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A Digital Data Acquisition System for High Subsonic Speed Wind Tunnels

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Abstract

The need to reduce time and cost of running high speed (transonic & supersonic) wind tunnels and to obtain reliable experimental data is very essential to the academic and industrial worlds of aviation. Data acquisitioning technology together with the advents in computer programming made the prospects of upgrading old technology wind tunnels (those manually driven and using mercury or water manometers) a reality. Simple hardware and software are available and are cheap and very effective and can be easily installed for the purposes stated. The present paper describes a data acquisition system, suggested and installed, by the author for use on the supersonic wind tunnel at the university of Hertfordshire/UK. The tunnel layout and the acquisition system are described together with some of the validation experimental runs. The experiments were carried out originally as part of the author's PhD research work investigating the effects of aerofoil surface irregularities at high subsonic speeds using the viscous Garabedian & Korn (VGK) method [1].

Keywords: Analogue to digital (A/D) card; Data acquisition; Digital to analogue (D/A) card; Hardware/software; Modified (indented) NACA 6410 aerofoils: I0082070; represents indentation extending from 0.20 to 0.70 with a maximum depth of 0.008 at the centre; I0081020; represents an indentation extending from 0.10 to 0.20 with a maximum depth of 0.008 at the centre of indent (all dimensions are relative to the chord length of the aerofoil); Pressure transducer calibration; Scanivalve; Supersonic speed; Transonic speed; Tunnel calibration; VGK code; Wind tunnel.

Symbols

A_w=Wind tunnel working section cross sectional area

A_t= Wind tunnel throat cross sectional area

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M=local Mach number

M_∞=Free stream Mach number

P_o =Wind tunnel Pitot pressure

P_s= Wind tunnel static pressure

γ = Specific heat capacity ratio (=1.4 for air)

1. Introduction

The classical pressure manometer techniques (manual techniques) used in measurements of pressure distribution over a model under test in a wind tunnel, are still widely used and are very reliable and effective in obtaining correct data although human errors are encountered during these tests. The human errors are mainly associated with the skill and experience of the operator (ability to stabilise the flow to the required supply pressure within the run time), the speed of the flow, responsiveness of the manometer equipment to the right moment of taking the reading, and the tunnel run-time which depends on the sustainability of the supplied pressure for the required time of testing. These issues are particularly important when dealing with high subsonic/supersonic speed wind tunnels specially when run by new students at universities in their first and second years of their undergraduate study. The aim of replacing the classical mercury/water manometers with a digital system is to reduce the number of experimental runs before arriving at a good (quality) run with confidence and reliable experimental data, thus saving time and cost. In this paper a digital system is explained with experimental data as applied to the supersonic wind tunnel at the University of Hertfordshire, UK.

2. The wind tunnel

The supersonic (200x230mm^2) blow-down wind tunnel at the University of Hertfordshire is of the intermittent blow-down type. It has a closed working section with solid walls and in its original supersonic configuration is capable of performing tests in the range of 1.5 to 4.0 Mach numbers and Reynolds numbers up to 1x10^8/metre. Pressure is supplied through external storage vessels that can be pressurised to 350 psig. (23 bar g) allowing a run time of up to 1 min. The working section has an area of 0.046 m^2. (0.203m. wide x 0.228 m. high), two circular side windows (0.203 m. diameter) are inserted in the steel side walls and positioned to give a clear view of the model for photography and flow visualisation. The working section is preceded by a settling chamber, which has a diameter of 0.914m, and has a series of screens to help expand the air and reduce turbulence. Model mounting and security is provided by a support structure that is mounted in a unit that can be separated from the working section thus providing easy access to the model. The model itself can be attached to the support structure via a specially designed “sting” to suit each particular model. The support structure also provides for powered pitching of the model allowing for model incidence angles between: -5^0 to + 20^0. After starting the tunnel, pressure is supplied to the settling chamber and working section through a manually operated valve; opening the valve increases the pressure and closing it decreases the pressure. Pitot pressure in the settling chamber can be directly measured via a pressure tapping provided at the top of the chamber. Pitot temperature can also be measured using a platinum resistance thermocouple also installed through a port at the top of the settling chamber. While the operator (using the above- mentioned manually operated valve) can reasonably control the pitot pressure, the temperature is not controllable. Tunnel static pressure can also be measured via static ports at one sidewall. Figure (1) shows a schematic diagram & plate (1) a general view of the tunnel, while further information regarding the tunnel performance and specifications can be found in reference 2.

