DELFT UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF AERONAUTICAL ENGINEERING

Report VTH-116

HIGH-ACCURACY INSTRUMENTATION
TECHNIQUES FOR NON-STEADY FLIGHT
MEASUREMENTS

by

O. H. GERLACH

DELFT - THE NETHERLANDS

May 1964
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Summary

A high-accuracy flight test instrumentation system, designed at the Technological University of Delft, Holland, is described. The system was designed to develop a method for determining performance as well as stability and control characteristics from measurements in non-steady, symmetric flight. The data-logging part of the instrumentation system and some high-accuracy transducers are described. Some calibration methods are discussed and a few preliminary flight recordings are presented.
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1. Introduction

As an introduction to the main subject of this paper, it may be useful to state very briefly the background of ideas from which the instrumentation techniques to be described, were developed.

Most flight test methods today are based on the classical assumption that the measurements are made when the aircraft is in a condition of steady flight.

However, a few fields exist where non-steady flight conditions are used to take the measurements. Two of these fields are mentioned here. The first concerns the well-known method of response measurements to determine stability and control characteristics. The other field concerns the less frequently used method of determining the aircraft's performance characteristics from measurements in non-steady flight.

Several years ago a question arose at the Department of Aeronautics of the Technological University of Delft, whether it would be possible to combine these two existing but separate flight test methods into one test technique.

Restricting the method to symmetric flight, it might be possible to derive in an ideal case, from measurements made during one non-steady manoeuvre, the aircraft characteristics indicated in Table 1, pertaining to the aircraft configuration as used in the manoeuvre and to the ranges of airspeed and angle of attack covered during the manoeuvre.

Table 1. Aircraft characteristics to be determined from measurements in non-steady flight.

1. Rate of climb in steady flight, as a function of airspeed.
2. Polar curve, \( C_L \) vs. \( C_D \).
3. Elevator angle to trim in steady flight, as a function of airspeed.
4. Stick displacement per g in manoeuvring flight.
5. Longitudinal stability derivatives, including those with respect to change of airspeed.
In view of the large amount of information to be derived ideally from measurements lasting less than about 1 minute, it might be expected that the new method could lead to a significant reduction in the required flight time.

On the other hand, it turned out very soon that the method requires some highly accurate instruments and a digital recording system capable of digesting a relatively large number of measurements per sec. Only when using such equipment, there is a chance that the possible results might actually be obtained.

Several fields can be mentioned where such a new method could be particularly useful. For example, one can think of flight testing at supersonic speeds, where the aspect of time saving appears to be rather attractive. Another application might be an investigation into the aircraft's behaviour near minimum drag speed. The problem of speed stability arising in this area, typically contains performance as well as stability and control aspects.

In order to find out how much of the theoretically possible results could be obtained in practice, a high-accuracy instrumentation system was developed for these combined measurements in non-steady flight. The actual hardware of the system was built for application in a laboratory-aircraft operated by the Technological University of Delft, a De Havilland DHC-2 "Beaver", fig. 1. Adaptation of the system to other aircraft should be possible without essential modifications to the equipment.

Concurrently with the development of the instrumentation system, a detailed theoretical study was made, in which the required accuracy of the instruments and the technique of data reduction for the proposed method were studied.

An investigation into the best type of manoeuvre to be utilized, also formed part of this theoretical study.

At the time of writing, March 1964, the instrumentation system has been finished but no complete results from actual tests can as yet be given. Techniques to calibrate the transducers to the required order of accuracy are now in their final stages of development.

It is proposed to deal in the following sections with some characteristics of the data-logging part of the instrumentation system first and to discuss some transducers in more detail thereafter.
2. The data-logging part of the system.

Fig. 2 shows in a block diagram the general arrangement of the instrumentation system. From the figure it can be seen that the layout of the system is rather straightforward in principle. The different transducers all have d.c. output signals of several volts maximum amplitude. The transducers are each followed by a filter. The filtered signals are fed to a scanner, which connects each signal according to a chosen programme with the digital voltmeter. The output of the voltmeter is first passed through a parallel-series converter and is then recorded on magnetic tape.

The actual system is shown in fig. 3 and 4. The total weight of the system is about 670 lbs, including the power supplies and batteries shown in the figures. No extreme efforts were made to reduce the seize and weight of the system to a minimum.

