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J.F. T. MacLaren

S. V. Kerr

R. A. Crawford

R.G. Hoare

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A COMPUTER CONTROLLED SYSTEM FOR THE ACQUISITION AND PROCESSING OF EXPERIMENTAL DATA FROM RECIPROCATING COMPRESSORS

J.F.T. MacLaren : S.V. Kerr : R.A. Crawford : R.G. Hoare
Professor Senior Lecturer Lecturer Research Fellow

Department of Thermodynamics & Fluid Mechanics
University of Strathclyde, Glasgow, U.K.

ABSTRACT

A system is described in which a digital computer was used to control the acquisition, storage, processing and display of experimental data from a reciprocating compressor plant. Analog signals were conditioned, passed to an analog-digital converter and transferred to a mini-computer with direct memory access. The maximum processing rate of the analog-digital converter was 100,000 readings per second. The digital signals were either stored in the computer memory or fed into double buffer stores which were emptied sequentially to a cartridge disc sub-system. Each set of data was read sequentially from a maximum of 16 transducers located in a compressor plant; a set was read at each $\frac{1}{2}$ degree crankangle during a compressor cycle. The stored data was processed and displayed in digital form or in graphical form. The system provided more accurate results than had been obtained by more conventional systems, the storage capacity was large, and data could be processed and displayed very rapidly.

INTRODUCTION

When assessing the validity of the predictions made by models which simulate compressors and their valves it is the small differences between such predictions and experimental records at various locations in the compressor installation which are significant. To assist meaningful comparison it is necessary that the experimental records be accurate. Preferably all the experimental measurements should be made during the same cycle of the compressor since there may be variations from cycle to cycle. The differences between the predictions by a simulation model and the experimental records of pressures in the plenum chambers and cylinders, together with the displacement of the valves in a two-stage intercooled air compressor may be observed in Figure 1. These differences might be regarded as small but they were sufficient for the authors to improve the simulation model and develop a new system to obtain more accurate experimental records.

THE SYSTEM USED PREVIOUSLY

The equipment used to obtain the experimental records shown in Figure 1 included a cathode ray oscilloscope (CRO) and a 12 channel ultra-violet (UV) recorder. Several inherent sources of error in such a recorder imposed limitations on the accuracy which could be achieved. In addition it was impractical to record simultaneously the output from the many channels to be monitored: the traces had to be recorded in batches. Hence the experimental traces in Figure 1 do not all pertain to the same cycle of operation of the compressor. Also, although each batch included a mark which denoted crankangle position, there were errors in the phasing of traces relative to each other: these were particularly significant when traces had to be subtracted one from the other to evaluate a pressure difference. For example, the important parameter of the pressure drop across a valve had to be obtained from the small difference between the traces of plenum chamber pressure and cylinder pressure, both of which may be changing rapidly with time (crankangle) at portions of the cycle of interest such as valve opening or closing. The manual process of scaling, linearising, rescaling and transferring the various traces added to the accumulation of errors. These errors, inherent to the system, might have been reduced by further development, but could not be avoided. In any case, operation of the system would have remained a time consuming chore. An alternative system was sought which would (a) avoid the several well known limitations of a CRO or UV recorder (b) record the signals from all channels during one cycle of the compressor (c) remove errors of phasing by reading the transducer to each channel virtually simultaneously at a precisely known time (crankangle) (d) provide records in greater detail during a part of the cycle of interest (e.g. during the few crankangle degrees during which a valve was opening) (e) remove the inaccuracies and tedium involved in the manual scaling, linearising, and final display of records in graphical form and (f) provide accurate records in digital form for subsequent calculations and for comparison with predictions made by models which simulate compressors on digital computers.

THE NEW SYSTEM

The arrangement developed to meet these requirements utilised the high speed of operation and the large storage capacity inherent in a digital computer. The system was based on a Hewlett Packard 2100 mini-computer with 16K memory. The peripherals to the mini-computer were standard Hewlett-Packard items except for the visual display unit (VDU) which was a Tektronix unit, Type 4010. A schematic diagram of the hardware is shown in Figure 2. The analog signals from the transducers in each channel were converted to digital form by the analog-digital converter (ADC) which had a maximum processing rate of 100,000 signals per second. Analog signals from transducers which sensed pressures and valve displacements were passed via the multiplexer unit and the ADC to the computer core by direct memory access (DMA). The signal could be stored in core or fed into buffer stores provided in the core. As one buffer store was filled another was emptied into the cartridge disc sub-system. Afterwards the stored data could be (a) printed on the teletype to provide a permanent record in digital form (b) displayed on the visual display unit (VDU) in either digital or graphical form (which could be photographed to provide a permanent record) (c) presented in graphical form by the graph plotter, or (d) transferred to paper tape for processing on a larger computer elsewhere.