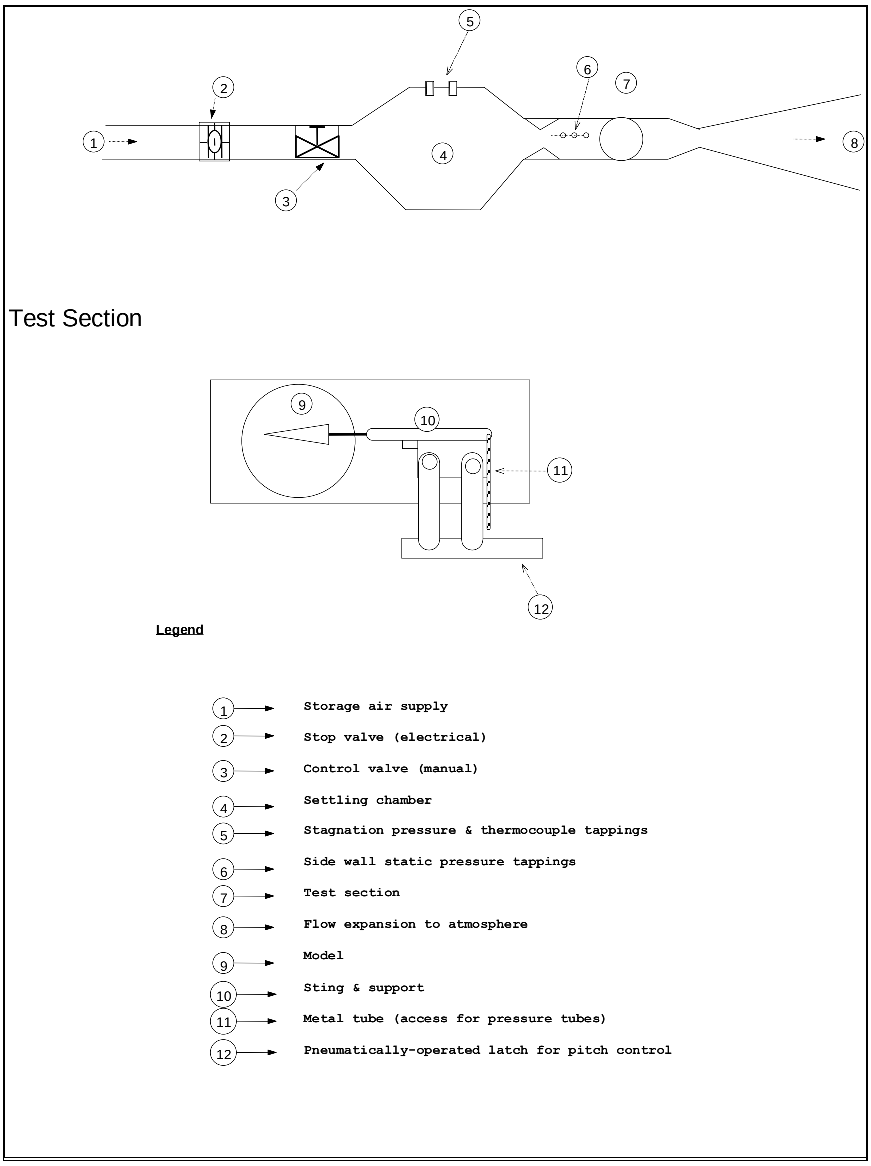

Figure 1: Supersonic wind tunnel schematic diagram

Figure 13: The supersonic wind tunnel at the University of Hertfordshire

2.1 Adaptation to transonic testing

To achieve subsonic speeds in the working section parallel liners are used at the exit of the settling chamber, with a throat section downstream of the working section. The Mach number is regulated by controlling the applied pitot pressure. The area ratio of the working section to the throat is related to the choking Mach number by the following relationship:

$$\frac{A_W}{A_t} = \frac{1}{M}\left[\frac{1+\left(\frac{\gamma-1}{2}\right)M^2}{\left(\frac{\gamma+1}{2}\right)}\right]^{\left[\frac{(\gamma+1)}{2(\gamma-1)}\right]} \qquad (1)$$

The ratio of the test section area to the throat area is 1.175, which gives a maximum Mach number of about 0.61 corresponding to choking conditions at the throat.

2.2 Tunnel calibration

Tunnel calibration in the transonic configuration was carried out by pitot/static pressure measurements and applying the equation:

$$\frac{p_s}{p_0} = \left[1+\left(\frac{\gamma-1}{2}\right)M^2\right]^{\left[\frac{-\gamma}{(\gamma-1)}\right]} \qquad (2.a)$$

Or equivalently:

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{p_s}{p_0}\right)^{\left(\frac{1-\gamma}{\gamma}\right)} - 1\right] \qquad (2.b)$$

Pitot pressure readings were taken from a line directly connected to the tapping in the tunnel's settling chamber, while the static pressure readings were achieved from one of the side wall tappings. Also calibration was performed using a pitot-static tube installed in the working section to provide a comparison between the two methods. Figure (2) shows the calibration results for the empty tunnel giving a comparison of the results of the two calibration techniques. This shows that the tunnel started to choke at the downstream throat at a Mach number of 0.60 approximately. Also shows that the results obtained from both of the calibration techniques are comparable with each other. The measurements were taken using the data acquisition system and software which was built for the purpose of fast data acquisition explained below.