Some details of the various elements of the system are given below.

2.1. The filters.

Leaving the transducers for a later discussion, the first elements to be considered are the filters.

With a few exceptions, all filters have identical dynamic characteristics. They are of second order and consist each of one operational amplifier combined with a suitable network. The cut-off frequency of the filters is 2.2. cps and the damping ratio is about .7.

Those signals which are specially susceptible to vibration and yet are to be measured with great accuracy, are passed through two of these filters in series. In this way a fourth-order filtering effect is obtained. The signals so treated are the rate of pitch, the X- and Z-accelerations and the elevator angle.

In total 20 amplifiers are carried in the instrumentation system. Special care was taken to ensure sufficient stability of the amplifiers and their networks. As a result the measured drift over a 2 hour period proved to be less than .5 mV. The noise generated in the filter is about + 1 mV.

With the heavy filtering required, it is, of course, necessary to correct the inevitable distortion of the low frequency contents of the signals.
The correction is based on the assumption that the low frequencies in the signals are passed without a change in amplitude and with a phase lag proportional to the frequency. As a consequence, the signals may be corrected simply by means of a forward shift in time. This correction is applied afterwards on the ground, in the digital computer. The required magnitude of .104 sec of the timeshift was determined experimentally. Tests made in the laboratory with manoeuvres simulated on an analogue computer, showed that the filters and the method to correct for their low frequency effects did not significantly degrade the accuracy of the measurements.

2.2. The scanner.

The next item to be considered in the system is the scanner. It mainly consists of seven rotating switches (Vactric, England), driven by a 400 cps synchronous motor. One switch rotates at 200 rpm and the six others, serving as sub-commutators, revolve at \( \frac{1}{8} \) th of that speed.

The scanner samples 80 signals per second. The entire cycle obtained by interconnecting the several contacts on the low speed and high speed switches, contains 192 different positions. The complete programme of one cycle is repeated therefore, once in \( \frac{192}{80} \) = 2.4 sec.

The signal sampling frequency varies between the different signals. The signals from the pitch rate gyro and two of the accelerometers, containing the highest frequencies and requiring the most accurate processing, are measured at .1 sec intervals. The lowest sampling frequency, once in 2.4 sec, is used for the free air temperature.

The 400 cps supply used to drive the synchronous motor of the scanner is obtained from the same high precision generator (Magnetic Amplifiers, U.S.A.), that also drives the pitch rate gyro. The generated frequency is kept constant within .01% by means of a small tuning fork in the generator.

This very accurate frequency of 400 cps serves as the single time base throughout the instrumentation system.

One characteristic typical of a digital data-logging system using a scanner may be mentioned here.

In the analysis of measured data it usually is necessary to know the values of all the different variables at the same instants in time. This is why, in an analogue system, the variables recorded for instance on a
photographic film are all read at the same instants. In a digital system using a scanner, however, the variables are measured one after another. As a consequence, before further analysis of the data can be started, the recorded variables have to be shifted in time. This applies to all variables except the one chosen as to be measured at the reference instants. In our system this variable is the rate of pitch.

The time shifts required by the different variables to correct for this effect of sequential measuring, are simply added to the shifts required to correct for the filter characteristics discussed earlier.

Mathematically speaking, a shift in time of a variable measured at regular intervals, is identical to an interpolation in time. This process is performed by the digital computer on the ground.

2.3. The digital voltmeter (DVM).

The next element in the diagram of fig. 2 is the digital voltmeter (Electronic Associates Inc., U.S.A.). This is an instrument designed primarily for use with analogue computers. The conversion time of the voltmeter, that is the time required to convert a d.c. voltage into a digital signal, depends on the magnitude of the voltage. The maximum conversion time is .01 sec. The maximum sampling rate could, therefore not be higher than 100 per sec. As the scanner also requires some time to step from one contact to the next one, the sampling rate was lowered to 80 per sec, or one measurement in 12.5 msec.

The accuracy of the digital voltmeter is .01⁰/o of full scale + bit in the last decade, for each individual measurement. The range of the voltmeter used, is 0 to 10 V.

