ROTATING VANE FLOW MEASUREMENT TECHNIQUES

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DECLARATION

This dissertation has not been nor is being currently submitted for the award of any other degree or similar qualification.

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SYNOPSIS

This thesis describes an investigation into the development and performance of vane flowmeter methods for the measurement of air and gas flow. To improve on existing rotating vane anemometer performance, a capacitance change vane sensing technique is investigated. In conjunction with Ower's dynamic equations steady state and step response measurements for a vane flowmeter with analogue and digital readout are presented.

A new form of respiratory anemometer which utilizes the capacitance change transducer has been designed to operate under discontinuous air and gas flow conditions in the presence of water vapour. The performance and calibration techniques for the flowmeter are discussed and comparisons provided with alternative sensor techniques. The design of an electronic respirometer is presented, which enables the respiratory tidal and minute volume of the patient to be continuously monitored under both operative and intensive care conditions.

Electronic techniques for the calculation of lung function parameters are investigated and the results obtained using the respiratory flowmeter discussed. An on-line digital computation method for the display and calculation of respiratory parameters is introduced. This technique provides an improved method for pulmonary data analysis and diagnosis, particularly when maximal expiratory flow volume patient curves are required.

The rotating vane instrument is also considered for applications in underground air flow measurement. In particular an intrinsically safe design for use in gassy mines is developed together with a multi-channel tone scanning system for remote monitoring in large mine complexes.

The investigation is concluded by considering further applications for electronic vane flowmeters. This includes a method developed for obtaining flow direction indication, and the design of a closed loop air flow control system for use in sterile enclosures for patients requiring transplant surgery and immunosuppressive drug treatment.

CHAPTER 1

Introduction

1.1 The Measurement of Air Flow

The value of a particular flow measurement technique can only be established by reference to alternative methods. Prior to an assessment of rotating vane anemometer principles, a brief review of such methods is therefore necessary.

When air and gas flow measurements are required to be made on either a laboratory or an industrial basis, the engineer is confronted by a continually widening range of possible techniques. The choice of transducer is governed by considerations of simplicity, cost, and the degree of accuracy and repeatability required. A complicated method should be avoided where a simpler one would suffice.

The majority of measurement techniques that have been developed during the past hundred years utilise some physical effect which arises from the flow. These effects can be broadly classified as:

1. pressure changes associated with the motion;
2. rate of cooling of a hot body, such as an electrically heated wire;
3. interaction of the flow medium with ultrasonic wave trains;
4. imparting an oscillatory motion to the air or gas as a basis for measuring volumetric flow;
5. use of the Doppler effect to scatter laser-produced light from impurity particles contained in the flow;
6. production of light beams to produce a fringe pattern which is used to measure the velocity of particles carried by the flow medium;

7. ionization of the flow by radioactive means which produces an ionization current as a function of flow rate;
8. consequent mechanical effects, such as the rate of rotation induced in a rotor made up of light vanes mounted in the stream;

In the majority of applications it is desirable for the air or gas flowmeter to have an electrical transducing mechanism. Such sensors, together with their associated electronic circuit can then provide:

1. improved performance - for example, it is possible to compensate for temperature, density and humidity variations and so eliminate the need for calibration charts and the application of correction equations;
2. linearisation of logarithmic and similar non linear laws to improve the sensor resolution;
3. remote reading operation which considerably enhances the utilization of the sensing principle, particularly in industrial applications. Such an instrument may then be suitable for use in hazardous and inaccessible areas of operation;
4. the elimination of mechanical readout mechanisms leading to improved portability and to increased flexibility of design. This can result in a simpler and more robust sensor having a wider area of application.

1.2 Air Flow Pressure Transducers

1.2.1 Measurement Techniques

The pressure effect is of considerable importance since it is dependent on the flow, and if such an instrument is correctly designed it can be used without individual calibration as a standard for the measurement of air flow. In particular, one type of pressure-tube anemometer, the pitot-static tube,[1] has been devised such that the geometry of the instrument has a minimal effect on the readings over a wide range of air velocity.

Many devices have been developed to create a differential pressure in a flow line to enable continuous velocity measurements to be made. The simplest and most commonly used method is the orifice plate,[2] which suffers the disadvantage of introducing turbulence, which results in a permanent pressure loss. To reduce this pressure drop a range of venturi[3] and flow nozzle tubes has been developed, whilst in a more recent (1953) development known as the Dall tube[4] a further improvement in pressure recovery has been achieved.

The Annubar differential pressure flowmeter, which has the same principle of operation as the pitot tube is designed to extend across the pipe into which it is inserted and to average the flow using four upstream sensing ports with an internal element to average the pressure from these ports.

In the Ventor Air Velocity Meter a differential pressure system is used to create a cross flow which is measured by a hot wire bridge arrangement. A Prandtl's type pitot tube is used to develop the pressure gradient and to create a cross flow in the actual measuring system which consists of separate reference and measuring flow channels. A pair of heated coils is placed in each channel and wired to form a Wheatstone Bridge which is unbalanced by the cross flow. This out of balance signal is proportional to the cross flow in the measuring channel which, in turn, is a square function of the air velocity.

Electronic linearisation is used to obtain an output which is directly proportional to the air velocity.

The differential pressure devices discussed above are all based on restrictions of a fixed size with the pressure gradient being a function of the flow rate.. There are, however, devices in which the area of restriction may be changed to maintain the differential pressure constant while the flow rate changes, and such instruments are referred to as variable-area flowmeters or rotameters.[2] In these instruments the air flows upwards through a tapered vertical tube in which a float, shaped like a top, rises until its weight is balanced by the difference of pressure above and below it caused by the motion of the air through the restricted passage around the float. When the tube is made of glass, the float position can be read against a scale calibrated directly in flow units.

1.2.2. Performance and Application

Air flow pressure transducers are mainly applied in continous flow measurement applications. At the present time pitot tubes tend to be used in situations where a permanent flow measurement transducer is either unnecessary or undesirable. They are of particular value in calibrating other types of anemometer and for determining a probable maximum flow for a permanent metering device or for exploring the velocity a various points in, say, a ventilation duct.

The averaging technique employed in the Annubar flowmeter overcomes the difficult problem of the selection of a single point to represent the average velocity in a flow line. The Annubar is therefore used principally for the measurement of gas emissions in stacks, and in this application it provides good accuracy on a nominally linear direct reading scale.

The Ventor Air Velocity Meter has been designed specifically for measuring air flow in mines although it requires an air filter system to avoid contamination of the heating coil arrangement. Rotameters are extensively employed in industry in fixed applications where the flow has to be constantly checked and maintained at a specified rate. The difficulty in obtaining an electrical readout mechanism restricts the range of applications in which air pressure transducers are applied.

1.3 Thermal Flowmetering Techniques

Hot wire anemometry was extensively investigated by L.V. King[5] in 1914, and remains of considerable importance as an air flow measurement technique. It consists basically of an electrically heated fine wire which is cooled by the streaming medium surrounding the wire. The cooling effect is measured by the resistance change of the wire, or alternatively by the current change which is required to maintain the wire at constant temperature, i.e. at constant resistance.

1.3.1. Hot Wire Probes and Film Sensors

In recent years considerable development work has been undertaken on hot wire probes and their associated circuitry. To reduce the problem of surface contamination various shielded probe designs have been proposed. For example, a particularly successful approach due to Simmons[6] uses a shielded wire in a twin bore silica tube. To overcome the reduced sensitivity caused by the shielding a thermocouple is used to measure the temperature difference produced by the air movement. At the present time the more common wire materials such as tungsten, platinum, and platinum-irridium alloy are being replaced in some applications by hot film sensors which consists of a conducting film on a ceramic substrate, for example a platinum film on a quartz rod.

1.3.2. Thermistor Flowmeters

The thermistor air flowmeter was first used by Hales[8] in 1948 for measuring wind speed in meteorogical experiments. In 1963 Seymour[9] designed a thermistor anemometer to measure air velocity profiles in a three dimensional flow channel in which the flow directions were not known with certainty. This instrument, which has a quoted accuracy of 0.5% in the range 0.5 to 100 m/s utilises a pair of thermistors, one (previously calibrated) in the variable-velocity air stream and the other (a 'calibration' thermistor) in a different part of the system.

1.3.3. Alternative Thermal Flowmeter Instruments

A number of air and gas flow anemometer designs based on the measurement of cooling rate have been developed. For example, the Anemotherm[3] gas-flow rate meter incorporates two helical resistance elements mounted side by side and enclosed in stainless steel tubes. By using a separate heating coil the temperature of one element can be raised above the other, and as the elements are adjacent they are both equally affected by ambient temperature changes. A bridge circuit, in which both elements are placed, provides an out of balance signal which is a function of the gas-flow rate.

An alternative approach is used in the Callender electric flowmeter,[10] which measures the heat energy that must be supplied to the moving air stream to maintain a specified temperature difference between the two cross-sections, one upstream and one downstream of the heat source.

In the Kata-Thermometer,[3] alcohol is heated to 40°C and the time for this to cool to 35°C in the air stream is measured. The air speed is calculated from this time using a simple equation containing empirically derived constants.

1.3.4. Performance and Application

The hot wire probe anemometer has the advantage that it can be made very small so that it does not affect the flow by its presence. Such sensors are however seriously affected by dust deposition or other surface contaminations and are subject to strain effects caused by air forces. Whilst the shielded probe technique may overcome some of these disadvantages, it is at the expense of speed of response.

Film sensors are less susceptible to contamination and they also exhibit a lower heat conduction to the supports, so that a shorter sensing length can be used. In addition they have an improved frequency response (when electronically controlled) than a wire of the same diameter, because the sensitive part is distributed on the surface rather than throughout the entire cross section.

Even though film sensors have these basic advantages, hot wire probes provide superior performance for many applications. Since the film probe generally has a lower temperature coefficient of resistance and a larger surface diameter it remains preferable to use a tungsten hot wire sensor in applications requiring the minimum of noise level and the maximum frequency response.

In general both hot wire and film probes are of considerable value in the study or turbulent flow conditions since the small sensor size results in a high spatial resolution and a low interference to the flow together with a short response time and high sensitivity[7].

Hot wire anemometers are also used for monitoring air flow in ducts and tunnels and for general wind speed indication. Such instruments are mainly of value when measuring the velocity of clean and dry air.