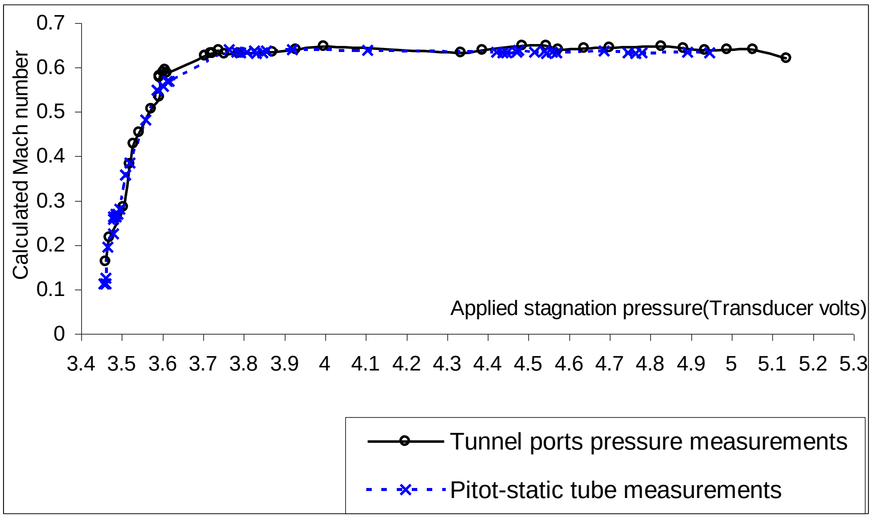

Figure 2: Tunnel Calibration

3. Data acquisition system

3.1 General

The supersonic wind tunnel run time is about 1 to 1 1/2 minutes and for extensive measurements of model surface pressure distribution, with pressure ports having small diameter (0.25mm approx.) a fast-response pressure measurement system must be used. Such a system must be able to sense and record the pressure values at all ports and sample each port a number of times within the time limit imposed by the tunnel run. Added to this time limitation is the settling time required for the ports after the start of the tunnel, or due to inadvertent (unavoidable!) pressure changes during the run due to the fact that the tunnel is operated by a hand-controlled valve. In addition, and in parallel to the surface pressure measurements required, tunnel pitot and static pressures are also measured continuously during the run. The hardware includes a scanivalve connected to the surface pressure ports outputting them sequentially to a transducer having a range of 0 to 30 psia (absolute pressure), with an output range of 1 to 6 volts. Two other transducers (input range 30 & 15 psia, output: 1 to 6 volts) were connected to the tunnel's pitot and static pressure ports respectively. (See schematic diagram-figure 3 below). Tunnel pitot temperature was also measured using a platinum resistance type thermocouple connected to a digital temperature reader. The transducer's output was fed into a data acquisition card which was capable, through programming, of data conversion (analogue to digital), simultaneously recording and sampling data from more than one source (up to 16 channel inputs) at a pre-programmed frequency (up to 150000 samples/second, if required). The Scanivalve was stepped from one port to the next after the number of required data samples was achieved at each port. This stepping sequence was controlled via a control box driven by the programmed digital output from the D/A converter, which formed part of the data acquisition card. A commercial software package (called HP-VEE) was used to program the acquisition process together with the output to drive the scanivalve. The programme uses a graphical (visual) language, thus reduces the need to write long routine programs that may be prone to syntax errors and may take a long time to develop and test.

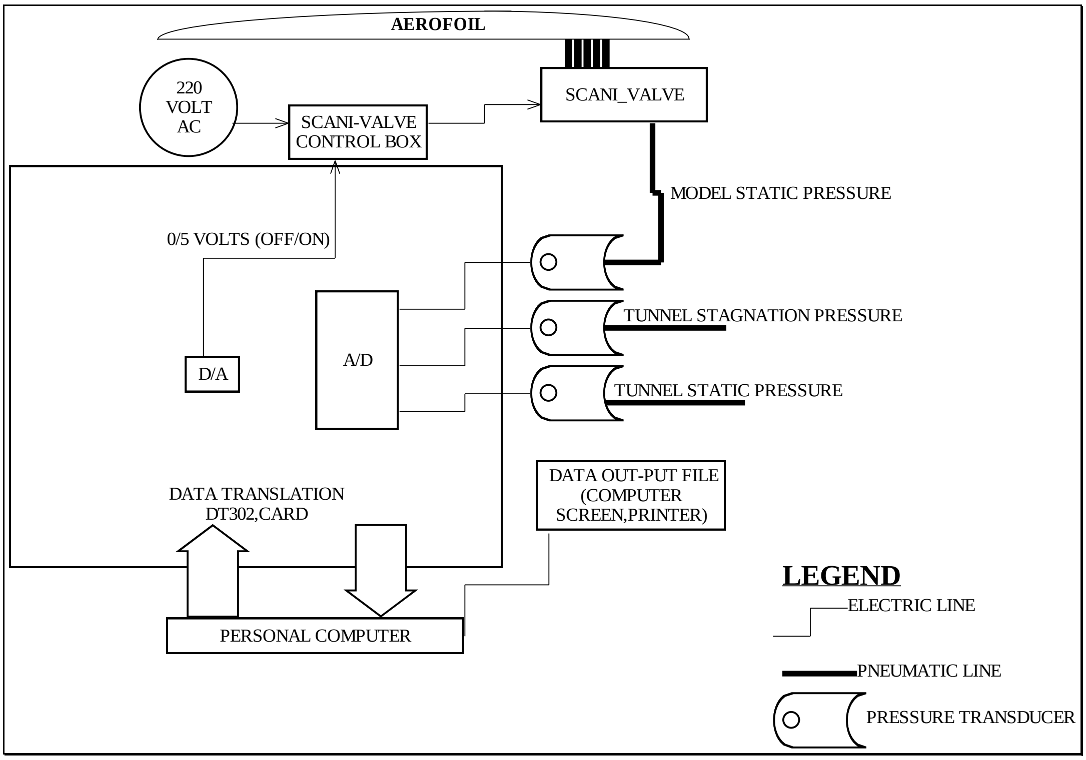

Figure 3: Data acquisition schematic diagram

3.2 Transducer calibration

As the transducers were of the absolute pressure type, their calibration was carried out using a vacuum pump connected to a mercury-filled U-tube manometer. The pressure port (input) of each transducer was connected to the same side of the manometer via a T-connection, while the output of the transducer was measured on a digital voltmeter accurate to 3 significant figures in the design range of the transducer output (1-6 volts). A shut-off valve was provided between the vacuum pump and the manometer (after the transducer connection point). This was used to re-pressurise the system gradually and facilitate data reading at intermediate stations (mercury column height versus transducer output). The equipment set up is shown in figure (4)