A peculiarity of the voltmeter is the relatively long time (20 msec) required to deal with a change in polarity of the input signal. For the normal application of the voltmeter in an analogue computer, this characteristic is of no consequence. Here, however, it necessitates the use of input signals of equal polarity. Where necessary a fixed bias voltage is added to the output of a transducer. This is done in the filters.

The voltmeter has two different outputs:
a. A visual display of the measured voltage in four decades.
   This display is a useful feature for setting up the equipment, calibrating some transducers, etc. It is not used for recording in flight.

b. An electrical output of the four decades, each in binary code (1-2-4-8).
   This is the usual binary coded decimal (BCD) code, 16 bits (4x4) are
required to represent the result of one measurement. The 17th or polarity bit is not used in our system.

When conversion of an input voltage has been completed, the digital information appears simultaneously at 16 pins of the output connector. The output of the voltmeter is therefore of the parallel type. With the type of recording on magnetic tape chosen in our system, it is necessary to have the digital signal in series form. Consequently a parallel-series converter is required.

2.4. The parallel-series converter.

This converter accepts the parallel output of the digital voltmeter and changes the signal into a series form. Also, some new information is added to the signal.

The number of each measurement within a cycle of 192 measurements is added for identification purposes. To indicate where a new measurement starts, a characteristic group of 8 bits - 1 zero and 7 ones - is made to precede the bits that represent the actual measurement. Finally a group of 4 bits is added to indicate the mode of operation of a separate system measuring changes in static pressure. This system is discussed in one of the following sections of this paper. For each measurement in total 40 bits appear in series at the output of the converter.

This means that the 80 measurements per sec require 3200 bits per sec to be recorded.

The converter was designed by a working-group of the Department of Electrical Engineering of the Technological University of Delft under Prof.dr.ir.R.M.M.Oberman. We are very much indebted to this group for their kind cooperation.

2.5. The tape recorder.

The digital information to be recorded now being available in series form, there is no need for a recorder with a highly constant tape speed, nor is there a requirement for many parallel tracks on the tape. Consequently an amateur stereo tape recorder could be used. With this recorder the zeros in the digital signal are recorded on one track and the ones on the other track. A tape speed of 15 inches per sec results in a packing density on the tape
of about 220 bits per inch. The recording technique is of the so-called non-return-to-zero type.

So far no difficulties have been experienced from drop out on the tape, even when using an ordinary amateur magnetic tape instead of a more specialized instrumentation tape.

The main features of the airborne data-logging equipment have now been described. Some brief remarks will now be made concerning the equipment used to process the magnetic tapes on the ground.

2.6. The ground equipment.

A picture of the ground equipment is given in fig. 5. The magnetic tape is played back on a second tape recorder. The playback is performed at $\frac{1}{8}$ th of the recording speed and the series information read from the tape is fed into a series-parallel convertor.

This unit rearranges the 40 bits per measurement into 10 characters of 4 bits and, as a means to check the correct operation of the paper tape punch, adds an imparity bit to each character.

The convertor also counts the total number of 40 bits for each measurement, as a check on drop out on the magnetic tape. In case there are too few or too many bits, an alarm is given on the paper tape. This convertor was also designed by the working-group mentioned before.

From the series-parallel convertor the information goes via a punch controller to the paper tape punch. This punch is capable of up to 110 characters per sec. In order to keep up with the magnetic tape, a speed of 100 characters per sec is required.

The paper tape thus produced is finally sent to the digital computer. This is a Telefunken TR4, centrally operated by the Technological University of Delft.

There is a simple reason why the information recorded in flight is not passed on to the digital computer directly from the magnetic tape: we want to be reasonably sure about the quality of the data to be handed to the computer. Therefore we want to print and possibly plot some parts of the data, before further digital analysis starts. In due time, when more experience with the system will have been accumulated, the data on the magnetic tape may well be transferred directly to the computer.
Experience with the data-logging part of the system has now been obtained over many hours. Thus far it has been operated mainly in the laboratory, but it worked very successfully in several flights as well. The system has proved to be highly reliable. As yet, no errors in the digital part of the system have occurred.

3. Description of some of the transducers.

The section below deals with some of the transducers, used in the instrumentation system. A summary of the quantities measured in the system, is given in the tabel 2.