A schematic diagram of the instrumentation on the compressor plant and of the controls for the data acquisition system is shown in Figure 3. The pressures at various locations in the plant were sensed by Kistler piezo-electric transducers. Valve displacements were monitored by Bentley-Nevada non-contact inductive transducers. The analog signals from the transducers were conditioned by conventional electronic equipment to be within the range ± 1 volt before being passed via the multiplexer unit to the ADC. The number of analog signal channels allowed for was 16.

Top dead centre (TDC) for each compressor stage had been determined statically and checked under dynamic conditions by means of a non-contact displacement transducer which sensed the piston movement. Markings had then been mounted on the flywheel at 90° intervals and sensed by an inductive transducer. The signal from this transducer, while suitable as a phase marker with a UV recorder, had a shape and direction unsuitable for use as the pulse to start the computer based system. A new phase marker with a pulse of sufficiently rapid rise time for this purpose was provided by sensing the light reflected from a strip mounted on the flywheel $90\frac{1}{2}^{\circ}$ before TDC. The light was sensed by a photo-diode through optical fibres which presented an aperture (1.5 in x 0.01 in (38 mm x 0.25 mm)) to the strip. The signal from the reflecter strip was conditioned to give a pulse of about 1 μs duration: this proved suitable to initiate the system.

Following the start, a trigger pulse was necessary at pre-specified small time intervals to instruct the system to acquire data sequentially from all the channels. This trigger pulse could have been provided by a clock but in recognition of a possible variation in angular velocity of the crankshaft during a cycle it was considered desirable to generate the pulse from the compressor crankshaft. A glass disc, with circumferential optical markings of 36, 360 and 3600 divisions, was mounted on the outboard end of the crankshaft. A light source was directed through the rotating disc and a fixed index. The Moiré fringes formed interrupted the light to a photo-diode. The diode sensed 3600 divisions during one crankshaft revolution and part of a decade counter was used to divide by 5, reducing the pulses to 720, so providing a trigger pulse at $\frac{1}{2}$ degree crankangle. The control program specified that after the start the trigger would operate 1000 times (i.e. initiate readings from all channels at each $\frac{1}{2}^{\circ}$ crankangle over somewhat more than one crankshaft revolution). The count to 1000 of the pulses from the optical pulse generator was accomplished by electronic hardware and displayed on four digitrons.

The 720 pulses generated per revolution were also utilised in conjunction with a crystal controlled clock oscillator to provide a digital revolution counter. The revolutions per minute were displayed to the accuracy of one decimal place and the reading was updated every 1.6 seconds: the reading during the period of data acquisition remained in the display.

A digital display of mean pipeline pressures in the compressor plant was obtained via an analog-digital converter which integrated the pressure over a few revolutions and updated at the same rate as the revolution counter.

The control programs were written in Assembler language, and made provision for two methods of operation. In the first method, buffer stores were provided in the computer core. One buffer was used to store incoming data from the ADC while, simultaneously, data previously acquired and stored in another buffer was transferred to store on the cartridge disc sub-system. This procedure had the advantage of allowing data greatly in excess of the capacity of the core to be acquired during a test, by re-using core which had been allocated as a buffer store, after dumping its previous contents onto the disc. It had the disadvantage of endangering the holding of data already acquired if the rate of acquistion of data was higher than the rate of transfer of data from the buffer store onto the disc. In the second method all data was stored in core. This permitted a somewhat higher rate of acquisition by eliminating the time to execute the instructions in Assembler for the transfer of data onto the disc but had the disadvantage of restricting the storage capacity to about 14 K words. A portion of the control program for this method of operation is shown in Figure 4. Instructions in lines 1 to 22 initialise the computer registers, starting locations, etc. in readiness for incoming data. Instructions in lines 23 to 32 take out from the recurring section of the program some of the setting commands for transfer of data via DMA. The DMA interrupt commences at line 33: it defines the appropriate core locations for transfer of data and "enables the bread board", i.e. it brings into operation the control circuits which link the computer with the $\frac{1}{2}$ degree crankangle trigger pulse. An overspeed check is incorporated to ensure that this information is correctly set up. The bread board interrupt at line 47 is initiated by the arrival of each $\frac{1}{2}$ degree crankangle trigger pulse, so commencing the sequential monitoring of all the transducer signal channels via the ADC. The limit set at line 55 stops acquisition of data after the readings from all the channels have been taken 1000 times: a cross-check is performed with the count to 1000 made by the electronic hardware.