In view of the availability of alternative techniques the development of thermistor anemometry for air and gas flow measurement has been limited mainly to a number of specific flow measurement applications. In all of these designs the problems of surface contamination, speed of response and ambient temperature stability have to be carefully considered against the advantages that are attained by the use of the technique. Thermistors continue to remain of value in the field of flow measurement, as is evidenced by the utilization of their temperature measurement capabilities in vortex precession and vortex shedding flowmeters (1.5).

Although the Anemotherm flowmeter suffers from contamination problems it is of value in measuring gas flow in the chemical process industry, but the Kata-Thermometer is now mainly of academic interest.

1.4 Acoustic or Ultrasonic Flowmeters

1.4.1. Measurement Techniques

These flowmeters employ an ultrasonic beam which is disturbed by the air or gas flow. Their application in the field of fluid flow is well established, but for air and gas measurement the technique remains in the development stage.

The majority of flowmeter designs[11] are based on the linear relationship which exists between the apparent sound velocity and the velocity of that medium. In a typical arrangement sound bursts are propagated alternately in opposite directions between a pair of pulsed transducers situated diagonally in the pipeline. Since the upstream signal is delayed and the downstream signal increased in velocity by the moving fluid, the alternate bursts yield a frequency difference which is an accurate measurement of the flow. In a recent development,[12] cross correlation techniques have been used in conjunction with a pair of ultrasonic transmitter-receiver units. This system is used to measure the variation in the acoustic energy caused by the density fluctuations of the flow medium.

1.4.2. Performance and Application

Although the basic principle of operation of an acoustic flowmeter is elementary, the resulting instrument must function independently of the intrinsic velocity of sound in the flow medium. The flowmeter design is therefore complicated by the fact that the velocity of the sound in a medium such as gas or air is a function of both the temperature and the density. To avoid spurious readings the gas must not contain solid or vapour particles of a size capable of interaction with the acoustic wave. In practice the area of application for such anemometers is therefore limited.

The acoustic technique involving the correlation of density fluctuations provides a method which overcomes these disadvantages, although at the expense of increased complexity and cost. In general, acoustic methods are restricted to closed channel applications involving fixed installations where they have the advantage of providing obstructionless measurement with no pressure drop caused by their introduction into the flow line.

1.5. Vortex Precession and Vortex Shedding Flowmeters

1.5.1. Measurement Techniques

Both of these techniques impart an oscillatory motion to the gas as a basis of measuring volumetric flow.

In the vortex precession type (swirlmeter) the gas enters through a set of stationary swirl blades which start the gas spinning around the centre axis of the meter thus forming a vortex. The vortex then advances through the meter like a screw having a pitch which is fixed and determined by the swirl blade arrangement and the body shape. A thermistor probe is used to sense the passage of the vortices before the flow is straightened by deswirlers as it leaves the meter. The number of vortices passing the sensor in a given time is directly related to the gas velocity and the system is designed with electronic circuits to count this parameter.

The vortex shedding meter operates on a principle observed by von Karmon - namely, that if a cylinder is immersed in a flowing stream with its axis at right angles to the flow, a series of vortices are shed alternately from the two sides of the cylinder. This action imparts an oscillatory motion to the fluid and there is a direct relationship between flow rate and the frequency of this vortex formation. A thermistor or hot wire probe is used to convert the temperature fluctuations caused by the oscillation into a voltage-time signal for processing.

1.5.2. Performance and Applications

Good performance data has been published[13] for vortex precession flowmeters for use with gases having different characteristics in density, viscosity, and conductivity. This type of instrument has been applied to measure the velocity of very inert gases such as nitrogen as well as extremely corrosive gases like chlorine. The response time to flow change is typically less than 100 milliseconds. The vortex shedding instrument is particularly suited to the measurement of gas and liquid flow in large bore pipes.[14]

Both of these instruments are however unsuited to portable measurement applications and they are susceptible to dust and moisture deposits.

1.6 Laser Doppler Flowmeters and Optical Fringe Anemometers

1.6.1. Measurement Techniques

The Laser Doppler Velocimeter makes use of contaminants in the flow(such as specks of dust, algae, or air bubbles) which are small enough to follow the flow pattern. These particles, which can be artificially added if required[15] (seeding), scatter light which is slightly shifted in frequency by the Doppler effect. This change in frequency is detected and related to the flow velocity.

In the Optical Fringe Anemometer the crossing of two light beams is used to produce a fringe pattern. The frequency of particles crossing the light fringes is linearly related to the instantaneous velocity of flow.

1.6.2 Performance and Applications

Published results[1[illegible]] for the Laser Doppler instrument indicates excellent accuracy under laboratory conditions although at a cost which is far in excess of many alternative (but possibly less accurate) methods. This technique has been applied in general wind tunnel monitoring and for the study of velocity profiles over aerodynamic surfaces.

Experimental results using fringe methods[16] have shown that in the case of gas flow measurement the low particle concentrations require frequency counting as distinct from frequency tracking or spectrum analysis methods of signal processing. In natural (unseeded) air such a measurement requires a period of up to 200s during which time the flow velocity must remain substantially constant. If this condition can be achieved in a particular application high precision may be obtained, although the cost of the electronic instrumentation required is high.

1.7 Tracer Methods for Gas Flow Measurement

1.7.1 Measurement Techniques

Ionization techniques can be applied for the measurement of gas flowrates, and the majority of these methods involve the continuous ionization of the flow by radioactive means with collection of the ions by electrode arrangements. The original ionization anemometer of Lovelock and Wasilewaska[17] used particles to provide an ion current which was a function of the flow rate. Their instrument suffered from the disadvantage that the output singal decreased as the gas velocity increased, although subsequent designs[18] have enabled the technique to be applied in the measurement of both moderate and low gas velocities.

As an alternative to ionization techniques, radiotracer dilution and residence time methods have been investigated during recent years. At the present time radioisotope tracers predominate in practice since low radioactive concentration levels are readily detected.

1.7.2. Performance and Applications

Ionization anemometers have the advantage that they do not obstruct the flow and they have a good low velocity measurement capability (quoted as 1 cm/s in a commercially available instrument). In addition, the low inertia ions yield a fast response time (typically two milliseconds)and the detection of flow velocity reversal can be achieved. Under steady state flow conditions a convenient empirical correlation between flow rate, pressure and ion current has been found to exist. Although accuracy is theoretically maintained under pulsating flow conditions, problems have been encountered in achieving such performance in practice.[20] The principal disadvantage of this type of flowmeter is that the output signal is also dependent on the state of the gas, and variations in the conditions of the gas inside the pipe can cause serious errors. In an attempt to overcome this problem both mechanical and electrical pulsing techniques have been considered with the latter providing the most satisfactory solution.[19] These anemometers require a high ionizing voltage which prevents their application in areas where intrinsic safety requirements have to be observed. A nonlinear correction factor is required for humidity variations, and if the moisture content of the gas changes during the measurement period (as in medical applications) the technique becomes impracticable.

Published flowmeter designs using both the constant-rate-injection and integrated-pulse-velocity methods[21] of radioisotope tracing indicate that high accuracy in closed channel industrial applications can be achieved, and a number of specific flow measurement problems have recently been investigated in this way (Ref. 21, Papers 5.4, 5.5 and 5.6).

The relative ease with which radioactive tracers can be detected has understandably limited the use of chemical 'tagging', with its attendant problems of detection, toxicity and possible explosion hazard. One exception is in the use of nitrous oxide which can readily be detected by an infra-red gas analyser with concentrations in air of less than 100 p.p.m, and which has been used to measure air flow in underground roadways.[22]

1.8 Mechanical Anemometers

1.8.1. Measurement Techniques

Mechanical anemometers are of two main types. In the first the air deflects a plate or a vane controlled by gravity or a spring; in the second, the working element is a rotor maintained in continuous rotation by the air at a rate depending on the air speed.

Deflection anemometers, such as the Velometer,[3] use a small vane under spring control carrying a pointer which moves over a scale calibrated in air velocity. The plate is mounted on a torsion wire passing through an asymmetric vertical or horizontal axis, and there is a subsequent relationsip between the air velocity and the torque on the wire necessary to hold the plate at right angles to the air current.

The rotary type of instrument can be subdivided into the cup anemometer and the vane anemometer. The former instrument is used mainly by meteorologists for measuring wind speed[23] and was originally constructed with four hemispherical cups carried with their bases vertical at the ends of four light arms. Following a detailed investigation by Sheppard[3] the design has been modified to use three conical cups. The Meteorological Office have adopted a larger and heavier form of this instrument for use in all weather conditions.

The vane anemometer is in effect a windmill consisting of a number of light, flat vanes mounted on radial arms attached to a common steel spindle. Eight vanes made of thin sheet aluminium or aluminium alloy are normally used and the air forces acting on the vanes cause the spindle to rotate at a rate depending mainly on the air speed. Prior to the advent of electrical transducer methods, mechanical gearing was used to transmit the spindle motion to pointers moving over graduated dials. To determine the air speed it is therefore necessary to record the time taken to achieve a pre-calibrated number of vane revolutions, the true air velocity then being obtained by reference to the calibration curve for the particular anemometer in use.

1.8.2. Performance and Application

In view of the alternative techniques that are available, there are few advantages to be gained in using deflection type anemometers such as the Velometer, and such instruments now find only limited application.

The vane anemometer has been widely applied for the measurement of air flow over the past fifty years. Its construction is such that it is ideally suited to portable operation and it has been used for measuring air velocity in large ducts,wind tunnels and small bore pipes (subject to a minimum size constraint imposed by the theory of operation). The vane flowmeter principle is also used in the design of medical respirometer instruments which are employed for patient monitoring under operative conditions.

Rotating vane anemometers are generally suitable for air velocity measurement over the range 0.25 to 30 m/s. If the velocity is too high the vane setting may suffer a permanent distortion, which will cause a corresponding permanent change in the calibration curve of the instrument. On the other hand, if the speed is too low, the friction of the bearings and the gearing will exercise an appreciable effect.

1.9 Objectives of this Investigation

The current demands from industry for flow measurement require high accuracy, good linearity in the operating characteristic, extending range, fast dynamic response, good reliability and low cost. These characteristics have to be compatible with a wide range of operational requirements including measurement in open channels or in closed conduits. The requirement may be to measure flow rate, or the volume or mass of fluid in steady or pulsating systems.