Tabel 2: Quantities measured in the instrumentation system.

1. Rate of pitch.
2. Acceleration along X-axis.
3. Acceleration along Y-axis.
4. Acceleration along Z-axis.
5. Elevator angle.
6. Angle of attack.
7. Rate of yaw.
8. Angle of roll.
9. Static pressure.
10. Change in static pressure.
11. Dynamic pressure.
12. Total pressure in slipstream.
14. Manifold pressure.
15. Free air temperature.

Not all the transducers in the system have any particularly interesting features. Within the scope of this paper, only some of the more accurate instruments can be described, viz.:

a) the pitch rate gyro,
b) the accelerometers,
c) a system to measure the change in static pressure.
3.1. The pitch rate gyro.

Rate of pitch is measured by means of a floated rate integrating gyro (type HG-5, Northronics U.S.A.) fig. 6. An instrument of this kind was chosen in the system because of its very large dynamic range. In this application of a rate integrating gyro, no use is made of the rate integrating capability of the gyro. The angular rate measurement performed with such a gyro is based on the force-balance principle as may be seen from the following brief explanation.

Fig. 7 shows the principle of the angular rate measurement. An angular rate about the input axis, which is the quantity to be measured, generates a precession torque about the output axis. This precession torque is balanced by another torque about the output axis, produced by a torque generator.

The torque exerted by the torque generator is proportional to the d.c. current flowing through the torquer. By means of a servo loop, the torquer current is continuously adjusted, such that the gyro gimbal maintains a fixed position relative to the instrument case. As a result the torquer current is proportional to the input angular rate. The torquer current can therefore be used as a measure of the input angular rate. Measurement of the torquer current is possible, by passing the current through a resistor of fixed value and measuring the voltage drop across the resistor.

It may be clear from this short description, that this principle of angular rate measurements in many respects resembles that of force-balance acceleration measurements.

The gyro used in our system has a range of ± 1 rad/sec and a drift rate in the order of 5°/hr, which implies a dynamic range in the order of 10⁵.

For the application here considered, a maximum rate of only ± 20°/sec is needed. The torquer current is therefore passed through a resistor of such magnitude that 5 V is developed at an angular rate of about 20°/sec. In this way the range of angular rates from -20°/sec to +20°/sec corresponds with a total change of voltage across the resistor of 10 V.

As the smallest change in voltage sensed by the DVM is 1 mV or .01°/o of 10 V, the smallest angular rate that can be detected by the system is .004°/sec or 14.4°/hr, almost equal to earth rate (15°/hr) and about three times the drift as given by the manufacturer.

Measurements of the different components of gyro drift (random, mass unbalance, etc.) have not been made thus far. For the application in our
instrumentation system these drifts are not too important, as long as they are small in comparison with the 14.4°/hr. The characteristics important here, are the repeatability and to a lesser degree the linearity of the calibration curve. The undamped natural frequency of the rate gyro is about 95 cps.

Only a static calibration of the gyro is performed. The natural frequency of the instrument is more than 40 times as high as that of the accompanying filters. Therefore the dynamic characteristics of the combination of gyro and filters are determined effectively by those of the filters only. The method to correct for the low-frequency filter effects has already been discussed.

The instrument itself, of course, is calibrated on a turntable (Genisco, U.S.A.). The sensitivity of the gyro is such, that small irregularities in the table angular rate are readily indicated. It proved therefore necessary to calibrate the instrument as follows.

The time for one complete revolution of the table is measured by an electronic counter, triggered on and off through a photoelectric device. From this time, the average speed of the turntable is determined. During the revolution timed, the indicated rate is recorded at regular intervals, some 30 to 40 times. As the time between successive recordings is at least .5 sec, it is not necessary to record the individual measurements on magnetic tape. The readings of the DVM are recorded directly on paper tape. The calibration is performed, using the same filters and DVM as in flight.

All analysis of the recorded data is made with the digital computer. For every calibration point, i.e. for every test angular rate, the average of all recorded DVM readings is determined. The average DVM reading (e_q) and the average angular rate of the table (q) are then related by an calibration formula.