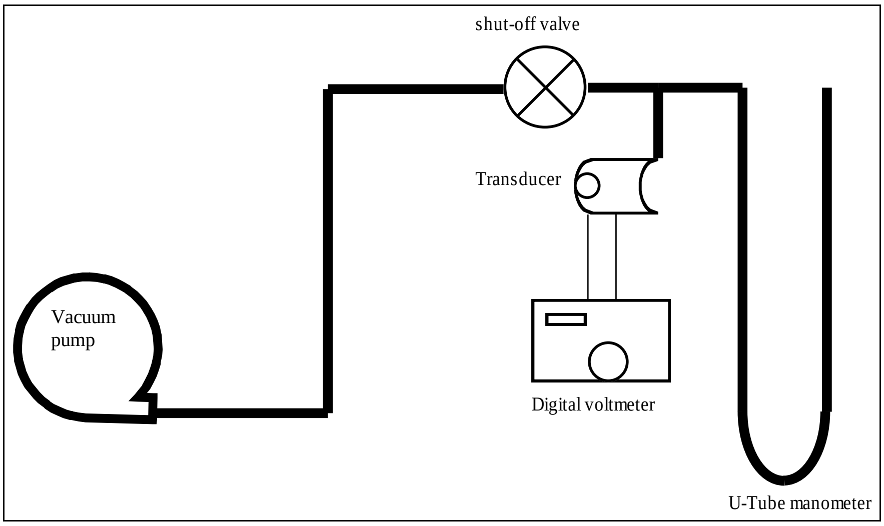

Figure 4: Transducer calibration set-up

The vacuum pump was started while the shut-off valve was open, and was run for a sufficient time until the difference in the mercury columns was at the maximum achievable (after a 30-minute run the difference in height was hardly changing). The shut-off valve was then closed and the vacuum pump stopped. The height reached (in mm Hg) was recorded against the transducer output (in volts), then the shut-off valve was slightly opened and closed very quickly and the new height (after stabilising) and transducer reading were recorded. The process of opening and closing the valve was repeated several times until zero height difference between the two sides of the U-tube manometer was restored. Height readings were subtracted from the value of the atmospheric pressure (which was equivalent to 748mm Hg, on the day of the calibration), the results here represent the absolute pressure value as sensed by the transducer. The process was repeated for all the transducers and calibration results are shown in figure (5).

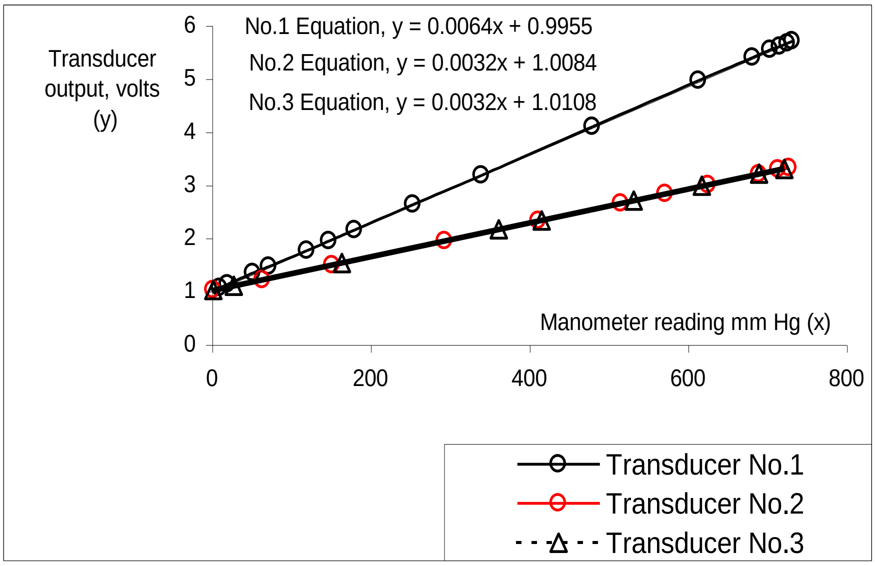

Figure 5: Transducer calibration results

3.3 Data acquisition software

As mentioned earlier, the program developed for the purpose of data acquisition is based upon a graphical programing language called HP-VEE. The program in HP-VEE consists of selected objects chosen from a menu window and connected to each other via lines that attach to the object's "pins". A group of objects and their specific connections makes up a program. Another software system used in conjunction with HP-VEE is the DT-VPI (Data Translation Visual Programming Interface), this adds objects in HP-VEE that are specifically designed to control data acquisition hardware supplied by Data Translation [3,4].

3.4 Acquisition sequence

Before the tunnel was started, the scanivalve was "homed" manually, this ensured that data from port No.1 were the first to be acquired. As the model's surface pressure holes were sequentially connected to the scanivalve ports, port No. 1 represents hole No.1 on the model (counting from the leading edge to the trailing edge on the upper surface) and so on. Acquisition was initiated by clicking a "start" button in the program after the tunnel had been started and the required pitot pressure reached. The specific software for the present work was designed to enable data to be acquired within the limited run time of the tunnel (1-minute approx.). It allows for the simultaneous acquisition of the tunnel's pitot and static pressures together with a scanned surface static pressure of the model under test. This provides for separate, but instantaneous monitoring of static pressure variations with the variations in the applied pitot pressure, giving an indication of any "lag" in the static pressure response. The measured variations (with time) in the provided pitot pressure (due to the tunnel being manually-driven) can be used to indicate a measured trend of the errors in the pressure coefficients distribution over the model under test. This allows for accounting for the experimental errors, which also can be used as a "nice to have" tool in judging (validating) computational fluid dynamics codes. The programme outputs data as both individual (raw) values of pressure and calculated values of pressure ratios and free stream Mach number. The A/D converter picks up the transducers' output signals and writes their respective readings to the output files after performing the required manipulation of the data. At each static port a pre-set number of data samples at a given frequency is taken and data are transferred to the output files before the scanivalve is stepped to the next port. The frequency and number of samples can be altered to allow for the following to be achieved:

a) Maximum number of ports to be scanned and sampled within the time limit during which the pitot pressure can be held reasonably constant by the operator –usually 30 to 45 seconds due to the continuous pressure drop in the main supply (the tunnel's storage vessels).

b) Sampling rate (number of samples at each port) must be such that the total sampling time at each port must cover the total time needed for the static pressure to respond to changes in the pitot pressure; that is to account for the "lag".

