRODUCTION

The Laboratory of High-Speed Aerodynamics (HSL) of the Department of Aerospace Engineering of the Delft University of Technology is a wind tunnel Laboratory specialized in fundamental research in aircraft related flow problems in the transonic-supersonic velocity range. The main facilities presently available at the HSL are:

- a 27*28 cm² transonic-supersonic blowdown wind tunnel
- a 15*15 cm² transonic-supersonic blowdown wind tunnel
- a 17*20 cm² transonic boundary layer blowdown wind tunnel will be available in 1985.
- a central laboratory computer and Data Acquisition System (DAS) consisting of number of digital inputs and outputs and 20 analog high precision input channels.

In most wind tunnel tests pressures are sampled by a number of pressure transducers—typically from 3 to 10 transducers—some of which may be installed in scanivalves scanning several pressure lines in succession.

Because of the required accuracy of the final results, high precision components are required in the data acquisition chain as well as fresh calibrations of these components for every new test set-up. The pressure transducers in use are of the straingauge bridge type adapted for use in Scanivalves or in similarly formed cavities. Each pressure transducer is supplied with D.C. current by an individual signal conditioner. The output of the transducer is fed to a precision instrumentation amplifier to accomodate the signal to the voltage level as required by the A/D converter. The computer controlled scanner and A/D converter features a precision and resolution of 0.01%. The digitized data of the selected channel(s) are stored in the computer.

To make full use of the precision of each of the components in the chain, it is necessary to calibrate the chain as a whole in each new test set-up.

A Mensor Quartz Manometer, using a quartz helical bourdon tube, serves as a pressure standard. In general, a complete calibration procedure consists of recording the Mensor manometer readings and the corresponding A/D reading at some 20 pressure levels. If executed by hand, this procedure is time consuming and the accuracy of the results depends on the sustained concentration and skill of the operator. For instance, to check the hysteresis of the transducer, it is important to distinguish between calibration pressures that are approached from a lower or from a higher level. But this possibility is lost if, due to unskillful handling of the pressure control valves, overshoots occur in setting the pressure. Also, the operator may be tempted to be too easily satisfied that a constant pressure level has been obtained. Altogether, the calibration procedure, some three quarters of an hour per transducer, was often found to yield results of only moderate quality.

The following describes how a calibration system has been developed, using the measurement and control functions of the available laboratory computer, which speeds up and refines the calibration procedure and unburdens the operator.
2. Description of the available equipment

As shown in Fig. 1, a geographical lay-out of the HS Laboratory, the laboratory computer system is situated in a central location between the main wind tunnels. Instrumentation cabling connects instruments near or inside the wind tunnels to the computer system. Several computer terminals are available near the wind tunnels to control measurements or to perform other functions of the laboratory computer. An overview of the central Data Acquisition System (DAS) including the laboratory computer is given in Fig. 2. The equipment in use with the calibration system is detailed below.

The laboratory computer system is a Hewlett Packard HP-1000 model 31. The system consists of an HP-21MX-E processor equipped with 64 Kbytes of RAM, two HP-7900 disk drives, several CRT terminals, a teletype, papertape punch and reader, a printer, a slave HP-2100 computer and a RTE-II operating system. The RTE-II operating system is capable of supporting several simultaneous tasks in real time. Because of the limited computer memory space, the HP-2100 computer of a former system has been retained as a slave computer to perform a number of actions requiring correct timing. The HP-2100 features a crystal timebase and a relatively simple communications and control program; its main task is to control relay contacts for general purpose servo mechanisms.

The analog measurements are taken by an Analogic AND5 5400 data acquisition system. This computer controlled system combines a multiplexer, a sample and hold amplifier and a precision (14 bits) -10 to +10 V A/D converter. The computer control offers the possibility to choose random channels and digitize the signals or to sample one of the channels at a high speed (50 KHz).

The amplifiers, Ectron type 751, accommodate the low level signals from strain-gauge bridges or thermocouples to input levels as required by the A/D converter. Gain is set by switch and fine tunable by vernier in a range of 1 to 1000, an adjustable low pass filter is available to prevent digitizing errors.