The formula used is of the type:

\[ q = c_0 + c_1 \cdot e_q + c_2 \cdot e_q^2 + c_3 \cdot e_q^3 \]

The quadratic and the cubic terms are added to provide small corrections to the dominating linear term.

The "best" values of the coefficients c in the formula are now determined by a so called regression analysis. This mathematical process-
based on the principle of least squares - minimizes the sum of the squares
of the differences. \( \Delta q \) between the measured q's and the q's predicted by the
formula from \( e_q \). The regression analysis is of course also performed on the
computer.

The result of the calculation is not only a set of values of the
coefficients \( c \). Also an estimate is obtained of the uncertainty in these
coefficients. Finally the computer prepares a list, giving the difference \( \Delta q \)
just mentioned for every calibration point. This list is used as a check
on errors that may have been made during the calibration and to detect any
systematic discrepancy between the calibration points and the formula.

Some of the results obtained from this procedure are shown in fig. 8.
By giving \( \Delta q \) as a function of q, it can be seen, to what extent the
calibration points fit the formula. Two curves are given, involving two
calibrations I and II, made on two different days.

The curve in fig. 8a shows \( \Delta q \) obtained by inserting the measured \( e_q \)
from calibration I in the formula based on the same calibration. It can be
seen, that the maximum value of \( \Delta q \) is about \( .008^\circ/\text{sec} \), corresponding to \( 2 \text{ m V} \)
on the DVM. The r.m.s. value of \( \Delta q \) is \( .0034^\circ/\text{sec} \).

A somewhat less favourable picture is presented by the curve in fig. 8b.
This curve gives \( \Delta q \), obtained by inserting the measured \( e_q \) from calibration
II in the formula based on the former calibration I. If the repeatability
of the calibrations were perfect, there would be no difference between the
two curves.

There is, however, a zero shift of about \( .007^\circ/\text{sec} \), and a difference
of about \( .1^\circ/\text{o} \) in the coefficients \( c_1 \) of the dominating linear term in the
formula for \( q \).

The r.m.s. value of \( \Delta q \) according to the curve in fig. 8b is \( .014^\circ/\text{sec} \).
It should be kept in mind, that the curves in fig. 8 present the characteristics
not only of the gyro, but those of the associated filters and the DVM as well.

It is evident, that rate of pitch q can be computed directly from the
measured voltage \( e_q \) by using the given formula, as soon as the coefficients \( c \)
are known from the calibration.

As an example fig. 9 shows rate of pitch, as deduced from a recording
made during a manoeuvre. Figure 9b gives a more detailed picture of the first
5 sec of the recording. From this latter figure an impression may be gained of the resolution and relative smoothness of the measured rate of pitch, obtained with the system.

These efforts to measure rate of pitch as accurately as possible, are made for two extra reasons, apart from the obvious one of just obtaining an accurate rate of pitch. In the first place, angular acceleration \( \dot{\alpha} \), required to calculate the aerodynamic moment \( M \), will be derived from \( q \) by numerical differentiation. This requires above all a measurement of \( q \) free from noise.

In the second place, angle of pitch \( \Theta \) will be obtained by integrating \( q \), taking into due account the corrections necessitated by an angle of roll \( \Phi \) and a rate of yaw \( r \):

\[
\dot{\Theta} = q \cos \Phi - r \sin \Phi
\]

Provided the two quantities \( \Phi \) and \( r \) remain small, as they should during the symmetric manoeuvre, they need not be measured with great accuracy.

For the calculation of \( \Theta \) (t) the initial value \( \Theta(0) \) of angle of pitch is also required. A first approximation of this angle \( \Theta(0) \) may be found by starting the measurements in a condition of steady flight, immediately preceding the non-steady manoeuvre. In this steady condition, \( \Theta \) may be determined from the readings of the X- and Z-accelerometers:

\[
\dot{\Theta} = \arctan \left( \frac{A_x}{A_z} \right)
\]

A method to obtain an improved value of the initial angle of pitch compares the changes in horizontal velocity computed from airspeed measurements, with the changes in horizontal velocity obtained by integrating measured accelerations. This method has not yet been tested with actual flight measurements.

It can be seen from the foregoing, that the pitch rate gyro, in combination with the digital computer on the ground, basically provides the information that otherwise could be obtained from three separate instruments: an angular accelerometer, a rate gyro and a vertical gyro or a stable platform.