In view of this wide range of requirements the choice of the flow sensing technique is often governed by the particular application under consideration.

In this investigation it is proposed to develop rotating vane flowmeter techniques to achieve the following objectives:

1. to improve the response time and the low velocity measurement capability by replacing mechanical gears by a non contacting electrical transducer;
2. to measure air and gas velocity and flow volume by processing the transducer signal;
3. to allow remote measurements to be made;
4. to facilitate multi-point monitoring or air and gas flow;
5. to produce a robust, portable instrument capable of reliable operation; under difficult environmental conditions, for example in the presence of high vapour or dust concentrations;
6. to produce an instrument whose performance and cost compares favourably with alternative techniques;
7. to have the ability to measure continuous and intermittent flow.

It is considered that a rotating vane anemometer which achieves these objectives constitutes an important flow measurement technique, and it is proposed to develop this type of instrument for use in two difficult areas of application:

1. anaesthetic and respiratory (lung function) monitoring;
2. underground measurements with particular reference to gassy mines.

CHAPTER 2

The Capacitance Change Transducer Applied to Rotating Vane Anemometry

2.1 Historical Review of Rotating Vane Anemometry Techniques

Prior to discussions relating to suitable vane sensing techniques it is of value to consider the historical development of rotating vane anemometry instruments. Such instruments have tended to evolve in order to satisfy two distinct areas of application, viz. general industrial air and gas flow measurement and medical respiratory and anaesthetic monitoring.

The vane anemometer, in the form of a number of flat light vanes, mounted on radial arms rigidly attached to a common spindle, was extensively investigated by Ower in a classic paper[24] in 1926. In this paper, Ower analysed the performance of the instrument when it was placed along the wind direction and the vanes were inclined to the wind in such a manner that a torque was produced which caused rotation in a path perpendicular to the wind direction and at a velocity which is a definite function of the wind speed. The motion of the spindle was communicated by suitable gearing to a pointer moving over a graduated dial. In addition to a theoretical analysis of the basic vane anemometer Ower considered the significance of additional parameters which arise in practice, i.e. readings obtained when the wind speed varies across the vane circle, effect of variation of air density and readings obtained in a fluctuating wind. Controversy relating to assumptions made by Ower to reduce the mathematical complexity of the investigation into the fluctuating wind parameter prompted his production of an additional paper,[25] some ten years later, dealing specifically with this aspect, and resulting in similar results and conclusions.

Many of Ower's fundamental conclusions relating to both of these papers will be discussed in this and subsequent chapters. It will suffice at this stage to quote his concluding remarks on the investigations undertaken; 'If the limitations and conditions (imposed by practical parameters as noted above)are observed, vane anemometers can be used with confidence to give all the accuracy that is ordinarily required. It should be remembered that, as with all measuring instruments, the vane anemometer has its particular sphere of usefulness, and it should not be condemned because it cannot be used to measure wind speed in all circumstances; obviously there must be cases in which other instruments, the pitot-tube, for example, will be more suitable. As an alternative to the pitot tube, the vane anemometer is a very valuable instrument, and for the measurement of very low wind speed it would appear to provide the most convenient means available'.

Whilst these conclusions were drawn prior to the advent of a number of alternative methods (as discussed in Chap. 1), they are nevertheless indicative of the sound foundation on which improvements to the technique can be built. It is interesting to note that prior to the development of the rotating vane theory the only published information on vane aerodynamics was that of Eiffel[3] who had investigated the aerodynamic forces acting on small flat plates. Ower originally assumed these results as the basis for his investigations, but at a later stage he and Duncan[26] measured the forces on actual anemometer blades and found reasonable agreement with Eiffel's theory. Eiffel's analysis is of particular significance when considering the theoretical performance of spinning vane flowmeters. This is particularly the case when those intended for anaesthetic and respiratory monitoring are considered (as will be discussed in Chapter 4), since the windmill vane assembly is then often replaced by a flat plate arrangement. Ower's investigations also included a solution to the problem of determining the angle at which the rotating vane anemometer blades should be set for rotation to commence at the lowest air speed. His analysis however neglected the changes in speed that occur as the air passes through the vane circle, and subsequently in 1932 van der Hegge Zigen[27] published a more rigorous theory which indicated that the optimum blade angle was 40° (compared with Ower's original estimate of 31°). In addition to the original considerations by Ower into the measurement errors caused by a fluctuating wind, both van Mill and Head have published information relating to this aspect of rotating vane anemometer performance. Head[28] derived an 'approximate pulsation factor' for various types of flowmeter and considered the effect on operation of sinusoidal, triangular and rectangular disturbances. In 1964 van Mill's results,[29] obtained by causing an approximately sinusoidal pulsating flow to pass through a turbine flowmeter, provided excellent experimental confirmation of Ower's original theory, which predicted an overestimation by the anemometer of the true air velocity. This error is readily calculated from an equation which relates the indicated and mean velocities via a term which is a function of both the pulsation amplitude and wave form. As previously stated Ower also investigated the effect of a non-uniform distribution of air speed across the vane circle. His results indicate that a rotating vane anemometer should not be used in a pipe having a diameter less than 6 or preferably 8 times the overall diameter of the vanes if errors greater than 1% in local velocity measurement are to be avoided. This restriction becomes more severe if the velocity distribution is more peaked than that for fully-developed pipe flow. For the determination of the volumetric rate of flow in the pipe, velocity observations must be made at various points in the cross section (whose positions are calculated in accordance with the rules formulated by Ower and Pankhurst in Ref.3 Chap. VI).

In 1955 Wright[30] utilised the rotating vane technique in an instrument designed specifically for medical applications. This flowmeter, which indicates the volume of gas passing through in one direction only, has been of immense value in the areas of application for which it was designed, and it remains in widespread use in anaesthetic departments throughout the world. Its attributes and limitations will be discussed in Chapter 4.

2.2 Rotating Vane Transducing Techniques

The need for removing the frictional constraints imposed by the gearing and readout mechanisms on rotating vane systems has prompted a number of attempts over the last two decades at achieving a non-contacting method for sensing rotation.

An early design used a photoemissive cell in conjunction with a light source, which was interrupted by the vane rotation. The bulky nature of such cells resulted in a somewhat unwieldy instrument and this problem was not overcome until the introduction of the miniature junction photocell. In 1961, Collins and Steele[31] published an anemometer design which used such a device and their results are of particular interest in that they compare their instrument performance with the Ower low speed anemometer[32]. The data provided indicates excellent repeatability (± 1%) and good linearity of frequency output against air speed above the threshold of 0.3m/s. In a later design by Mahdi & McPherson[33] light from a miniature lamp was focussed onto a phototransistor which was connected in a Schmitt trigger bi-stable circuit. The resulting pulse train, the frequency of which is proportional to the rate of rotation of the vane rotor, was then converted to a d.c. voltage by a transistor pump circuit. The magnitude of this voltage therefore represents the air velocity (assuming transient flow conditions do not exist). Again the published results show good linearity of air velocity with output voltage and the overall anemometer performance has been shown to be in accordance with Ower's theoretical predictions. The present state of the art in optoelectronic devices will enable fundamental improvements to be effected in such designs; for example a solid state low current light emitter can replace the filament lamp. However the severe problems created in many applications by dust and moisture deposits will still remain, and in view of the alternative sensing methods that are to be discussed, there is little to recommend the adoption of such techniques.

It should be noted that in liquid turbine flowmeters, pick-off methods are somewhat simplified by the application of magnetic transduction techniques. The resulting vane drag which produces only small errors in liquids is, however, unacceptable in air or gas flow measurements. The most commonly used system is to allow ferroelectric blades to cut through the magnetic field produced by a permanent magnet embedded in a pick-off coil. As each blade passes the pole pieces, a time-varying voltage is induced in the coil, of frequency proportional to the flow rate. An alternative technqiue which has received little attention in recent years uses the conductance change when a polystyrene or perpex blade passes a probe[34]. This change has then been used to modulate a 10kHz bridge circuit.

It is evident that each of the above transduction techniques will suffer limitations when applied to the rotating vane anemometer as used for air and gas flow measurements. The ideal sensing principle should possess the following features in order to attain the maximum benefit in the applications for which it is sought:-

1. Insensitivity to moisture, dirt and interfering vibrations;
2. It must require no modifications to the rotating vane assembly and at the same time it must not require any specific type of vane construction in order to achieve operation. It must be remembered that in medical applications it is required to sense the rotation of a single flat vane.
3. The method must occupy minimal space in order that its addition to the instrument causes the minimum disturbance to the flow being measured. This criterion also ensures that the method can be applied to a wide range of possible rotating vane designs.
4. The electrical circuits associated with the sensing

principle should, if possible, consume minimal current at a low operating voltage to ensure portable operation of the instrument from small batteries. The current consumption of small filament lamps or even light emitting diodes is an inconvenient design factor which often necessitates the use of bulky rechargeable cells.

5. The sensor output signal waveform should, for convenience, have a spectrum content which is capable of long cable transmission without the use of signal conditioning circuits. For example, the approximate square waveform generated in the optical transducing methods requires filtering before such transmission is achieved. The generated signal waveform should also remain relatively consistent in spectrum content and amplitude throughout the rotational velocity range. This specification should apply wherever the sensor is placed relative to the pick-up point and when, owing to lack of sensitivity the signal is lost, this must occur abruptly, whatever the rotational velocity. To achieve this specification and avoid 'missing pulses' at certain flow rates the magnitude and waveshape generated by the mode of operation must therefore not be a function of the rate of cutting of field lines, as in the magnetic type of tachometer pick-off.

It is proposed that these specifications can be achieved by using a capacitance sensing technique. The capacitance change that occurs when the vane of a rotating vane anemometer sweeps past a sensing area is normally less than 0.5pF, with a minimum residual capacitance of 10pF. To attempt the measurement of absolute capacitance values is an unnecessary complication in this instance, in that the requirement is essentially one of sensing capacitance change as the vane passes a datum point or sensing area.

Designs have been commercially produced in which the capacitive unbalancing of a bridge circuit is used to sense vane rotation. The severe problems experienced in the unbalancing of the bridge with changes in temperature, moisture content and dust deposits, especially after periods of time from an initial setting, has resulted in such instruments being withdrawn from general use.