The Endevco type 4470 signal conditioners are mainly used to provide each pressure transducer with a highly stabilized DC supply. The supply voltage is sensed as near to the transducer as possible in order to obtain high accuracy. Balancing of the strain-gauge bridge by applying external resistors proved to be undesirable as it has a negative influence on the linearity of the calibration. The pressure transducer in common use are Scanivalve compatible straingauge flush diaphragm 1/2" types:

- Statham type PA208TC absolute pressure
- Statham type PA856TC absolute pressure
- Statham type PA3131TC differential pressure
- Druck Limited PDCR22 differential pressure

Available pressure ranges are from 0.3 Bar to 0.8 Bar. Most of the Statham transducers are over 15 years old and they suffer from defects or weak calibration results, except for a few of the oldest PA208TC types. The Druck limited PDCR22 transducers are very good although the so called 'end caps' delivered by the manufacturer to adapt the transducer to the Scanivalve transducer cavity may cause problems due to corrosion. This corrosion is probably the result of contamination by chemicals from the O-rings used for sealing. Minimal, yet measurable leakage occurs when an end cap is affected and calibration and measurement results become unreliable.
The design of the calibration system

The following points were taken into account in the design of the calibration system:

- The DAS has a fixed position in the laboratory. The distance to the wind tunnels varies between 20 and 50 meters. A network of instrumentation cabling connects the transducer, or other instruments or signal sources near the wind tunnels, to the analog or digital channels of the DAS. The network also provides the connections to control probe traversing mechanisms, angle of attack mechanisms, Scanivalves etc.

- Because of the required high precision it is necessary to calibrate transducers in the completed test set-up. The effects of inaccurate bridge supply settings or uncalibrated amplifier settings are eliminated in a procedure that calibrates the complete chain (assuming that the base quality of all components is very high). Because of the need to provide reference pressure near the wind tunnels, a network of pneumatic lines connects a pressure source and a pressure measuring line to each windtunnel.

- The Mensor Precision Manometers, used as a pressure standard, are equipped with a quartz bourdon helical tube. The quartz helix gives the instrument an excellent sensitivity and very low hysteresis. However the quartz tends to creep slowly under constant load, so the calibration procedure may not take too much time. Another disadvantage of the quartz material is its sensitivity to mechanical shocks. Shocks may result in zero point shift of the instrument. It is therefore preferable not to move the pressure standard from one wind tunnel to another, but to install it in a permanent position close to the central DAS.

- Although the quartz bourdon tube reacts very rapidly to pressure changes, the nulling mechanism that provides the readout of the instrument runs some two minutes for a pressure step from zero to full scale. If the Mensor output is used as input for a computer program controlling calibration pressures, the maximum achievable rate of pressure change is limited to the maximum speed of the nulling mechanism. Accordingly the maximum speed is 750 scale units per second (full scale corresponds to 100,000 units).

- Increasing the reference pressure will initially cause a small adiabatic increase of the air temperature in the system. Due to heat exchange with the walls of tubing and other parts, the air temperature adjusts rapidly to the ambient temperature, causing a slight drop in the set pressure. The reverse occurs when the reference pressure is decreased. In actual practice this means a slight overshoot if the valves controlling the reference pressure are shut abruptly; this overshoot is not acceptable if it is desired to measure the hysteresis error of the calibrated transducer. Therefore it is important that the pressure regulating valves should be closed gradually when approaching the desired pressure level, to maintain temperature equilibrium in the pneumatic lines.

- Leakage of the pneumatic system leads to unreliable results. The program has to check for leakage and wrong connections prior to starting a calibration procedure.

- Safeguarding of the components in the system against overloads is important. Overloading a sensitive instrument as a quartz manometer or a pressure transducer may damage such expensive devices. Absolute pressure readings as well as the rate of the manometer's nulling mechanism are to be monitored constantly. If one of them exceeds maximum allowable values, immediate closing of the
valves is mandatory. Separate protection is added by incorporating a pressure reducing valve, to be set to the maximum allowable pressure for the system, in the pneumatic supply line.

Taking these considerations into account, a calibration system was developed (fig. 3) consisting of the following parts:

- A reference pressure source, controlled by the computer of the DAS.
- A precision quartz bourdon manometer.
- A network of nylon pressure tubes, connecting the transducer(s) under test to the pressure source and to the precision manometer.
- A computer program for the HP-1000 computer to control the pressure source, perform the calibration procedure and to record the results.

4. The reference pressure source

The pressure source is a simple device consisting of two precision needle valves, each actuated by a servo motor. One of the valves is connected to the air pressure system of the laboratory, the other to a small vacuum pump (fig. 4). During a calibration procedure, the vacuum valve remains initially closed as the successive pressures are reached by opening and closing the pressure valve. When the highest pressure has been reached, the pressure valve is closed completely and the vacuum valve is then used to reach the following calibration pressure levels.

The servos are controlled by the computer program in an open loop in an on-off manner using the HP-2100 controlled relay contacts. This may be done as the absolute setting of the valves is not important to the program which only uses the manometer readings to derive control information.

The servos are geared to the valves so that the travel from closed to full open takes 15 seconds. The resolution of the timing of the on-off relays, being 10 ms, is adequate to control the calibration process. When the motors are switched off they are short circuited to brake fast by using EMF. Positioning by a closed loop servosystem or a steppe drive was considered but not adopted because of the relatively high complexity compared to the on-off control method.