The paper study mentioned in the introduction, indicated that the methods just described, might be worth exploring in practice.
3.2. The accelerometers.

As had been indicated in table 2, three accelerometers are used in the instrumentation system. They are Donner (U.S.A.) type 4310 force-balance accelerometers.

The instruments are mounted orthogonally in a temperature-controlled box, fig. 10. They have different ranges, chosen such that the sum of the acceleration to be measured and the acceleration due to vibration, remains within the instrument's range. The following table shows the ranges employed. The undamped natural frequency of the instruments is about 150 cps.

<table>
<thead>
<tr>
<th>Sensitive axis</th>
<th>Range in g</th>
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<tr>
<td>X</td>
<td>-1</td>
</tr>
<tr>
<td>Y</td>
<td>-.5</td>
</tr>
<tr>
<td>Z</td>
<td>-1</td>
</tr>
</tbody>
</table>

It may be remarked here, that the Y-accelerometer is used only for the purpose of applying some relatively small corrections to the measured values of the X- and Z-accelerations \( A_x \) and \( A_z \). This means, that \( A_y \) does not enter into the data analysis in a major way. The sampling frequency of \( A_y \) is, therefore, relatively low, once in .3 sec, as compared to the frequency used for \( A_x \) and \( A_z \), which is once in .1 sec.

The three accelerometers are calibrated - statically only - in two phases, as follows.

In the first phase, calibration is performed between -1 and +1 g on a rotary, tiltable indexing table (Optical Measuring Tools, England). The three instruments are calibrated on this table simultaneously. The table, with the box containing the instruments mounted on it, is brought successively in about 140 predetermined positions. In each of those, the three instrument readings and the table attitude relative to the vertical are recorded directly on paper tape.

A second phase is carried out on the turntable, where the calibration of the Z-accelerometer is extended beyond +1 g.
The calibration points of the three instruments are analyzed on the
digital computer using a calibration formula, in a manner similar to the
method described for the rate gyro.

For each of the instruments a calibration formula is set up, which the
calibration points should obey. This formula contains several secondary
terms, to include effects such as instrument nonlinearity and misalignment and
crosscoupling. As an example, the formula used for the X-accelerometer is:

\[ A_x = c_0 + c_1 e_x + c_2 e_x^2 + c_3 e_y + c_4 e_z + c_5 e_x e_y \]

where \( A_x \) is the measured acceleration along the X-axis and \( e_x, e_y \) and \( e_z \)
are the voltages produced by the three respective accelerometers. Similar
formulas are used for the Y- and Z-accelerometers.

The unknown coefficients in the three calibration formulas are determined
for each accelerometer separately by means of a regression analysis, in the same
way as for the rate gyro.

Results obtained by following this procedure, are given for the
X-accelerometer in fig. 11. As in the case of the rate gyro, the differences
\( \Delta A_x \) between the measured \( A_x \) - a known component of g during the calibration -
and the values predicted by the formula from the measured values of \( e_x, e_y \) and \( e_z \), are presented as a function of \( A_x \).

\( \Delta A_x \) given in fig. 11a was obtained by inserting the data points of
calibration I in the formula, using the coefficients c found from this same
calibration. It can be seen that the maximum value of \( \Delta A_x \) is about .001 g.
The r.m.s. value of \( \Delta A_x \) is .00035 g, equivalent to 1.6 mV on the DVM.

Just as in the case of the rate gyro, these figures include the
characteristics of the filters and the DVM as well. It seems that a scatter
of this magnitude might well be caused by the filters and the DVM alone.

An idea of the repeatability of the calibration may be obtained from
fig. 11b. Here the data points of calibration II have been used in conjunction
with the coefficients c found from calibration I, to obtain \( \Delta A_x \). The values
of \( \Delta A_x \) in this case are certainly not larger than those in fig. 11a. The
r.m.s. value of \( \Delta A_x \) in fig. 11b is .00034 g.