In order to associate a particular core location with a known crankangle it was necessary to identify the crankangle at which recording started. The press button switch to start the system was connected to the phase marking pulse. Starting was delayed, (monitored by a binary counter), by a pre-determined interval of four phase marking pulses (i.e. four revolutions of the crankshaft). This ensured that if the starter switch was pressed during the generation of the phase marker pulse the trigger pulse was ignored for starting purposes. The fifth pulse opened the gate (Figure 5) of the circuit which divided by 5 the 3600 pulses per revolution generated at the outboard end of the crankshaft so providing the $\frac{1}{2}$ degree crankangle trigger pulses. Since the phase marker had been set up at $90\frac{1}{2}^{\circ}$ before TDC, the first sequential monitoring of the channels occurred at the first $\frac{1}{2}$ degree trigger pulse after the phase marker pulse, starting the system at 90° before TDC. Thereafter the process was repeated and the records stored at each $\frac{1}{2}$ degree crankangle till the total of 1000 was reached. Figure 5 provides a schematic diagram of the arrangement.

USE OF THE NEW SYSTEM

A comparison between the previous system of recording using a UV recorder and the computer controlled data acquisition system was made by injecting into each an input of known form by means of a square wave generator. At comparatively low frequencies the traces on the UV recorder showed some distortion and, as the frequency was increased, reduction in the amplitude of the traces became more severe. In contrast, at frequencies of up to 5000 Hz the shape of the records from the data acquisition system was unimpaired.

Measurements of pressures and valve displacements in a compressor plant were recorded using the data acquisition system. Phasing of the various traces in relation to TDC and to each other was now very precise since each reading was taken sequentially (but virtually instantaneously) from all channels at each $\frac{1}{2}$ degree crankangle during a single compressor cycle. Comparison with the experimental records in Figure 1, where a UV recorder had been used, showed that the data acquisition system was able to reveal details which had not appeared in the traces from the UV recorder. For example, the trace of discharge plenum pressure showed a number of high frequency oscillations which did not appear in Figure 1 because of damping in components of the UV recorder.

The data acquisition system was used to check the validity of the assumption which had been made when developing the mathematical model that the variation of angular velocity of the crankshaft was negligible. The time interval between the pulses provided once per revolution by the phase marker on the flywheel was divided into 36 equal intervals of time using a phase locked loop. During the revolution, 3600 pulses were generated at equal intervals of distance (i.e. at 1/10 degree crankangle intervals) by the optically marked glass disc mounted on the end of the crankshaft. These pulses were conditioned to have about 1 μs duration and the number generated (nominally 100) in each of the 36 equal time intervals during the single crankshaft revolution was counted and passed to the computer in binary form. The results observed at several compressor speeds and with various discharge pressures showed a maximum deviation of 2. It was concluded that the speed fluctuation during a crankshaft revolution was within $\pm$ 2%.

A part of the cycle of operation of a compressor could be examined in detail. This facility was used to measure valve displacement at precisely known intervals of time during opening. Hence mean values of valve velocity during each interval could be calculated. The transducers used to sense valve displacement had been calibrated in situ and the calibration data stored in the computer.

Programs were written to linearise the output from the transducers and then calculate valve velocity. An example of the results obtained is shown in Figure 6. For convenience each interval of time between displacement readings was equal and was the time to move through $\frac{1}{2}$ degree crankangle. Hence the time interval (microseconds), shown as Δt in Figure 7, depended on compressor speed (revolutions per minute):

$$\Delta t = \frac{60 \times 10^6}{\text{rev/min} \times 720}$$

For example at 400 rev/min, $\Delta t = 210$ μs.

For detailed study of valve behaviour it would be useful to have additional experimental points on the velocity curves in Figure 6, particularly near to valve seat and stop. It might appear that such points could be obtained by taking valve displacement readings at time intervals smaller than $\frac{1}{2}$ degree crankangle and dividing the difference between adjacent displacement readings by the smaller time interval. However, the resolution of the ADC on an analog signal (which had been conditioned to be 1 volt or less) was ±2 mV because the digital equivalent had to be stored in 9 binary bits. So there was some uncertainty about the value of each point plotted in Figure 6. Either at low velocity or when using a short time interval the change in valve displacement may be so small that it is swamped or possibly lost altogether because of the ±2 mV discrete levels in the digital form of each of the two adjacent valve displacement readings which are to be subtracted. Therefore, a compromise has to be made between having a relatively large time interval between readings with a scarcity of points or having a small time interval with a larger number of points of greater uncertainty.