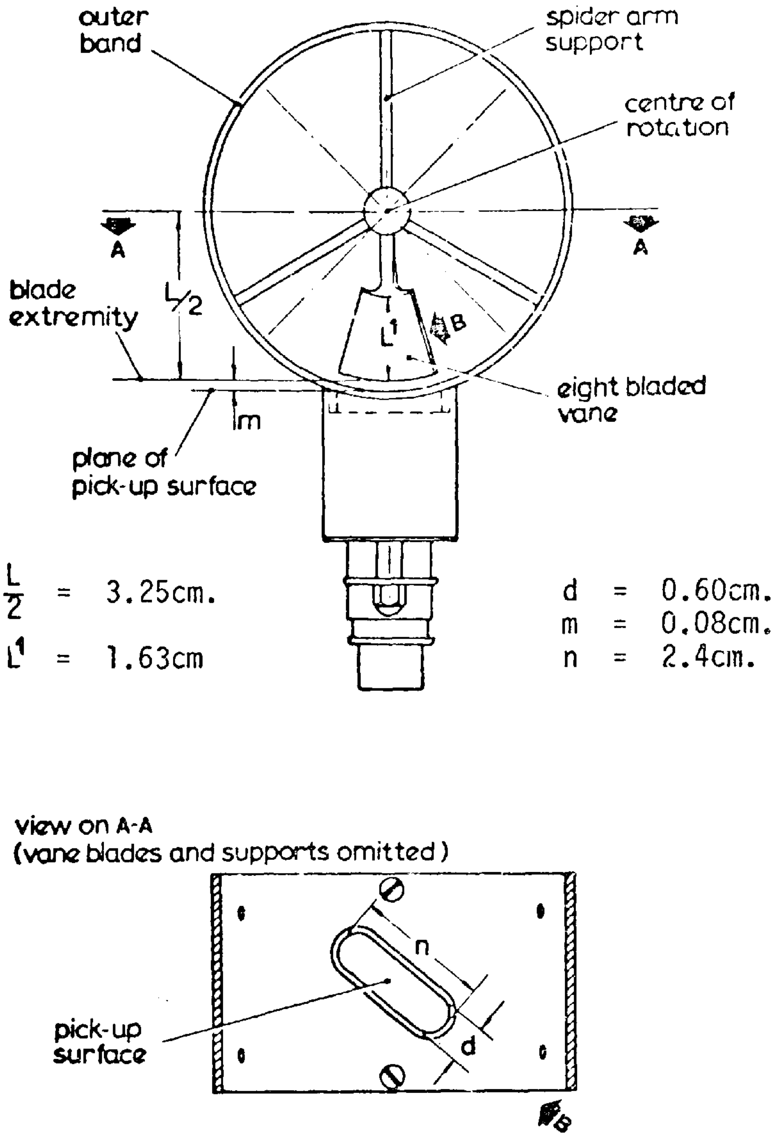
2.3 Analysis of Rotating Vane Capacitance Variation

The suitability of the capacitance change technqiue for sensing vane rotation depends on two factors;

1. The availability of a simple electronic circuit technique which can convert the capacitance change with vane position into a voltage-time replica.
2. The signal obtained from the circuit is suitable for transmission over long cable lengths and on telemetry systems, i.e. has a low spectrum content.

The form of the capacitance variation between a vane of the type used in rotating vane anemometers and a sensing or pick-up area which is located on the periphery of the circle swept out by the vane edge, Fig. 2.1a, can be evaluated theoretically by using an appropriate system model as shown in Fig. 2.1b.

The capacitance per unit length of unequal co-planar strips, which has been evaluated by Smythe[35] using elliptic function

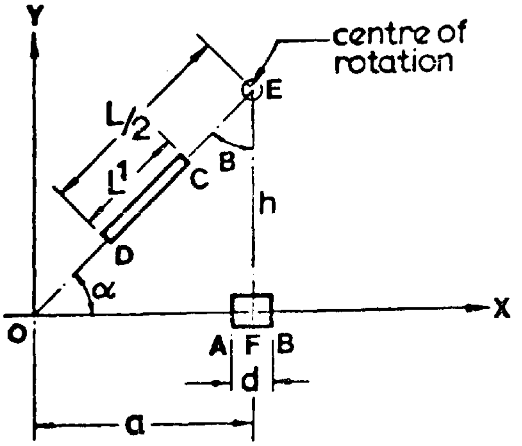


$\frac{L}{2}$ = 3.25cm.

L^1 = 1.63cm

d = 0.60cm.
m = 0.08cm.
n = 2.4cm.

Fig.2.1a. Typical Vane Construction and Dimensions



$$h = \frac{L}{2} + m$$

Fig. 2.1b. Theoretical Z Plane Equivalence

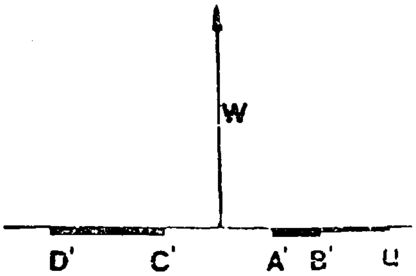


Fig. 2.1.c. Transformation to the W Plane

transformations, may be employed to calculate the vane capacitance variation.

Smythe's analysis shows that for Fig. 2.1c;

$$C = \frac{2\varepsilon K(1 - k^2)^{\frac{1}{2}}}{K(k)} \qquad \text{.... 2.1}$$

where K(k) and $K(1 - k^2)^{\frac{1}{2}}$ are elliptic integrals of the first kind and;

$$k^2 = \frac{(U_b - U_c)\ (U_a - U_d)}{(U_a - U_c)\ (U_b - U_d)} \qquad \text{.... 2.2}$$

This result may be applied to the vane model[36] where the terms U_a, U_b, U_c, and U_d relate the dimensions of Fig. 2.1b in the Z plane to the W plane of Fig. 2.1c. The relevant section of the Z plane can be transformed into the upper half of the W plane by using the transform;

$$W = Z^{\pi/\alpha} \qquad \text{.... 2.1b}$$

All points on OE transform to points along the negative real axis of the W plane. The transformation therefore provides points in the W plane which correspond to the points A, B, C, D in the Z plane.

The polar coordinates of A, B, C, and D can be written as follows;

For A $\quad r = h \cot\alpha - \frac{1}{2}d$

$\theta = 0$

For B $\quad r = h \cot\alpha + \frac{1}{2}d$

$\theta = 0$

For C $\quad r = h \operatorname{cosec}\alpha - (\frac{1}{2}L - L^1)$

$\theta = 0$

For D $\quad r = h\ \mathrm{cosec}\alpha - \tfrac{1}{2}L$

$\theta = 0$

Using the transform:

$W = Z^{\pi/\alpha}$; then the point corresponding to A in the Z plane is given by:

$$W_A = (r\ e^{j\theta})^{\pi/\alpha} = r^{\pi/\alpha}\ e^{j\theta\pi/\alpha}$$

$$= (h\ \mathrm{Cot}\alpha - \frac{d}{2})^{\pi/\alpha}$$

In the same way for B, C, and D respectively:

$$W_B = (h\ \cot\alpha + \tfrac{1}{2}d)^{\pi/\alpha}$$

$$W_C = -(h\ \mathrm{Cosec}\alpha - (\tfrac{1}{2}\ L - L^1))^{\pi/\alpha}$$

$$W_D = -(h\ \mathrm{Cosec}\alpha - \tfrac{1}{2}L)^{\pi/\alpha}$$

Referring to Fig. 2.1c in the W plane:

For A $\quad U_a = (h\ \cot\alpha - \tfrac{1}{2}\ d)^{\pi/\alpha}$

For B $\quad U_b = (h\ \cot\alpha + \tfrac{1}{2}\ d)^{\pi/\alpha}$

For C $\quad U_c = -(h\ \mathrm{cosec}\alpha - \tfrac{1}{2}L^1)^{\pi/\alpha}$

For D $\quad U_d = -(h\ \mathrm{cosec}\alpha - \tfrac{1}{2}L)^{\pi/\alpha}$ 2.3

and where the transformation is valid for:

$$0 < \alpha < \cot^{-1}\frac{d}{2h} \qquad \text{.... 2.4}$$

Substitution of these equations into eqn. 2.1 for the capacitance between unequal coplanar strips will therefore provide data on the variation of the capacitance with vane angle (per unit length of pick-off area) within the range for which the transformation remains valid as indicated by eqn. 2.4. The specific capacitance value is assumed to be approximately one half of that given by eqn. 2.1 since the electric flux contribution due to the far side of the vane relative to the sensing area (as it approaches up to the maximum value of eqn. 2.4) is negligible compared with the other side. In this respect Smythe's unequal coplanar model of Fig. 2.1c assumes perfect flux symmetry with respect to both halves of the W(u,v) plane i.e. for both +v and -v values so that an improved representation is obtained when the capacitance contribution due to flux linkage in the +v (say) section of the W plane is considered. Although this assumption will become less valid as the vane approaches the pick up area, the geometry of the problem suggests that the errors then introduced are unlikely to become significant. It is considered that the adoption of a more rigorous analysis for this field problem - which would involve considerable mathematical complexity - is unnecessary in this instance, since there are further factors which will complicate the prediction of specific capacitance values in an actual anemometer (as discussed later), and secondly it is the form of the capacitance variation that is of interest.