Program flow execution starts with retrieving data from the first port, and after this is done the D/A converter is activated to send a signal to the scanivalve control box, thus stepping the scanivalve to the next port. This cyclic execution continues for specified counts to cover the total number of ports available, unless dictated by the maximum tunnel run time. The present author designed the specific program for this purpose (designated as "scandata.vee"). Figure (6) shows a schematic flow chart of this program. To assess the results obtained through the data acquisition system as outlined above, experimental runs were conducted on a modified

NACA64010 aerofoil section (with an upper surface indentation) using the open jet slow speed wind tunnel at the University of Hertfordshire. This model was used previously [5,6] to assess the performance of the Viscous Garabedian & Korn (VGK) [7,8] code for an aerofoil surface with indentations at slow speeds. The data obtained here (using a water manometer for the pressure measurements), would provide a direct comparison with that obtained using the data acquisition system. The experimental results and data comparisons are given below.

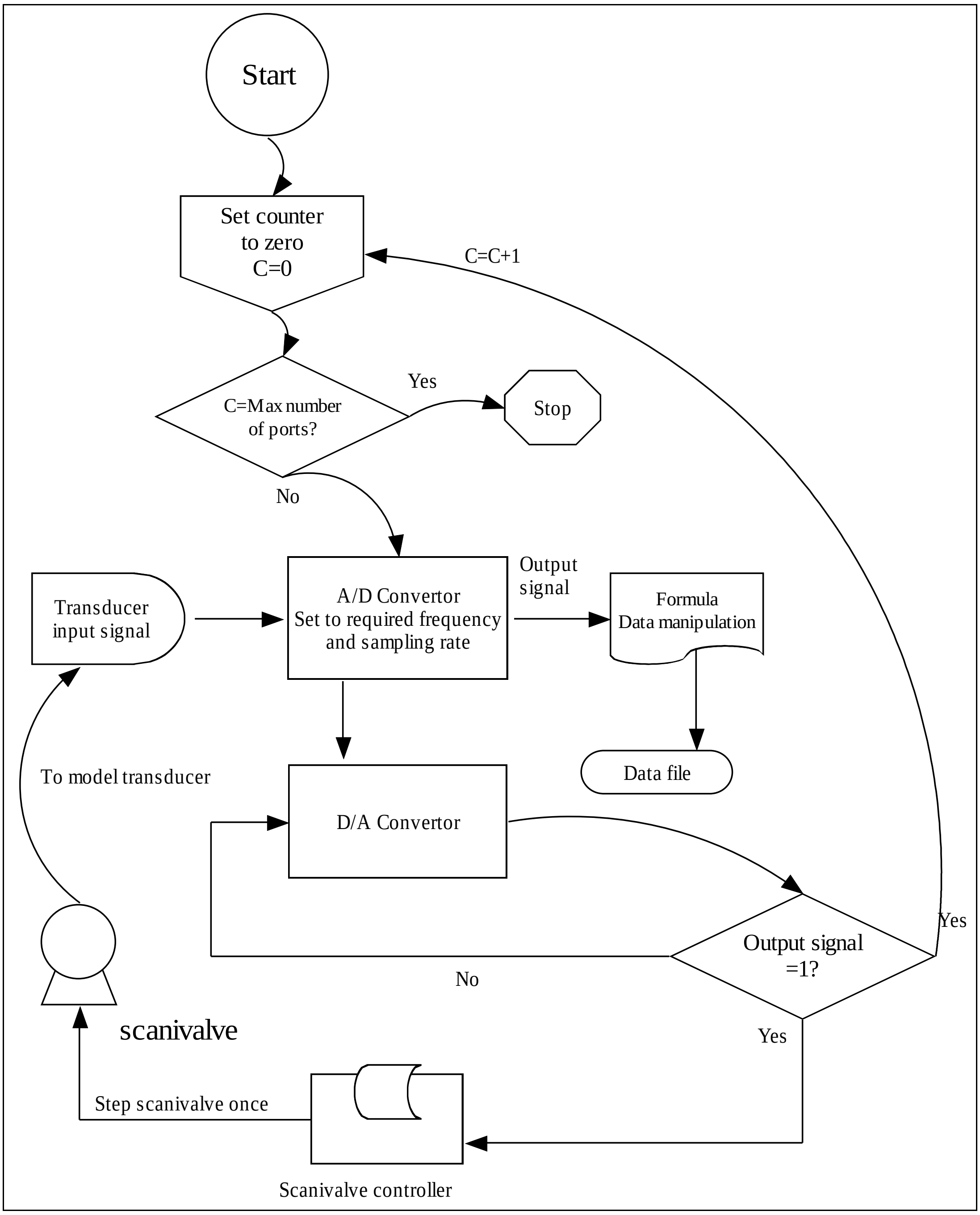

Figure 6: Data acquisition programme “scan data.vee” flow chart

3.5 System limitations/constraints

The suggested system (hardware and software) although for the purpose of high speed intermittent wind tunnels, its setup and calibration (validation of data obtained with previously known data) still needs to be performed with slow speed (continuous) wind tunnels. The reason is mainly due to the fact that the high speed wind tunnels usually run for a short time (about 1 to 2 minutes) before losing the flow energy from the main supply tanks. In addition, the flow setting time of the tunnel takes between 15 to 30 seconds of the run time depending on the skill of the operator. Nevertheless, this limitation is only procedural and mainly depends on the availability of slow speed tunnels. Another constraint is the fact that the acquisition of the pressure data (the static pressure distribution over the immersed model) is measured via a single pressure transducer which receives the readings input through a Scanivalve (stepper motor). This entails that any large pressure variations (pressure gradients) between consecutive ports may not be fully captured by the transducer. This limitation introduces some errors to the experimental data which must be accounted for. Such errors depend on the transducer responsiveness, the lengths of the connecting pipes (between the ports and the Scanivalve), the transition time between ports (stepping time) and the pressure gradient between consecutive ports.

4. Experimenting with the proposed data acquisition system

4.1 Preliminary slow speed runs