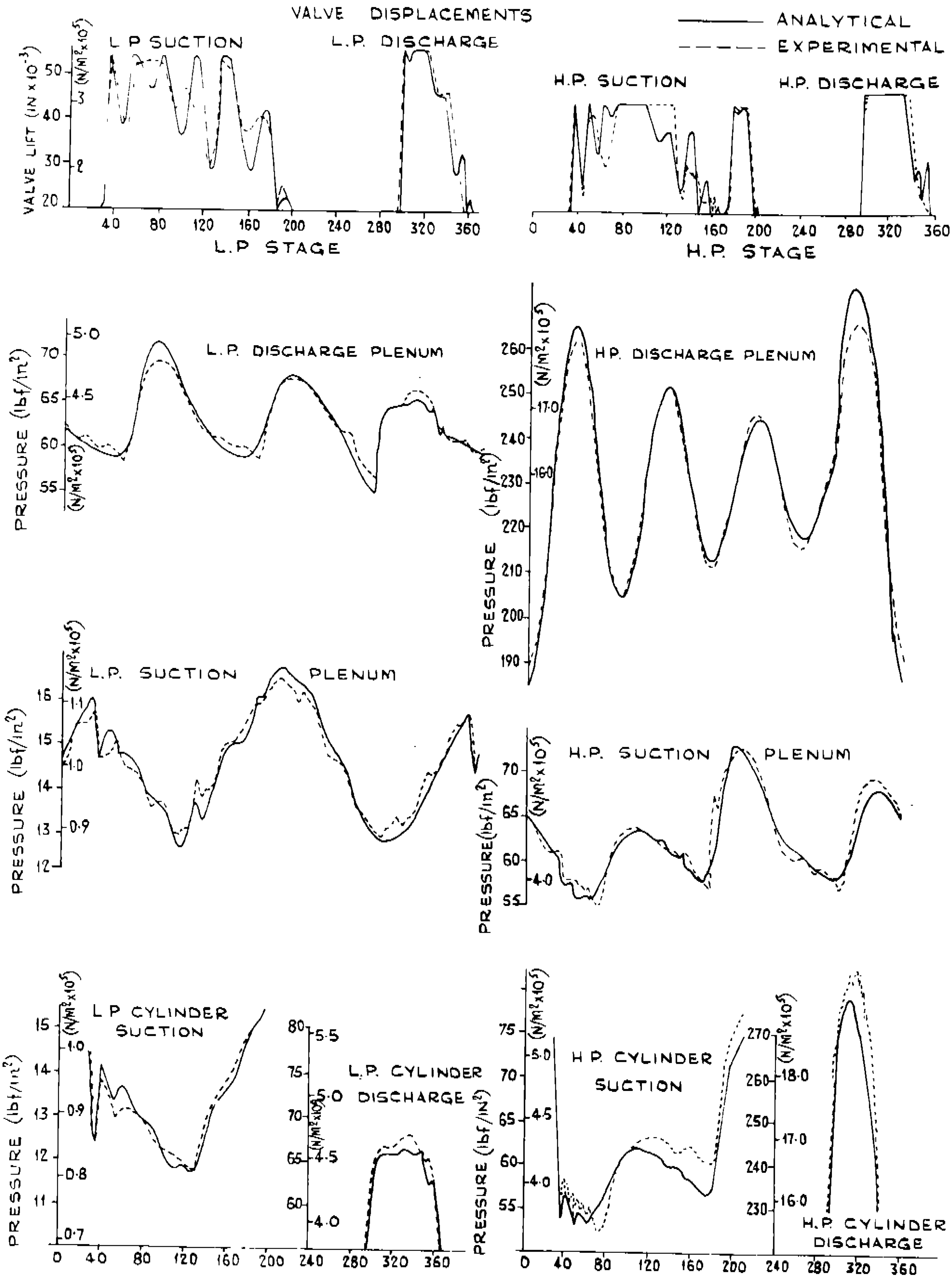
The scheme was modified so that effectively the relatively large time interval was utilised but a larger number of points was obtained. The maximum rate of the ADC was 100,000 readings per second, i.e. the shortest time between readings was 10 μs. Following initiation by the pulse generated at each $\frac{1}{2}$ degree crankangle, consecutive readings were read at this maximum rate and fed into consecutive channels of the ADC. Hence the readings in each channel were easily identifiable and adjacent readings in any given channel were spaced as shown in Figure 7 at the relatively long time interval Δt (e.g. approximately 210 μs when the compressor speed was 400 rev/min). The mean velocity over this time interval, Δt, was calculated and plotted at the arithmetic mean value of the two valve displacements involved. Each reading of the set in the next channel was recorded 10 μs later than the corresponding reading in the adjacent channel. For expediency, only nine of the sixteen available channels were employed and to assist clarity in Figure 8 only points from the five alternate channels are plotted, i.e. in a group of five points in Figure 8 adjacent points are displaced in time by 20 μs. The ±2 mV limitation in the resolution of the ADC remained and since Δt had not been changed (except by any change of compressor speed) the uncertainty in any point was unaltered. However, Figure 8 reveals that the discrete levels involved were so close together that single line curves for valve displacement could have been drawn with confidence. At the lower compressor speed (360 rev/min) shown in Figure 8 the suction valve did not reach the stop during the first opening phase. The scatter of points on the velocity curves arises from the basic problem of subtracting two displacement readings of similar magnitude. The wide scatter of points following impact of the suction valve plate on the stop at compressor speed 500 rev/min may be due to the plate having a vibration of high frequency but of such small amplitude that the effect is not visible in the corresponding displacement curve. However, curves of mean velocity have been added by hand to Figure 8. These experimental curves have significance in relation to the development of simulation models of compressors where information is required regarding "squish" damping on a valve plate near to its stop, impact velocity and the effective coefficient of restitution.