If typical vane and pick up area dimensions are considered, as indicated in Fig. 2.1a, then a theoretical graph showing the variation of the capacitance with vane angle can be drawn for angles within the confines imposed by eqn. 2.4, as shown in Fig. 2.2.a. These results can be compared with static measurements which have been made on a vane anemometer constructed to have approximately the same dimensions as the model of Fig. 2.1a. To obtain accuracte values for the vane angle a magnified screen projection of the mechanical arrangement was used and the specific capacitance values were then measured using a digital readout autobalance bridge. The results

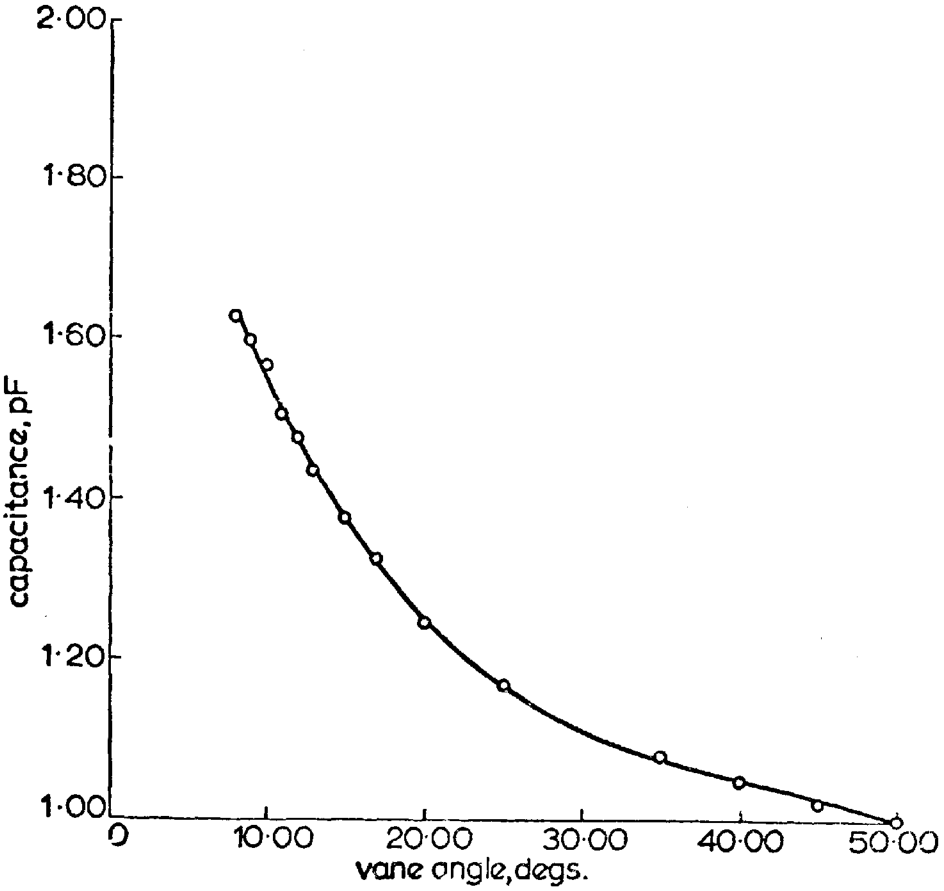


Fig.2.2.a. Theoretical Capacitance Variation for Vane Anemometer Configuration

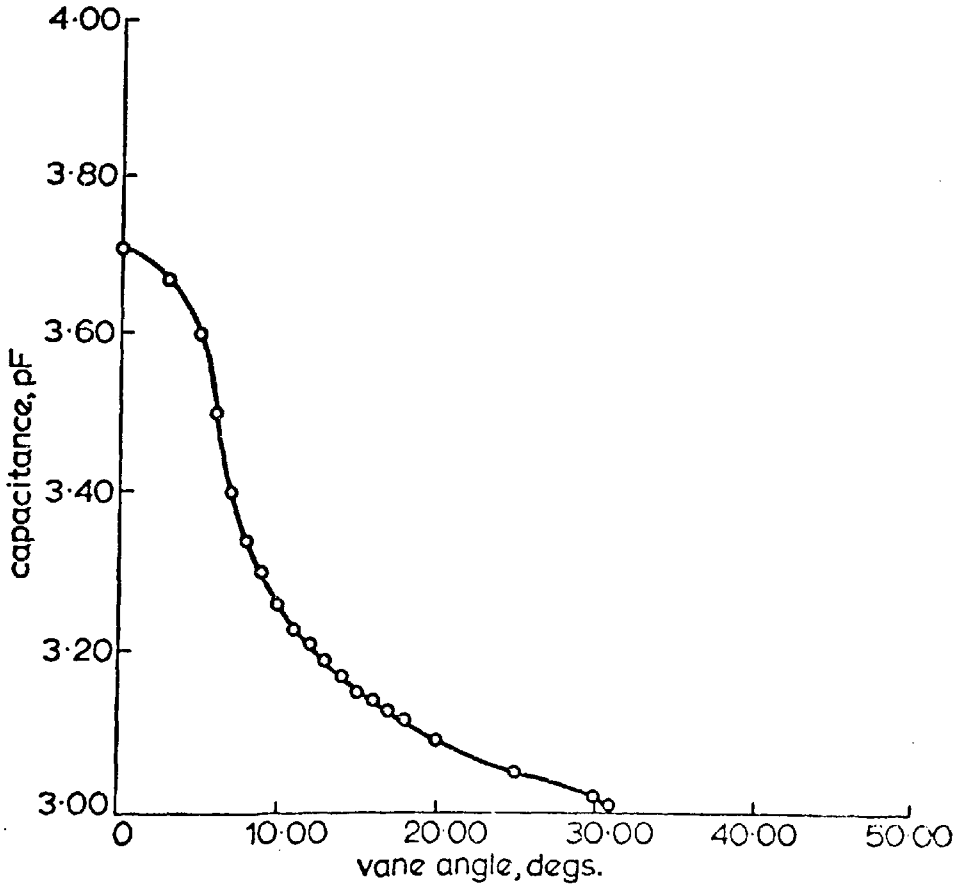


Fig.2.2.b. Measured Capacitance Variation for Vane Anemometer Configuration

obtained are shown in Fig.2.2b and as can be observed a curve of the same general shape as in Fig.2.2a is obtained. Difficulty has been found comparing actual with predicted capacitance values since the curved aerodynamic design of the vane cannot be represented in all respects by the model used. In addition the inevitable residual capacitance of an actual system is difficult to predict however comprehensive the theory.

If the results shown in Fig 2.2a are considered it is possible to evaluate the theoretical capacitance change which such an anemometer will provide as each vane passes the sensing or pick up area. For a vane angle in excess of 50^0 the capacitance value will continue to decrease to the residual value which is governed by the capacitance existing between the sensing area and the outer cage of the anemometer. However in a typical eight bladed anemometer this decrease will not be realised since the following vane on the rotor will already be approaching the pick up area.

From Fig. 2.2a it can be observed that for a change in vane angle from 10^0 to 30^0 the corresponding change in the factor $^C/2$ equals 0.5. For a sensing area length of n = 2.4 cm a theoretical capacitance change in air of 0.21pF therefore occurs, which compares favourably with the actual value of 0.25pF obtained from Fig. 2.2b. From the measured results it can also be observed that a capacitance change value of 0.5pF occurs (i.e. between the values of 0^0 and 15^0 with a residual value of approximately 3.2pF), for an eight bladed anemometer having these dimensions. Unfortunately the theory cannot directly predict this change since some of the values lie outside the permitted range. The best theoretical approximation (0.35pF) is obtained by vertical extrapolation of the curve in Fig. 2.2a with an assumed levelling of capacitance values in the region where the vane passes over the sensing area.

If suitable circuit techniques can be designed to convert this capacitance change into a voltage-time replica, then the smooth form of the curve (as indicated by Fig. 2.2a and 2.2b) is ideal for transmission purposes. Of particular advantage is the fact that the curve shape is not a function of the rate at which the vane sweeps past. In addition if a perfect circuit conversion from capacitance change with vane angle to a voltage-time signal is achieved, then the peak signal amplitude will remain constant as the flow rate varies. If the distance between the vane edge and the sensing area is increased this will remain of the same form as predicted by the above theory.

It is necessary that the required technique must be capable of evaluating smaller capacitance change values than the predicted 0.5pF available, since this value has been obtained with a carefully adjusted small air gap between the vane edge and the sensing area. Critical dependence on such a parameter must of course be avoided on a production basis since it can readily lead to the loss of signal from one or more of the vane blades, and this can cause serious error in the indicated air flow from the anemometer.

The above measurements also verify that the capacitance change must be sensed in the presence of a relatively large residual capacitance value which must be assumed to be at least an order of magnitude greater.

2.4 Circuit Techniques for the Detection of Small Capacitance Changes.

There are in general three methods which can be considered for indication of capacitance changes:

1. A circuit being caused to oscillate by the increased capacitance and the output then shaped to provide a square wave signal.
2. The frequency of an oscillatory circuit being varied by the changing capacitance, and a frequency to d-c conversion then employed to provide an analogue signal which changes in amplitude as the capacitance varies.
3. The amplitude of a periodic signal being varied by the change and observed directly as a variation in the d-c component of the signal

2.4.1. Variation in the Maintenance of Oscillatory Conditions.

Whilst this technique may be successfully employed in an inductive type of transducer, there are practical problems which limit its value in sensing a small capacitance change. In the first case the percentage increase in mutual inductance between a pair of coils, caused by the vane passing through the air gap separating them is considerably greater (>50%) than the capacitance change shown to be available in the rotating vane anemometer (assumed<10%). This percentage increase in mutual inductance is sufficient to allow a circuit to reliably oscillate only when the vane passes through the gap. For example, if the maintenance equations for a separately coupled (emitter-collector) tuned transistor oscillator are investigated it is found that the value of mutual inductance required for satisfactory oscillation is about twice that estimated to commence oscillation in a linear mode.

It is difficult to generalise on the performance of various oscillator circuit configurations with respect to the possibility of achieving a similar performance from a 10% (say) capacitance change. Whilst such a circuit may be theoretically conceived it is apparent from the small capacitance change available that careful individual adjustments on each production anemometer to which it was applied would be required. The problems that arise in practice from moisture and dirt deposits - which can radically reduce the assumed percentage change - further add to the realisation that such techniques are impractical. Furthermore any change in the form of the anemometer construction (for example vane size and spacing relative to the sensing area) would require readjustment of the circuit parameters.

The Colpitts oscillator can be considered as a typical example of a circuit configuration in which oscillation conditions are readily attained. If an analysis for the starting conditions for such a circuit is performed[37] then it is found that the criterion for oscillation requires, to a good approximation, that the transistor current gain be greater than or equal to the ratio of the tank capacitance values (one of which would be formed by the anemometer configuration.) For this application a stability of current gain in excess of the percentage change of capacitance is therefore required. Since this transistor parameter varies considerably on a production basis, and it is also related to the specific circuit bias conditions, individual circuit alignment is required. Under operating conditions moisture and dust deposits on the anemometer will readily invalidate this alignment.

2.4.2. Frequency Modulation Technique.

The feasibility of the second method, in which an oscillator is frequency modulated by the capacitance change can be investigated be considering the relationship:

$$f = \frac{K}{\sqrt{LC}}$$

which is applicable in all LC oscillator configurations, where K is a circuit constant.