From these results it might be concluded, that, with the present equipment
in the instrumentation system, hardly any improvement may still be expected
as regards the calibration of the X-accelerometer.
Some measured accelerations, obtained from recordings in flight are presented in fig. 12. Here a time history of $A_z$ is given, as measured during a manoeuvre. The quality of the data is again shown more clearly in the enlarged picture of the brief period of "steady" flight, preceding the manoeuvre. Quite obviously, the quality of the recordings not only depends on the instrumentation system, but also on the prevailing atmospheric conditions.

3.3. The measurement of the change in static pressure.

The last instrument to be described is a system in itself, rather than a single instrument. It is used to measure changes in the static pressure and it begins to measure at the moment the manoeuvre of the aircraft starts. Knowledge of the change in static pressure is required, to determine change of height and flight path angle during the manoeuvre.

Before describing the system in some detail, it may be advisable to indicate briefly how the static pressure is obtained.

From a swivelling static tube, mounted one chord length ahead of the R.H. wingtip, a static pressure is obtained, which after suitable correction for position error, equals the undisturbed static pressure. In order to reduce the magnitude of pneumatic lags in the system to be described, the pressure from the swivelling static tube is not fed directly to the measuring instruments. Instead, only the difference with the static pressure at one spot in the cabin is measured with a sensitive differential pressure gauge. The cabin pressure at that spot can then be used as a source of "raw" static pressure. The static pressure as referred to in the following section is this cabin pressure.

The system to measure the change of static pressure is rather simple in principle, as depicted in fig. 13a. It contains a highly sensitive differential gauge (Ateliers de Construction de Bagneux, France) as the sensing element. The full scale range of this instrument is $\pm 2$ mb, corresponding to a change in altitude of $\pm 60$ feet at sea level. One side of the gauge is continuously connected to the cabin pressure. The other side remains in connection with the interior of a thermosflask.

The operation of the system is as follows. All that is necessary to obtain the change in cabin pressure, is to shut off the interior of the thermosflask from the atmosphere, by closing the valve at the entrance of the flask.
Changes in the cabin pressure are then sensed by the differential pressure gauge. These changes can be simply measured and recorded.

As might be expected, there are some complications if such a system is brought into actual operation and if some accuracy is demanded of it.

The first complication coming to mind is the limited range of the sensing element. If the change in cabin pressure is caused by a change in aircraft altitude, the point can be reached very soon, where the differential pressure gauge is at the limit of its range. This is the reason why the actual system consists of two identical parts, as shown in fig. 13b.

The system is switched on by closing the two valves A and B, guarding the gauges against inadvertent overpressure.

Normally only one of the two parts is in operation, the other part being passive. This means that either valve C or D is closed. As soon as the operative part of the system reaches about 80% of its full range, the second part comes into operation as well. The two parts operate together for a short period of about .5 sec in order to provide some overlap in the pressure measurements. Thereafter, the once operative part is made passive and the other part remains in operation. This new situation remains unaltered, until the now operative part reaches again a differential pressure of about 80% of its full range etc.

All switching of the pressure lines in the system is done by means of glass valves, operated by rotary solenoids, fig. 14 and 15. These solenoids are commanded by an electronic system, also shown in fig. 14.

From this short description of the system it may be apparent, that a combination of two identical parts results in a system for measuring the change of static pressure with a high sensitivity, which cannot easily be damaged by overpressure.

The system apparently has three different modes in which it can operate: either of the two parts can be active, or both. For the data analysis it is essential to know the mode of the system for every instant during the manoeuvre. This is why in the airborne parallel-series converter, described earlier, the mode of this system is indicated with every individual measurement.

The system described so far can still be considered rather straightforward in its conception. The operation of the actual hardware is extremely simple, as all switching is done automatically. The system needs only be turned on and off and this is done by the same switch that commands the beginning and the end of all recording for a manoeuvre.
The main difficulty of the system lies in its extreme sensitivity to changes in the air temperature inside the thermosflask of the operative part of the system. It can easily be shown, that even a change as small as .01°C inside the flask causes a change in indicate differential pressure, corresponding to a change in height of about 1 foot. This is the reason why actually two thermosflasks instead of one are used in each part of the system.

The scope of this paper does not permit, however, a full discussion of the possible errors in the system due to temperature influences. It must suffice here, to state that the system has proved to operate very satisfactorily in the laboratory as well as in flight.