CONCLUSIONS

The great capacity of a digital computer with disc storage and the high speed of operation of an analog-digital converter provided the basis of a system to record experimental data from reciprocating compressor plant. Signals could be recorded at 10 μs intervals from up to 16 channels at $\frac{1}{2}$ degree crankangle intervals during one compressor cycle. The ADC imposed an upper limit to the rate of operation of the system: a limit to the accuracy was imposed by the resolution of the ADC. However, the imperfections of transducers in their locations within a compressor plant to sense and produce the correct signal as the analog input to each channel may be the major limitation on the accuracy of the overall system in practice.

While the prime objective had been to obtain this improved accuracy, a major additional advantage was that experimental results could be readily recalled, linearised, scaled and displayed in a convenient digital or graphical form: this was accomplished within two minutes following a test and so greatly facilitated the conducting of a test series.

Use of the computer based system avoided most of the errors inherent in more conventional measuring systems and also the errors which accrue during the many hours of labour required when using manual methods to translate results from a CRO or UV recorder.



SPEED 475 REV/MIN : L.P. & H.P. CRANKANGLES 180° OUT OF PHASE.

FIG. 1. COMPARISON OF EXPERIMENTAL AND ANALYTICAL RECORDS FOR A TWO STAGE INTERCOOLED AIR COMPRESSOR.

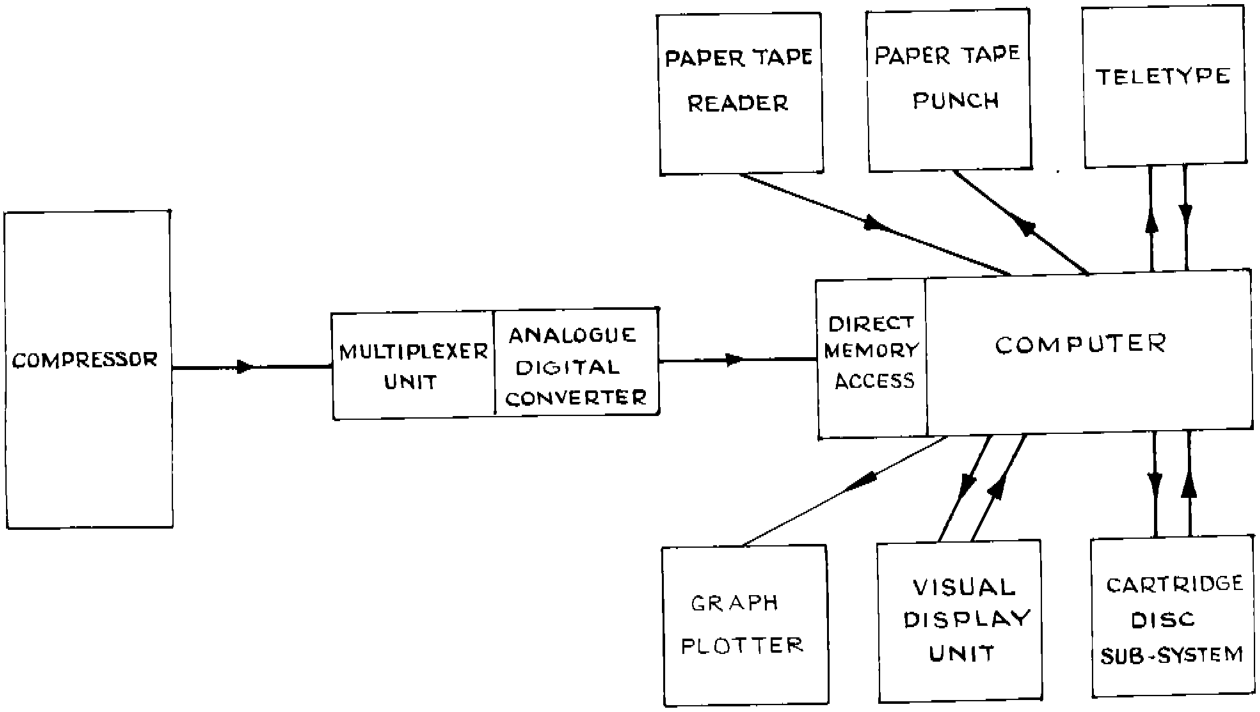


FIG. 2. HARDWARE CONFIGURATION FOR DATA ACQUISITION SYSTEM.