The rotating vane anemometer configuration, in conjunction with a suitable inductor value, can therefore form the frequency determining element of the chosen circuit.

If the residual capacitance value C_{res} of the anemometer causes the oscillator to operate at a frequency f, then for a change ΔC as the vane sweeps past the sensing area, a corresponding change in the oscillator frequency Δf will occur. If it is assumed that the ratio $\frac{\Delta f}{f} << 1$ which is valid in this application, then,

$$\frac{\Delta C}{C_{res}} \simeq \frac{-2\Delta f}{f}$$

The assumed 10% capacitance change available from the anemometer will therefore produce only a 5% change in the frequency of the oscillator. With the small ΔC value available the generated frequency is required to be of the order of 0.5MHz (say) so that a satisfactory L-C ratio can be achieved.

As in the previous method this technique would prove very difficult to implement within the terms of this transducing requirement. The problem of oscillator stability with respect to temperature and supply voltage fluctuations, and the subsequent difficulties encountered in the resolution of such small frequency changes by relatively simple circuit techniques eliminates the L-C oscillator method from further consideration

Alternative oscillator circuits in which the generated frequency is inversely proportional to the capacitance, for example the Wien Bridge, the Phase Shift oscillator and the Astable Multivibrator[38,39] will improve on the performance of the L-C type by producing a percentage change in frequency of the same order as that of the capacitance change. Nevertheless the problems of stability and conversion of the frequency change still exist together with the requirement that the mean signal level produced by the circuit must be capable of reflecting the capacitance change at the highest rotational velocity of the vane.

2.4.3. Amplitude Modulation Technique

In conjunction with a suitable circuit configuration the amplitude modulation method has a number of fundamental advantages when compared with the other techniques considered:

1. The principle can be applied without individual adjustment (for example resonant tuning, or similar preset value requirements), to any type of rotating vane assembly.
2. External factors such as dirt and moisture will only limit the amplitude of the output signal and in no way affect the frequency.

3. The modulation envelope will take the form of a time varying signal, the modulation frequency being proportional to the rotational velocity of the vane assembly.

In order to realise these features without recourse to a bridge arrangement, a circuit in which the d.c. component of a periodic signal is modulated by the capacitance change has been considered. The technique can be analysed by considering the waveform shown in Fig. 2.3a applied to the RC circuit of Fig. 2.3b, where C_X represents the variable capacitance component. A half wave rectified signal has been chosen in this instance because it can be readily generated and in addition represented, to a good approximation, by a simple equation.

Using the Fourier Series, the half wave rectified signal can be expressed as [40]:

$$v(t) = \frac{V}{\pi}\left(1 + \frac{\pi}{2}\sin\omega t - \frac{2}{3}\cos 2\,\omega t - \frac{2}{15}\cos 4\omega t\right) \ldots \quad 2.5$$

This signal spectrum shows a strong fundamental term with rapidly decreasing amplitudes for the higher harmonics. To a good approximation the signal can therefore be represented by:

$$v(t) \approx \frac{V}{\pi}\left(1 + \frac{\pi}{2}\sin\omega t - \frac{2}{3}\cos 2\,\omega t\right) \quad \ldots.\ 2.6$$

For the circuit of Fig. 2.3b the transfer function T(s) can be written as

$$T(s) = \frac{C_X}{C_X + C_L}\frac{(s + a_1)}{(s + a_2)} \quad \ldots.\ 2.7$$

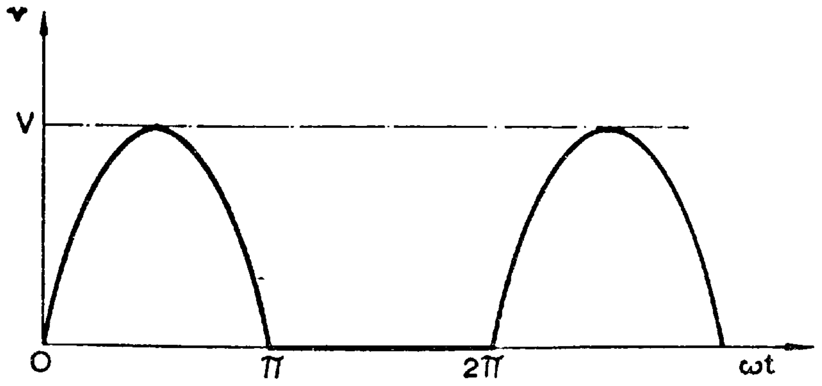


Fig.2.3.a. Suitable Input Waveform

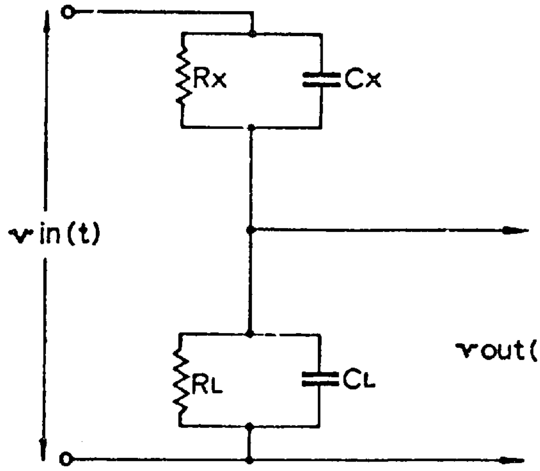


Fig.2.3.b. General Circuit Requirement

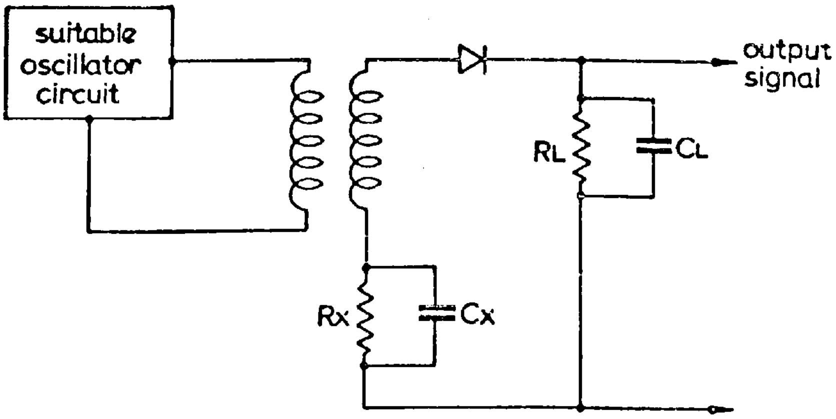


Fig.2.3.c. Practical Realisation of Circuit Technique

where:

$$a_1 = \frac{1}{C_xR_x} \text{ and } a_2 = \frac{1}{\frac{R_xR_L}{R_x + R_L}(C_x + C_L)}$$

If the signal expressed by eqn. 2.6, is applied to the circuit of Fig. 2.3b then:

$$v_{in}(s) = \frac{V}{\pi s} + \frac{V}{2}\frac{\omega}{(s^2 + \omega^2)} - \frac{2V}{3\pi}\frac{s}{(s^2 + 4\omega^2)} \qquad \text{.... 2.8}$$

In conjunction with 2.7 the resulting output voltage can be written:

$$v_{out}(s) = \frac{C_x}{C_x + C_L}\left[\frac{V}{3\pi}\frac{1}{(s + a_2)} + \frac{V}{\pi s}\frac{a_1}{(s + a_2)} + \frac{V}{2(s^2 + \omega^2)} + \frac{\omega V (a_1 - a_2)}{2(s + a_2)(s^2 + \omega^2)} + \frac{2V(4\omega^2 + a_1a_2)}{3\pi(s^2 + 4\omega^2)(s + a_2)} - \frac{2V a_1}{3\pi(s^2 + 4\omega^2)}\right] \qquad \text{.... 2.9}$$

The variation of the output voltage with respect to time is therefore;

$$V_{out}(t) = \frac{C_x}{C_x + C_L}\{\frac{V}{3\pi}\exp(-a_2t) + \frac{Va_1}{\pi a_2}(1 - \exp(-a_2t)) + \frac{\omega V}{2}\frac{\sin\omega t}{\omega} + \frac{\omega V}{2}\frac{(a_1 - a_2)}{(a_2^2 + \omega^2)}(\exp(-a_2t) + \frac{a_2}{\omega}\sin\omega t - \cos\omega t) + \frac{2V}{3\pi}\frac{(a_1a_2 + 4\omega^2)}{(a_2^2 + 4\omega^2)}(\exp(-a_2t) + \frac{a_2}{2\omega}\sin 2\omega t - \cos 2\omega t - \frac{2V}{3\pi}a_1\frac{\sin 2\omega t}{2\omega}\} + \frac{R_L}{R_x + R_L}\frac{V}{\pi} \qquad \text{.... 2.10}$$

If the following circuit conditions are now imposed:

$$t > \frac{1}{a_2} > \frac{1}{a_1}\ ; \quad a_1 >> a_2 ; \quad \omega^2 >> a_1 a_2 \qquad \ldots .\ 2.11$$

Then equation 2.10 closely approximates to:

$$v_{out}(t) \cong \frac{C_x}{C_x + C_L}\left[\frac{V}{3\pi} + \frac{V}{\pi}\frac{R_L}{R_x + R_L}\;\frac{C_x + C_L}{C_x} + \frac{V}{2}\sin\omega t + V\frac{(1 - \cos\omega t)}{2\omega C_x R_x} + \frac{2V}{3}\;(1 - \cos 2\,\omega t)\right] + \frac{V}{\pi}\;\frac{R_L}{(R_x + R_L)} \qquad \ldots .\ 2.12$$

The d.c. component of v_{out} (t) which is a function of C_x can therefore be written as:

$$v_{out}(d.c.) = \frac{C_x V}{C_x + C_L}\left(\frac{1}{3\pi} + \frac{1}{2\omega C_x R_x} + \frac{2}{3\pi} \right) \qquad \ldots .\ 2.13$$

over the range where $\omega C_x\ R_x >> 1$ and where $C_x << C_L$ then

$$v_{out}(d.c.) \simeq \frac{C_x}{C_x + C_L}\;\frac{V}{\pi} \simeq \frac{C_x V}{C_L \pi} \qquad \ldots .\ 2.14$$

Eqn. 2.14 shows that within the constraints imposed, the d.c. output voltage will track the capacitance change, i.e.