These runs were carried out in the open jet slow speed wind tunnel at the University of Hertfordshire, using a modified NACA64010 (with an upper surface indentation designated here as I0072468) model. This was the same model used for the tests in references 5,6. The original tests [5,6] were performed to assess the performance of the VGK code with an indented aerofoil section at slow speeds. The main objective of performing these runs here was to assess results obtained via the data acquisition system through comparison with the existing data of reference 6, which was obtained through direct water manometer measurements. Since run time and controllability of speed in the slow speed wind tunnel do not constitute limiting factors-as in the intermittent blow down transonic tunnel, these runs should provide a useful indication of the correct tuning of the parameters affecting the accuracy of the data acquired electronically. That is the number of samples and frequency (speed of acquisition) required to be representative of the experimental data. This was done by acquiring data at a certain frequency and number of samples, so that the total time needed to scan all the ports was less than the time allowed for in the high speed tunnel. Results were then compared with the existing data [6], and with those of repeated runs. Accuracy of data was then assessed and repeatability of results used to indicate whether settling time required -to avoid the effects of pressure lag- between port stepping is adequate. A number of trial and error settings were examined and it was found that a frequency of 12Hz and 10 samples of data at each port was satisfactory to cover 30 ports in about 30 seconds of run time. Because pressure differences between successive ports were not the same for the low and high speed runs, the setting of such parameters required re-examination when considering the high speed runs. Experimental results, (M_∞=0.13) compared with VGK are shown in figures (7) and (8). Compared to reference 6, these results support the validity of the data obtained via the acquisition system and indicate better agreement with VGK outside the region of indentation. Within the indentation, however, the indicated disagreement, figure (7), is thought to be due to errors in the input data for the geometry of the indentation (input into the VGK code). In figure (8), measured co-ordinate data are used and as seen here the agreement between the present work, experimental data and VGK is excellent. Comparing experimental data [6] obtained through a manual pressure measuring system (water or mercury manometer) and the data obtained by the acquisition system (present work) indicates that the data acquisition data is in a much better agreement with the theoretical data calculated by VGK. This indicated that the proposed data acquisition system is more reliable and can eliminate (to a good extent) the experimental human errors.

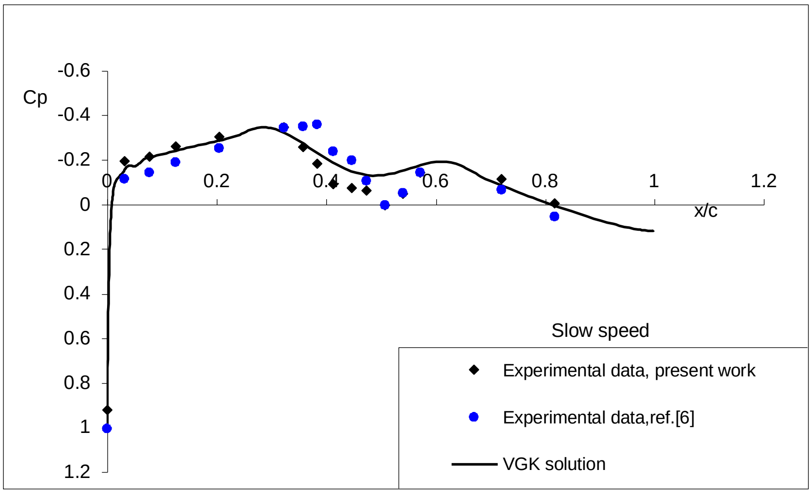

Figure 7: Slow speed experimental and theoretical (VGK) upper surface Pressure distribution, (for I0072468, theoretical geometry used in VGK)

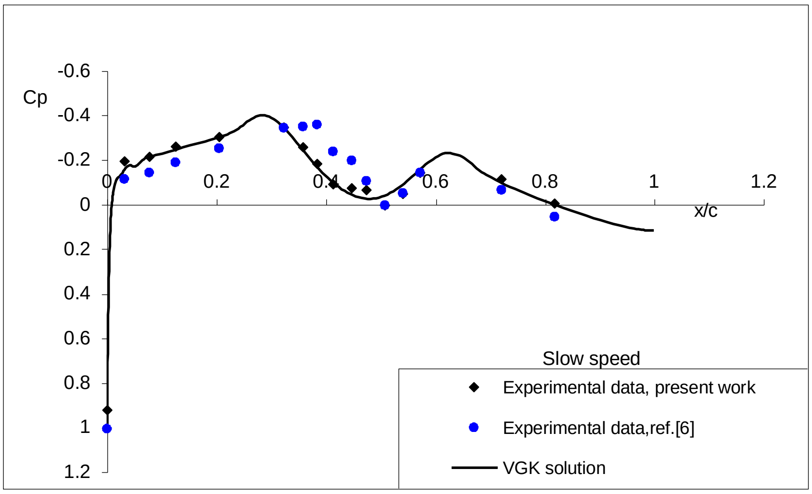

Figure 8: Slow speed experimental and theoretical (VGK) upper surface Pressure distribution, (for I0072468, measured geometry used in VGK)