From the information obtained so far, it is estimated that the accuracy of the measurements of the change of static pressure, over a period of about 10 sec, corresponds to about 4 inches change of altitude at sea level. This is equivalent to about .30 of the full scale range of the sensing elements. Recordings made in the laboratory have shown this figure to be quite feasible. Quantitative measurements in flight are still to be made.

It has to be kept in mind, that the system only measures the change in cabin static pressure. A correction to obtain the undisturbed static pressure remains necessary, as was mentioned earlier.

It is a straightforward matter to convert the change in static pressure \( \Delta p \) into a change in height \( \Delta h \).

Calibration of the sensitive differential pressure gauges used in the system, takes place with the instrument shown in fig. 16. Differential pressures between 0 and 10 inches of water column (.35 lb/sq in) are generated in this tilting piston pressure gauge.

The instrument was built at our University according to a description by U.O. Hutton in the Journal of Research of the National Bureau of Standards, Vol. 63C, no 1, 1959.

A piston of known weight can move inside a glass cylinder with a known cross section. By varying the tilt of the cylinder, a variable component of the piston weight rests on the air below. In this way a variable pressure of known magnitude is generated below the piston.

In order to virtually eliminate the friction between piston and cylinder, the latter is rotated by a rubber belt, driven by a small electric motor. As the piston is ballasted asymmetrically, it does not rotate with the cylinder. The
clearance between piston and cylinder is only a few microns, causing the piston to rest on an air bearing inside the cylinder. The cylinder itself runs on an air bearing at its lower end, where it is supported.

The accuracy obtained with this instrument is about 0.015 \% of the maximum pressure. Such a small differential pressure corresponds to about 1.5 inches of air column at sea level.

The instrument is used as a primary pressure standard. Nevertheless it proved to be extremely simple to operate.

4. **Concluding remarks.**

In this paper a brief description has been given of some of the work, performed in the past few years at the Department of Aeronautics of the Technological University of Delft.

This work concentrated on the development of a flight test method to measure various aircraft characteristics in non-steady flight. To this end, a high-accuracy instrumentation system has been developed. A description of the system was given in this paper, together with a discussion of the techniques used to calibrate some of the more accurate transducers in the system.

A final remark may still be made concerning the use of high-accuracy techniques, such as described in this paper, for flight test purposes. It is not meant to imply that the usual techniques of conventional accuracy should be expected to generally give way to these more accurate ones. It is believed, that these new techniques are not an end in themselves. Their use can be justified only in cases where measurements of more conventional accuracy do not satisfy the requirements. The proposed flight test method is such a case, other applications may arise in the future.
Fig. 3 OVERALL VIEW OF THE INSTRUMENTATION SYSTEM.

A. FILTER NETWORKS
B. SCANNER
C. DIGITAL VOLTMETER (DVM)
D. PARALLEL-SERIES CONVERTER
E. TAPE RECORDER
F. CONTROL AND INSTRUMENT PANEL FOR OBSERVER

G. EQUIPMENT TO MEASURE DYNAMIC PRESSURE AND CHANGE IN STATIC PRESSURE
H. THERMOSTAT CONTAINING SERVO-ALTIMETER
K. ±10 V REFERENCE SUPPLY
L. BATTERIES
M. POWER SUPPLIES
a) CALIBRATION I, \( \Delta q - q \)

b) DATA POINTS OF CALIBRATION II INSERTED IN FORMULA OF CALIBRATION I

FIG. 8: RESULTS OF TWO CALIBRATIONS OF PITCH RATE GYRO
a) CALIBRATION I, $\Delta A_x - A_x$

b) DATA POINTS OF CALIBRATION II INSERTED IN FORMULA OF CALIBRATION I

FIG. 11: RESULTS OF TWO CALIBRATIONS OF X-ACCELEROMETER.
FIG. 12: NORMAL ACCELERATION, RECORDED IN FLIGHT.
FIG. 13: SYSTEM TO MEASURE CHANGE IN STATIC PRESSURE
Fig. 14 EXTERNAL VIEW OF SYSTEM TO MEASURE CHANGE IN STATIC PRESSURE.
Fig. 15 SYSTEM TO MEASURE CHANGE IN STATIC PRESSURE, TOP SECTION REMOVED.