$\Delta v_{out}(d.c.) = K\Delta C_x$ where K is a circuit constant .. 2.15

The voltage v_{out} (d.c.) will follow the maximum rate of change of C_x if the time constant $\frac{R_x R_L}{R_x + R_L}\ (C_x + C_L)$ is designed to be small compared with the time time taken for the anemometer blade to sweep past the sensing area at the highest flow rate. This ensures that the exponential terms in eqn. 2.10 make no significant time varying contribution, i.e. exp $(-a_2t)$ always approaches unity.

The method can be implemented by a circuit of the form shown in Fig 2.3c which operates at an arbitary frequency of 2MHz. This frequency readily allows the imposed circuit conditions of 2.11 to be attained in conjunction with the value of C_x predicted from the anemometer capacity measurements (R_x=100 k ohm, R_L=330k ohm, C_L=500pF).

A practical realisation of this technique can be achieved by using a single transistor LC oscillator mutually coupled into a full wave rectifying circuit. In such a circuit it is difficult to predict theoretically the performance by using the Fourier series in conjunction with the transfer function as shown above, as the diode conduction angle will vary as the result of changes in the value of C_x, since the impedance of the rectifying circuit is finite. This effect limits the range over which the output voltage is linearly related to the value of C_x (as shown by eqn. 2.14 for the half wave rectified signal). The results obtained from a tachometer test arrangement are shown in Fig 2.4a where the measured capacitance change between the sensing or pick up area and the rotating component (located on a motor shaft) has been plotted against the peak output signal obtained from a full wave version of the circuit shown in Fig. 2.3c. It will be observed that over this range of ΔC_x, with low residual values (1.7pF), the linearity predicted by the theory is achieved, since the diode conduction angle change is negligible with such small capacitance change values. The results also indicate that excellent sensitivity is possible when using this technique, for example the graph shows that a signal caused by a change in

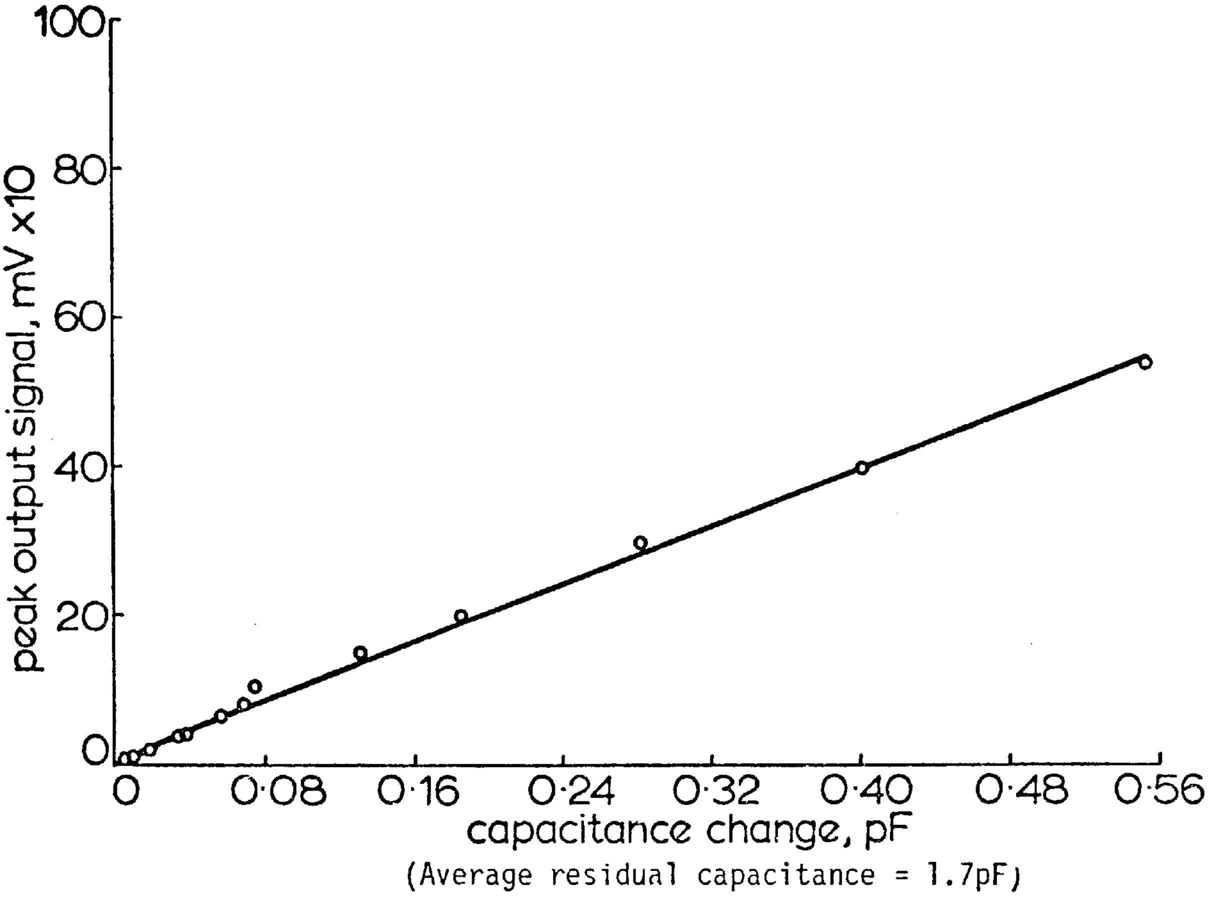


Fig.2.4.a. Transducer Output Signal for Small Capacitance Change Values

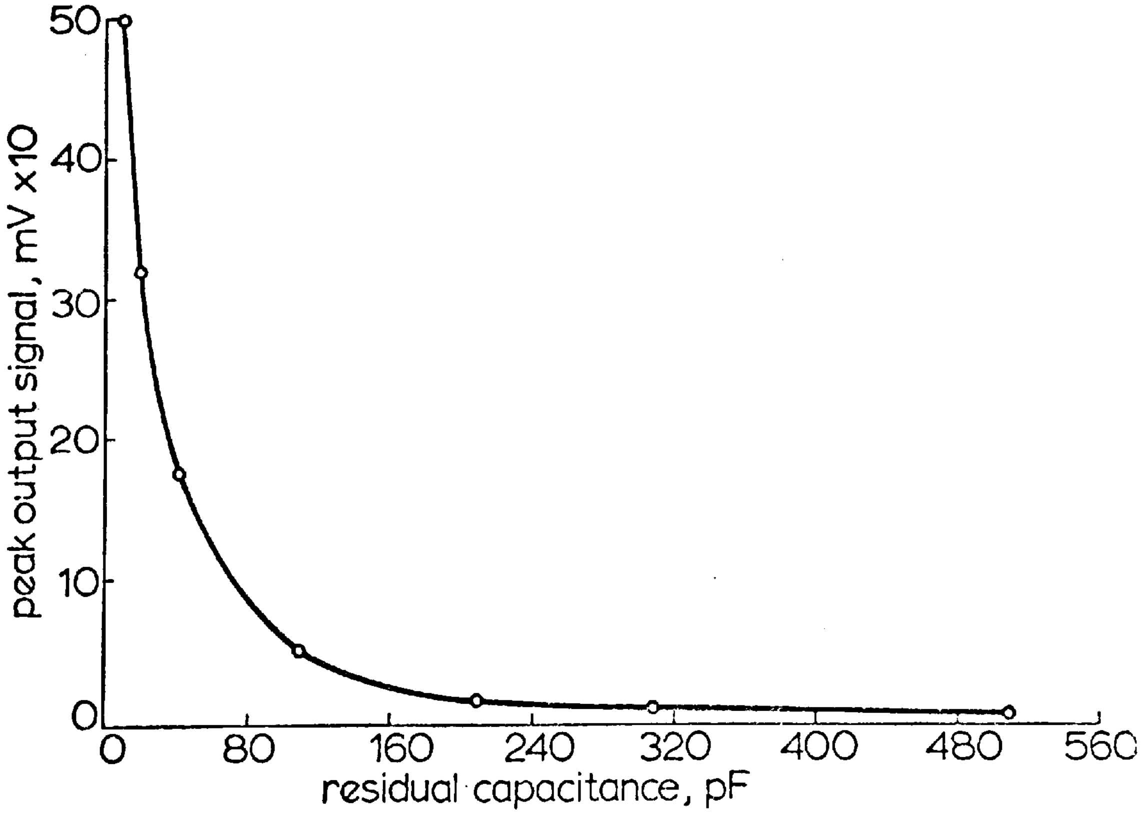


Fig.2.4.b. Transducer Output Signal with Residual Capacitance Added

capacitance of less than 0.01pF (with a residual capacitance of 1.94pF) can readily be sensed.

The circuit resolution performance for a given change of C_x in the presence of a residual capacitance C_{res}, has also been investigated. A rotating vane anemometer which produced a change of 0.5pF with C_{res} = 10pF as each vane swept past a fixed sensing area, was loaded with fixed capacitance values to simulate residual effects, and then driven at a constant velocity in a wind tunnel. The results shown in Fig 2.4b exhibit the expected non linearity as C_x is increased over the range where resolution of the signal still occurs. The measurements also indicate that it is possible to detect the ΔC_x of 0.5pF with a residual capacitance of up to 300pF added, and with the addition of a single section L-C filter to the output circuit to further reduce the carrier (2MHz) signal, a well defined 5mV change occurs with C_{res} of 450pF.

It is apparent from these results that the capacitance change values previously predicted for the conventional rotating vane anemometer (i.e. ΔC_x = 0.5pF, C_{res} = 10pF), can readily be resolved by this circuit technique. Furthermore such capacitance values enable the circuit to operate in the linear region (as indicated in Fig. 2.4a) so that the capacitance chance as the vane passes the sensing area will be transformed into a voltage-time replica.