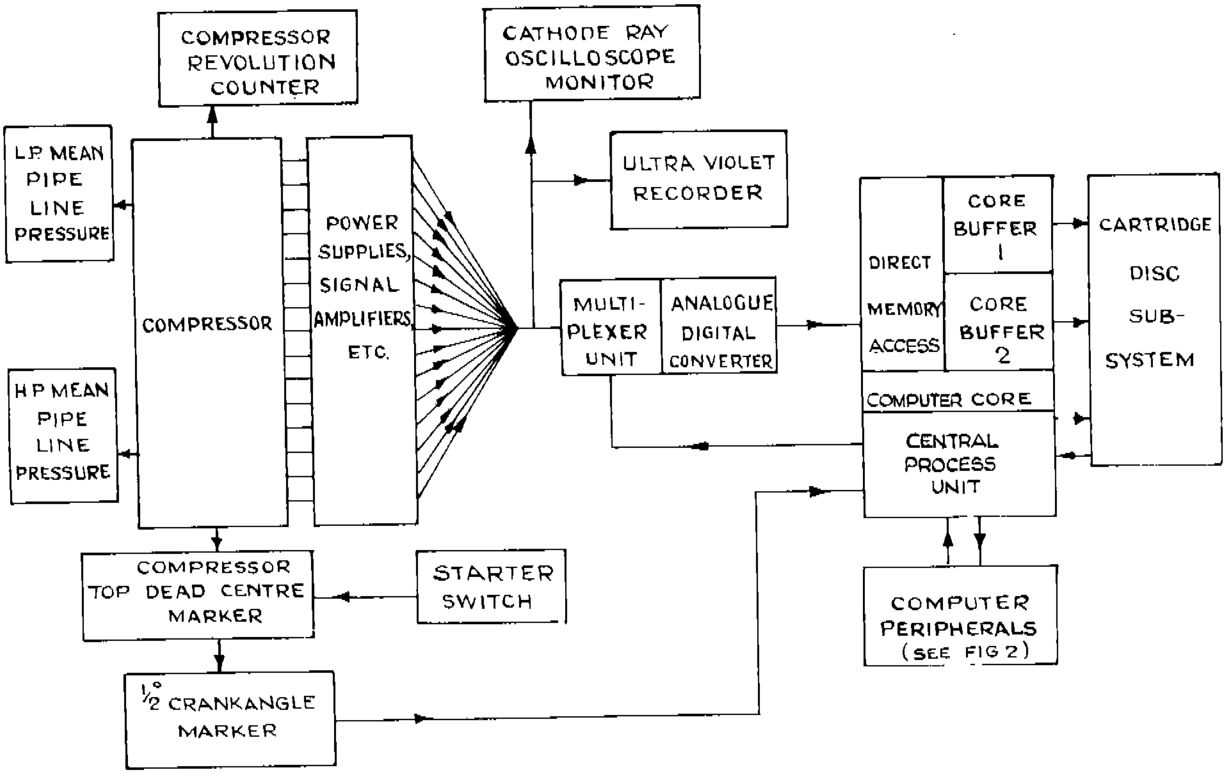


FIG 3. INSTRUMENTATION AND CONTROL CONFIGURATION FOR DATA ACQUISITION SYSTEM.

```
0001  ASMB,L.B, A            ASSEMBLER CONTROL
0002            ORG 1200      CORE STARTING LOCATION
                 .
                 .
0023  SET       LDA CV1       INITIATE DMA CHANNEL ONE
0024            OTA 6         FOR DATA TRANSFER FROM ADC
                 .
                 .
                 .
0031  CMD       OCT 40000     CONTROL FOR ADC
0032  *
0033  DMAI      CLC 2         DMA INTERRUPT LOCATION
0034            LDA CW2       CONTROL WORDS OUTPUT TO
0035            OTA 2         APPROPRIATE INTERFACE CARDS
0036            STC 2         TO ENABLE TRANSFERENCE OF
0037            LDA CW3       DATA AT NEXT BREAD BOARD
0038            OTA 2         INTERRUPT
0039            CLE 11B
0040            STC 6,C
0041            .CLB          CLEAR B FOR OVERSPEED CHECK
0042            STC 10B,C     SET CONTROL, CLEAR FLAG ON
0043            JMP *         BREAD BOARD. WAIT FOR
0044  *                       INTERRUPT
0045  CW2       OCT 102000    LOCATION OF WORD TRANSFER
0046  *                       COUNTER
0047  BBI       STC 11B,C     DATA TRANSFER BEGINS
0048            SZB           OVEPSPEED CHECK
0049            HLT 60B       HALT 102060 FOR OVERSPEED
0050            CCB           FILL B REGISTER WITH 1'S
0051            STC 10B,C
0052            LDA CW2       COUNT DATA TRANSFERS
0053            ADA NCHAN
0054            STA CW2
0055  LOOP      CPA LIM       LOOP UNTIL INTERRUPT IF
0056            RSS           NUMBER OF DATA TRANSFERS IS
0057            JMP LOOP      LESS THAN LIM. OTHERWISE
0058            HLT 77B       HALT 102077
                 .
                 .
                 .
0062  LIM       OCT 121500    LIMIT CHECK FOR TRANSFERS
0063  *
0064            ORG 6B
0065            JMP DMAI      DMA INTERRUPT COMMAND
0066            NOP
0067            JMP BBI       BREAD BOARD INTERRUPT COMMAND
0068            CLC 11B       ADC INTERRUPT COMMAND
0069            END
```