5. The computer program

The program package was written in FORTRAN and divided into "real time" and "background" modules so that a calibration process could run simultaneously with other computer activities.

The program gathers in an interactive phase the necessary control and identification parameters to execute a calibration. After checking the system the program controls the execution of a calibration procedure and records the calibration data in a disk file. The last module of the program reads the disk file and produces polynomial coefficients following a least square method from the calibration data. A more detailed description of the program is given below.

5.1 Parameter Input Phase (PIP)

The program derives the date from the internal system clock of the operating system and asks for the following:

- Which of two available Manometers is selected (choice of a 3 Bar and a 10 Bar model).
- The number of transducers that will be calibrated simultaneously.
- For each of the transducers the channel number must be specified. Transducer serial number and amplification factors may be given optionally.
- The number of calibration points requested. (a standard value is 20 points, more or less is allowed)
- If necessary, a reduced maximum rate of change of reference pressure is prescribed. Such a reduction is important when calibrating at low absolute pressure levels. Due to the long pressure lines a significant propagation delay destabilizes the control loop of the program. A reduction in rate of change of up to 50% inhibits instability at a cost of a 20% to 30% increase of total calibration time.

- The calibration range, given by minimum and maximum calibration pressure
  The PIP module checks the system by a short opening of the vacuum control valve. The Mensor manometer has to react by a fast decrease of the reading followed by a nearly stable pressure reading. If the pressure drop is too small or if the stability of the reading is not satisfactory, the program asks for a correction before starting the calibration.

5.2 The calibration

In the specified pressure range, defined by a minimum and a maximum calibration pressure, a specified number of calibration points will be taken. Half of them are taken as the pressure increases to the maximum value, the other half when subsequently the pressure decreases again to the minimum value. The procedures below are repeated as often as necessary to complete the calibration.

In the following the pressure will be expressed in scale units (s.u.) of the Mensor manometer reading (Full scale is 100,000 s.u.)

5.2.1. Calculation of the next calibration point

The interval between calibration points is calculated as:

\[
Q_{\text{STEP}} = \frac{(Q_{\text{HIGH}}-Q_{\text{LOW}})}{(NPTS/2 - 0.5)}
\]  

(1)

in which:

- \(Q_{\text{HIGH}}\) = Maximum calibration pressure (Mensor scale).
- \(Q_{\text{LOW}}\) = Minimum calibration pressure (Mensor scale).
- \(NPTS\) = Number of calibration points required.
- \(Q_{\text{STEP}}\) = Number of scale units per interval.

In the first leg (increasing pressure) of the procedure the setpoint \(Q_{\text{SET}}\) is calculated as follows:

\[
Q_{\text{SET}} = Q_{\text{LOW}} + I \times Q_{\text{STEP}}
\]

(2)

I increments from 0 by 1 until \(Q_{\text{SET}}\) is larger than \(Q_{\text{HIGH}}\) and a switch to the following formula for the second leg (decreasing pressure) occurs:

\[
Q_{\text{SET}} = Q_{\text{HIGH}} - I \times Q_{\text{STEP}}
\]

(3)

I increments from 0 until \(Q_{\text{SET}}\) is below \(Q_{\text{LOW}}\) and the calibration is finished. Following this method for the calculating of the setpoints these points are evenly spaced and equally assigned to rising and lowering legs.

The setpoints are in fact only target points; they are used to control the reference pressure source as a function of the difference of the setpoint (in scale units) and the pressure as read by the Mensor manometer. To avoid an overshoot of the pressure, the rate of change of reference pressure should be limited so that the Mensor is able to keep up with it. The rate of pressure change (\(QVEL\)) is therefore prescribed according to the function

\[
QVEL = V_{\text{MAX}} \times 0.5 \times (C1 \times \text{ARCTG}((Q_{\text{MENS}}-Q_{\text{SET}})/C2) + C3)
\]

(4)
in which:

\[ \text{QMENS} = \text{Mensor reading in scale units.} \]
\[ \text{QSET} = \text{Mensor setpoint} \]
\[ \text{VMAX} = \text{Maximum velocity of Mensor mechanism.} \]

Constants defining the velocity profile:

\[ C_1 = .637 \]
\[ C_2 = 300. \]
\[ C_3 = .93 \]

Values of QVEL as given by this formula are given in fig. 5. The actual speed of response of the Mensor manometer is 750 scale units per second. However, the computer program assumes VMAX with a safety margin to be 600 scale units per second. As mentioned before, a lower value for VMAX is used at very low absolute pressure levels.