4.2 High Speed Runs [1]

Experimental runs on the high speed wind tunnel were carried out on a number of aerofoils with different indentations on the upper surface. These runs were, again, performed to assess the VGK performance with surface irregularities at high subsonic speeds. The experimental data was collected using the present data acquisition system and the results shown here (figures 9 &10) are taken from reference (1) with the modified NACA 6410 aerofoil (designated as I0082070). These results show that reliable data can be obtained using the acquisition software. Also shown in figure (11) the variations in the wind tunnel static/pitot pressure ratio as picked up by the software. Such variations indicate the quality of the run and, also, provide a quantifiable source of the experimental error (the human error). In fact, it can be seen that in this figure settling time is reached after about 15 seconds. The standard deviation for the static/pitot pressure ratio was calculated as 0.2905% (for the whole run), while for the period after settling (15 seconds), the standard deviation was found to be 0.045% which, of course would indicate more dependable experimental results. Regarding the set-up of the data acquisition system it was also found that a frequency of 12Hz and 10 samples /port was adequate to produce reliable and repeatable data. The frequency, however, was increased to 25Hz for the runs with the I0081020.dat profile [1]. This was done to reduce the overall run time (by about 50%) allowing better tunnel-drive control, hence reducing the standard deviation in the applied pitot pressure. A "nearly constant" applied pitot pressure reduces the resulting variations in the tunnel's static pressure, hence the effects of non-settling are reduced. Figure (12) indicates the wind tunnel static/pitot pressure ratio variations and for the whole run the standard deviation is found to be 0.0912%. The overall test results obtained by the proposed data acquisition system as shown in figures 9, 10 below, again, indicate very good agreement with the theoretical predictions by VGK. However, as shown in figure 10 (where here the indentation used sharply changes curvature), the indicated acquisition data (experimental) within the indentation region shows some discrepancy with VGK at two points in the graph just after the ordinate with the maximum depth of the indentation. This discrepancy is due to both the VGK and the data acquisition. It has been shown [] that VGK is more efficient with smooth ordinate data input (accordingly large changes in curvature specially around inflexion points could lead to unreliable data). Also high pressure gradients can affect the pressure readings as picked up by the transducer (responsiveness to pressure changes between two consecutive ports).

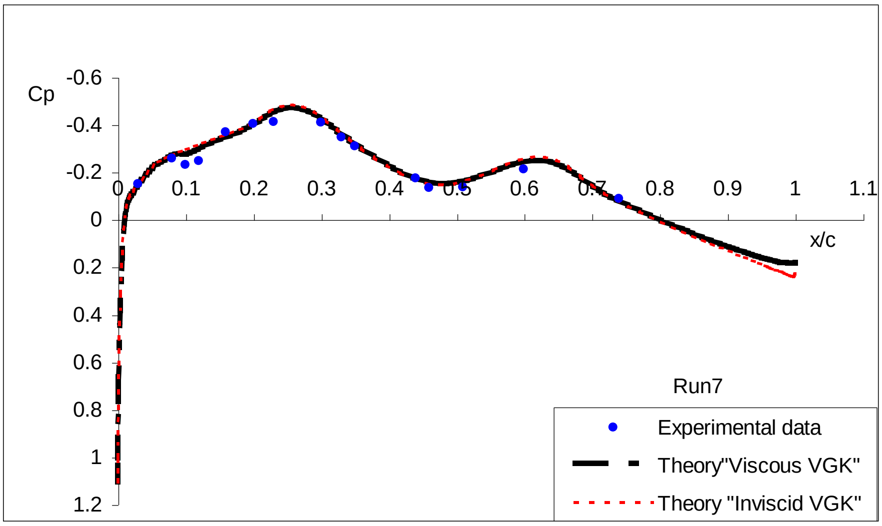

Figure 9: Experimental data compared with VGK theoretical predictions using (I0082070) profile. M_∞=0.613, α=0.0 degrees. Sampling frequency=12 Hz with 10 samples at each port

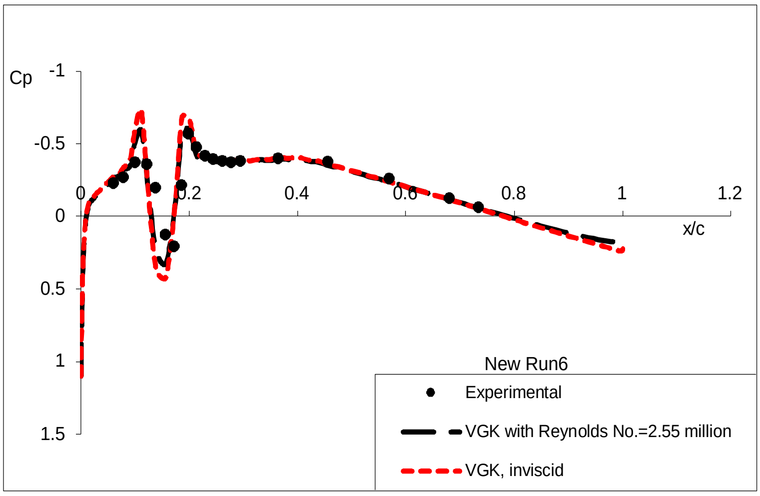

Figure 10: Experimental data compared with VGK theoretical predictions using (I0081020) profile. M_∞=0.6123, α=0.0 degrees. Sampling frequency=25 Hz with 10 samples at each port