FIGURE 4 PART OF CONTROL PROGRAM FOR ACQUISITION OF DATA

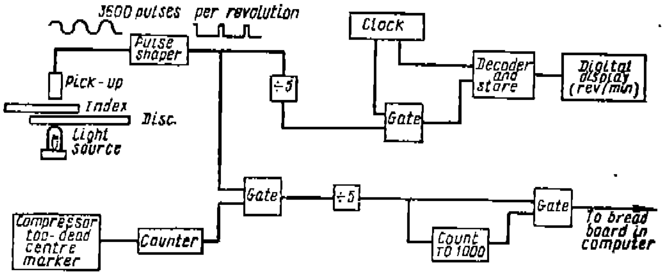


FIGURE 5 ARRANGEMENT OF TRIGGER PULSE SYSTEM

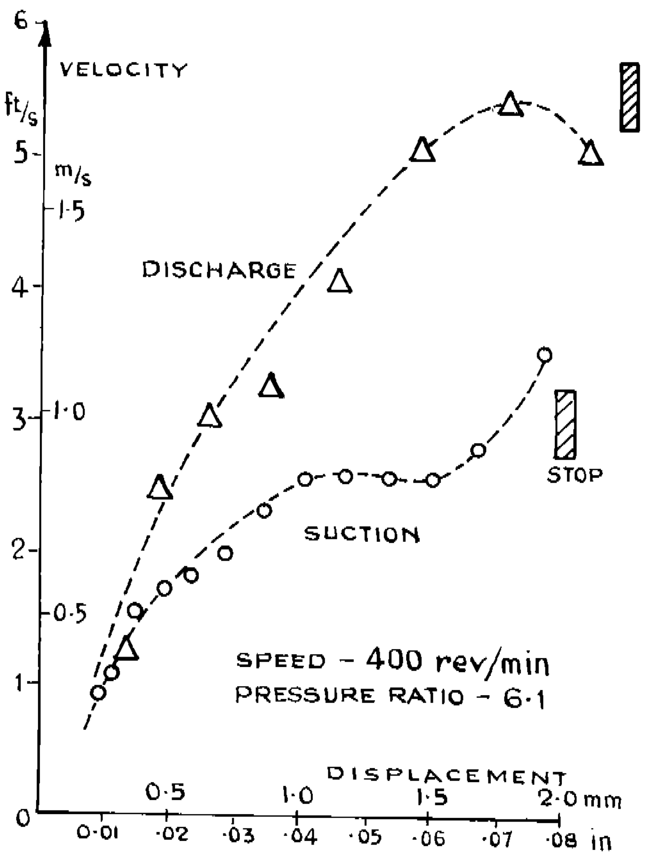


FIGURE 6 VELOCITY OF OPENING VALVE