5.2.2. Control of the Reference Pressure Source

For each new setpoint, the first step is to detect in which direction the reference pressure has to change in relation to the current Mensor reading. This direction determines which of the valves has to be used, the other valve remaining firmly shut. The reference pressure is controlled by opening the valve. The Mensor manometer is read at 100 msecs intervals and the real rate of pressure change is calculated. This rate is compared to the prescribed rate QVEL obtained by feeding the Mensor manometer reading into formula (4). If the measured rate of change is outside the tolerance field (see fig. 5), a corrective servo control command is given to the regulating valve. The valve is controlled in fine steps. Each step consists of actuating the servo's during a calculated time Tr of closing the relay contacts. Tr is calculated by an algorithm that compares the duration of the previous closing time to the effect on the rate of pressure change as derived from the Mensor manometer readings. It proved to be useful to limit Tr to a minimum of 20 msecs and a maximum of 300 msecs (full travel of the valve takes 15 secs).

When the manometer reading has reached a value close to the setpoint, it will still vary slowly. The program control then exits this control routine and enters the following routine.

5.2.3. Measurement of calibration data

It should be noted that reaching the exact value of the setpoint is not as important as reaching a stable calibration level close to the setpoint without prior overshoots. The measurement routine achieves this by gradually closing the valve in small steps, continuously checking the stability of the manometer reading. If an overshoot, however slight, is detected the valve is opened a little again to repeat an approach without overshoot to a slightly higher stable pressure (resp. a slightly lower pressure in the decreasing pressure cycle). When the manometer reading is stable within 2 scale units in 8 seconds, the data required for the calibration are sampled. The analog channels are read by the multiplexer and A/D converter; to minimize noise effects and to increase statistic reliability, each measurement is taken in tenfold. The mean values are stored on disk for later reduction. The calibration then proceeds to the next setpoint.

5.3 Data Reduction, Presentation of Results

The calibration data from the calibration procedure or from an existing disk file are used as input for the last module of the program. The Mensor manometer readings are reduced to pressure units (Bar). For each calibrated transducer the
data are fed into a least square algorithm that produces polynomial coefficients. Using the obtained coefficients, the output of the transducer is converted into calibrated pressures. A table is printed in which, for each calibration point, the reference pressure is printed next to the calibrated pressure as well as the difference between the two values. A graph of these differences (residual errors after calibration) is printed alongside the table to allow a quick look of the quality of the calibration.

6. Discussion of obtained results

A Survey of the evolution of the pressure in the system during a typical calibration process is given in fig. 6. The first pressure step is the program's check of the calibration network for leakage or wrong connections. The following steps are the calibration steps. Notice the decrease of $dP/dT$ when the required pressure level is nearly reached. The pressure levels in the rising and in the lowering leg are shifted so that a total number of more or less equally spaced calibration levels is formed. Results of a typical calibration are presented in table 1. The measured values of the transducer under test and the reference manometer (Mensor) are given in the first and second column respectively. The pressures calculated from the measured values by using the polynomial coefficients, given below the table, are found in the third column. The fourth column gives the difference between second and third column. This difference is presented also in a quick look logarithmic graph printed on the right. In most cases a linear calibration fits very well; polynomials of a higher degree are fitted when necessary. The residual errors, appearing as the deviation of the ideal linear or polynomial function from the actual calibration points, tend to be very low. For a good Statham transducer values of 0.05% to 0.1% are found, for Druck Limited transducers values of 0.02% to 0.04% are found. Repeatability of the results of these complete calibrations is satisfactory. Over a period of three months a change in calibration slope results in worst case differences of 0.02%. All mentioned results are measured relative to a Mensor precision manometer which specifies an absolute accuracy of 0.012% and an insignificant hysteresis.
GRAAD VAN DE POLYNOMEN  3
AANTAL PUNTEN  20
DATUM  24-6-1985
KANAAL  3
VERSTERKING  200,00
TRANS. NRD  32762,00
GRAAD  KWADR. SDM
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COEFFICIENTEN IN Y(X) = SDM (Z(I) * X^(I-1) )
1   1.00487866D+01
2   .864623095D-04
3   .20692762D-10
4  -.53654534D-14

Table 1: Results of a typical calibration
fig.1: Plan of the H.S. Laboratorium

1. Transonic Supersonic windtunnel
   27 × 28 cm²

2. Transonic Supersonic windtunnel
   15 × 15 cm²

3. Transonic Boundary Layer windtunnel
   20 × 17 cm²

4. Lab. Computer system and Data Acquisition system

5. Control room

6. Model preparation room
Fig. 2: DATA ACQUISITION SYSTEM
FIG. 3: CALIBRATION SET UP
FIG. 4: REFERENCE PRESSURE SOURCE
FIG. 5: Rate of pressure change as function of the distance to the setpoint
Fig. 6: Evolution of the pressure during a typical calibration process