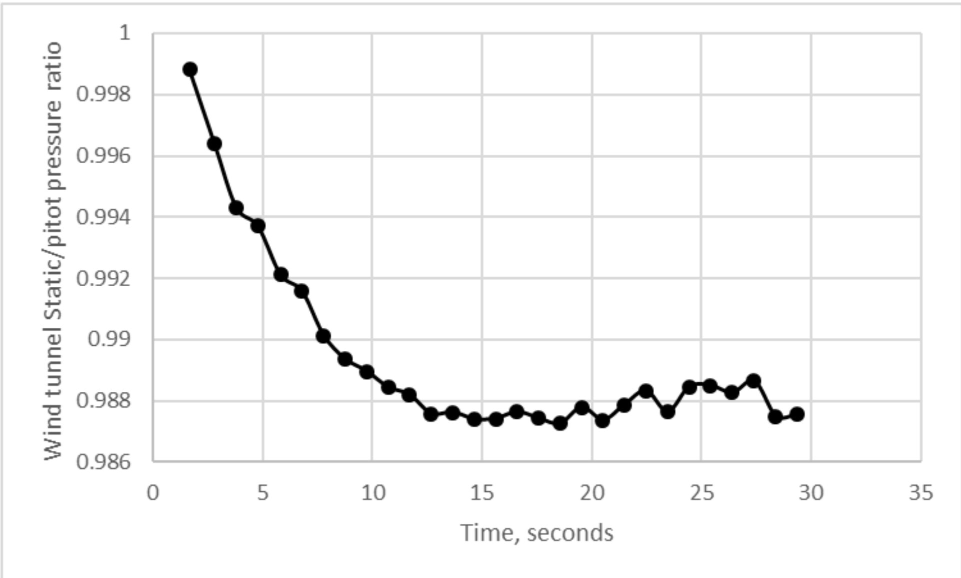

Figure 11: Variation of tunnel static pressure with applied pitot pressure (Sampling rate at 12 Hz),standard deviation for the whole run time =0.2905%, standard deviation for data after 15 seconds (settling time) = 0.045%

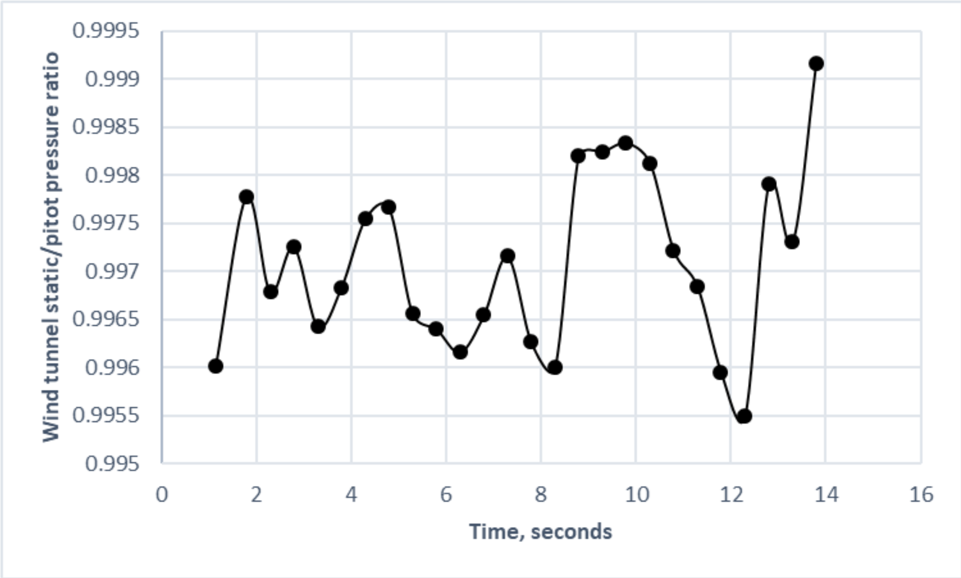

Figure 12: Variation of tunnel static pressure with applied pitot pressure (Sampling rate at 25 Hz), standard deviation for the whole run time=0.0912%.

5. Conclusions

A data acquisition system for use with high speed wind tunnels was described. Experiments were carried out on a slow speed wind tunnel on a modified NACA6410 aerofoil section. These runs helped to compare with previously obtained results using the water manometer for pressure measurements on the surface of the aerofoil together with the data obtained using the VGK code. The system then was installed on the high speed wind tunnel and results and experimental runs were carried out up to the maximum achieved Mach number for the tunnel (in the transonic configuration). The data obtained here showed the acquisition system was reliable and data is dependable. The system helped to reduce running time and cost (by avoiding the need to carry out more than one run to achieve good results when the ability to control the tunnel run is an issue). The system also helped to produce additional information by monitoring the variations in the applied pitot pressure thus helping to account for this source of human error and to reflect its effects on the output data (pressure distribution on the aerofoil surface). All results were compared with those predicted by the VGK code and showed excellent agreement with each other.

6. Recommendations

It is recommended that the proposed data acquisition system can be used to replace the classical techniques to data measurements in wind tunnels. The system provides reliable data in addition to the benefits of time and cost savings. With some adaptation, the system can also be set up and applied to a wide range of instrumentations in different industries.

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