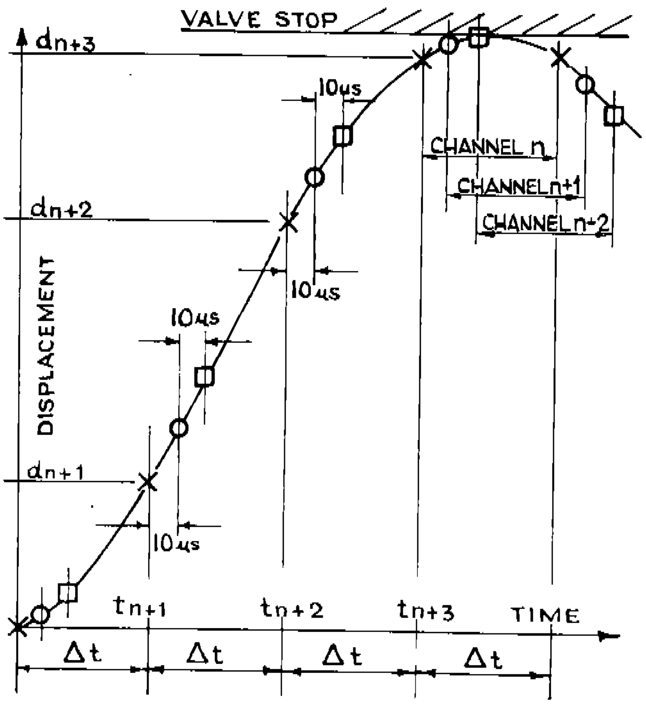
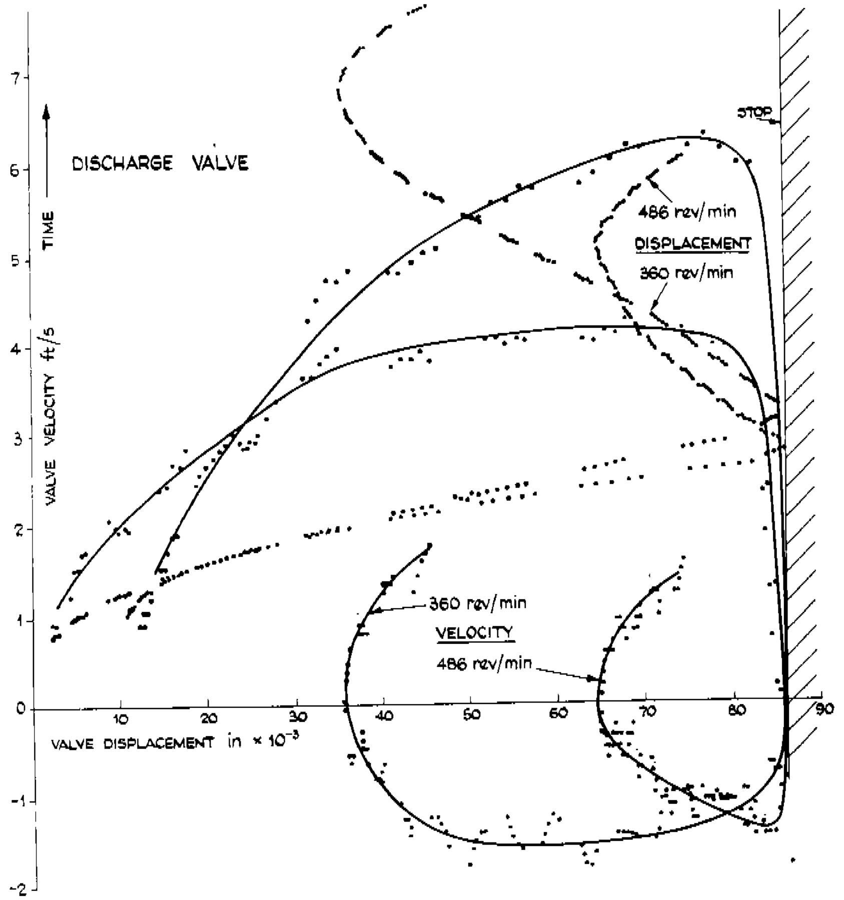


FIGURE 7 CALCULATION OF VALVE VELOCITY



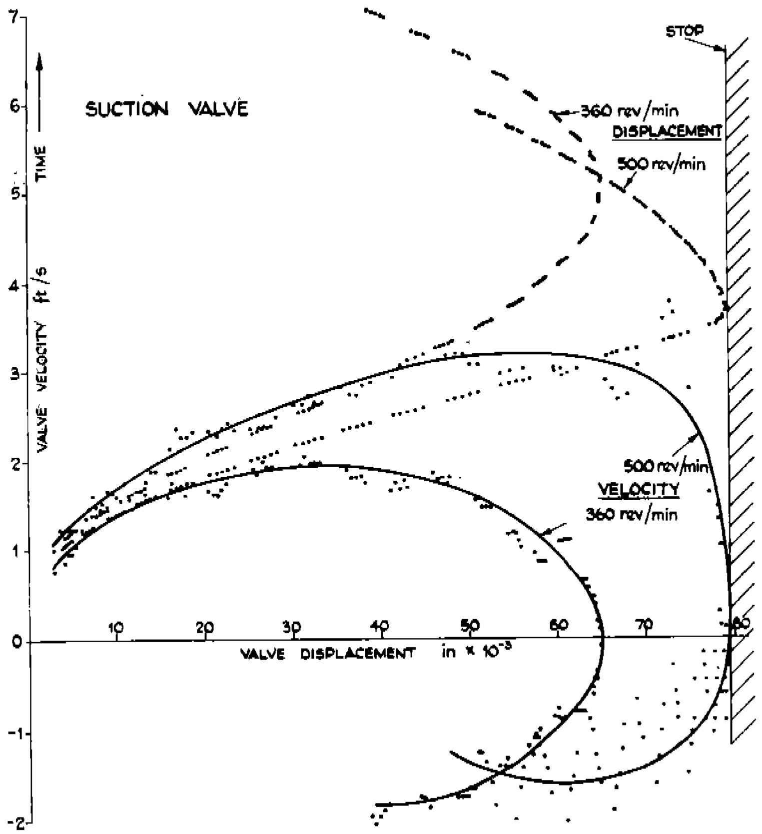


FIG. 8.

DISPLACEMENT AND VELOCITY OF OPENING VALVE USING MULTICHANNEL TECHNIQUE.