The output signal waveshape shown in Fig. 2.5a for a constant flow rate has been analysed with a Real Time Octave Analyser (Bruel & Kjoer Type 3347). The results shown in Fig. 2.5b demonstrate that the waveform has a low harmonic content, i.e. 2nd harmonic 13dB below the fundamental and all remaining components are more than 20dB below the 250Hz signal. This may be compared with a half-wave

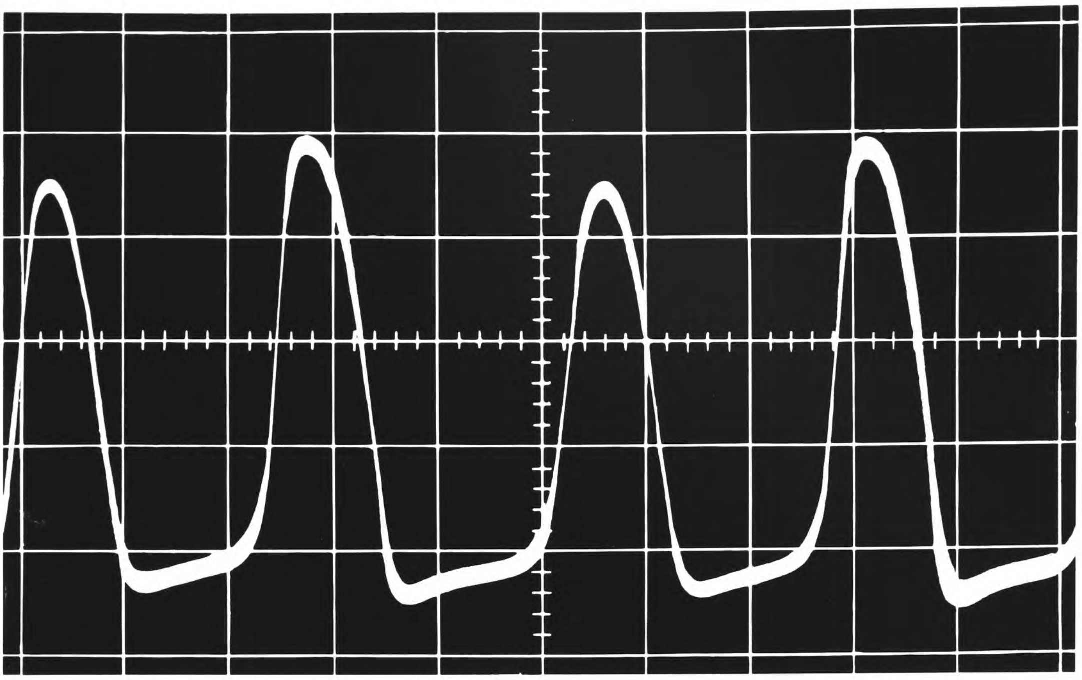


Fig. 2.5.a Characteristic waveform for a rotating vane anemometer with capacitance change transducer (period T = 4ms)

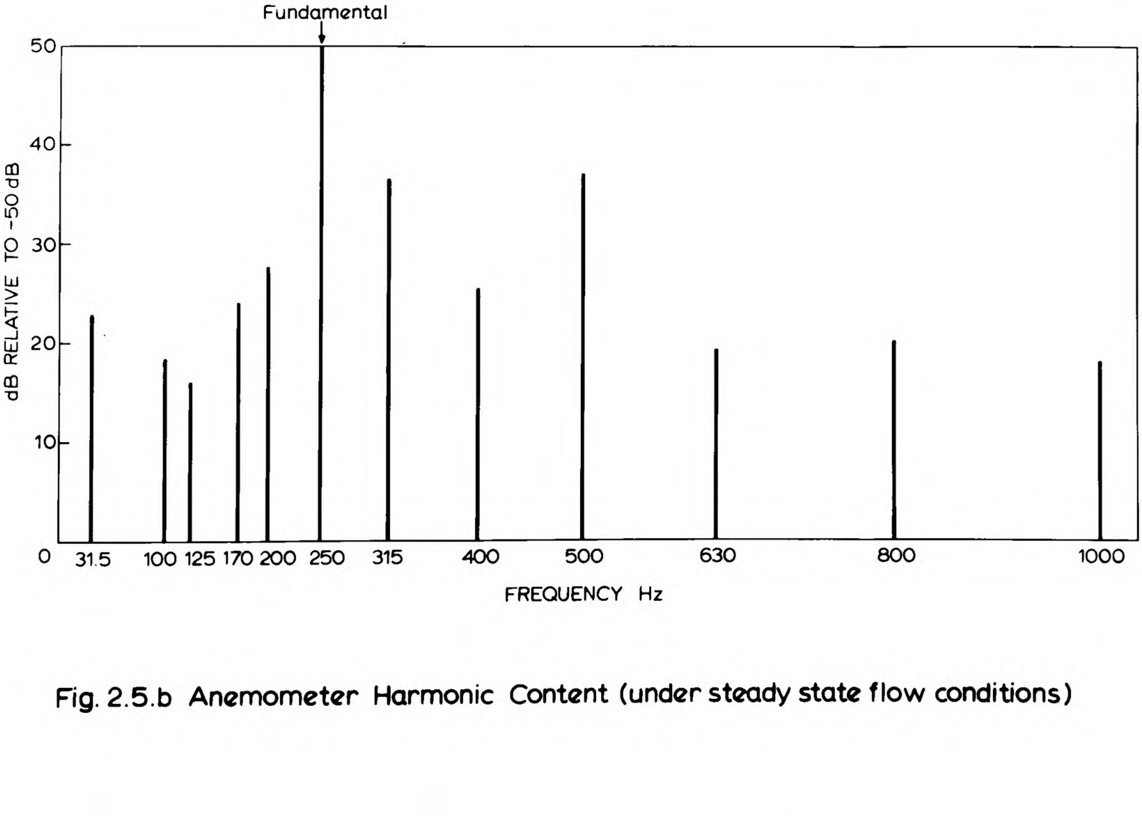


Fig. 2.5.b Anemometer Harmonic Content (under steady state flow conditions)

rectified sinewave in which the 2nd harmonic is 7dB down and all remaining components are more than 20dB below the fundamental). It is interesting to note in Fig. 2.5b, the existence of component frequencies below the fundamental. Such components occur because of the difference in amplitude from one blade signal to the next, i.e. the distance between the sensing area and each blade will vary in practice and thereby affect the magnitude of the capacitance change generated. This amplitude variation pattern is repeated at an eighth of the fundamental frequency (for an eight bladed anemometer) or at 31.25Hz in this instance, and has the affect of amplitude modulating the anemometer voltage-time waveform. The low harmonic content of this anemometer signal justifies the assumption that it is of a form ideally suited to transmission over long cable lengths and on basic telemetry systems.

2.5 Conclusion

Although the capacitance variation generated by vane rotation past a sensing area represents only a 5% change in capitance in a conventional anemometer, the adoption of a suitable circuit technique allows the principle to offer considerable advantages when compared with alternative transducer methods. The important practical features of the capacitance change method can be listed as follows:

1. If the sensing area is encapsulated in an epoxy resin to eliminate the conductive component that exists between the sensing area and the vane, then the presence of considerable deposits of moisture and dirt will not affect the transducer operation. Although the moisture in particular will reduce the

effective capacitance change the circuit sensitivity, as indicated by the graph in Fig. 2.4a enables the principle to be used for the measurement of liquid flow. In the latter case the drag-free advantage over the magnetic pick off method allows measurement at low flow rates, and in small bore pipes, where miniature vane assemblies are necessary.

2. The circuit technique described does not require any pre-set adjustments to be performed in order to achieve correct operation. Furthermore the frequency generated is arbitrary in that production tolerances on the components used are non-critical (e.g. the difference between operation at say, 2MHz and 2.5MHz is negligible).
3. The generated frequency can drift whilst in operation and its amplitude fluctuate without affecting the performance (assuming that the rate at which such variations take place is much slower than the lowest flow rate being measured - an assumption which is justified in practice).
4. Since neither amplitude nor frequency stabilisation techniques are required to be employed in the generator circuit, a simple single stage transistor L-C oscillator is adequate for this application. Such a circuit can therefore be encapsulated in a small enclosure and since the required current consumption is minimal (5mA at 9v) it can obtain its power from a small dry cell.
5. The generated waveshape, which is readily transmitted over long cable lengths, is not a function of the magnitude of the capacitance change available in a given arrangement.

6. Whilst the instantaneous amplitude of the output signal is dependent on the value of capacitance change generated, this is relatively unimportant in that the frequency of the signal represents the flow information. The only requirement in this respect is that a certain known minimum amplitude value must be obtained under all operating conditions in order to trigger a pulse shaping circuit which converts the waveform into a rectangular pulse train. With a single stage transistor amplifier following the transducing circuit this condition is readily achieved in all practical instances.
7. The anemometer blade material can be of a non-metallic form if necessary - the requirement being that a change in the relative permittivity occurs when the vane passes the sensing area. Experiments have indicated that a plastic type material can be used for the vane material with a vacuum coated metal layer being added to increase the signal amplitude if so desired.
8. When the flow rates of various gases are required to be measured (as in anaesthetic applications) the change in dielectric constant from one gas to another can cause a change in the magnitude of the capacitance change generated. With the high resolution of the method described, the effect of such variations can however be neglected in practice.
9. Measurements have shown that the circuit technique can resolve capacitance changes as small as 0.01pF which will allow the rotation of all practical vane configurations to be sensed.
10. The residual capacitance results of Fig. 2.4b indicate that the capacitance change may be sensed at a location remote from the transducer circuit, i.e. the effect of the capacitance change is transferred along a length of screened cable.

CHAPTER 3

Performance Measurements on the Rotating Vane Anemometer with Analogue and Digital Readout

3.1 The Vane Anemometer With Analogue and Digital Readout

The flow measurement performance of a rotating vane anemometer with a capacitance change transducer system can be evaluated by using a circuit arrangement as shown in Fig. 3.1.

The transducer signal is converted into a rectangular waveform of the same mark-space ratio by Schmitt trigger, or pulse shaper (comparator) microcircuit.

This waveform can be directly coupled into a timer-counter instrument to provide a frequency (or period) indication. The anemometer can be calibrated by using this digital readout arrangement and a flow-rate against frequency graph can be produced.

To convert the flow-rate signal into an analogue signal a circuit is used which enableseach incoming pulse to generate a constant height/width pulse, which is 'averaged' to give an output proportional to the incoming pulse rate. The averaging is usually accomplished by a filter network, the complexity of which is governed by the type of presentation required. For example, a meter showing pulse rate in terms of vane rotation must not show fluctuation on the lowest pulse rate expected (assuming constant air flow); thus any damping applied at the low frequency end of the scale will in general be more than adequate in the higher readings. However, if it is necessary to follow sudden changes of frequency, any filter which is

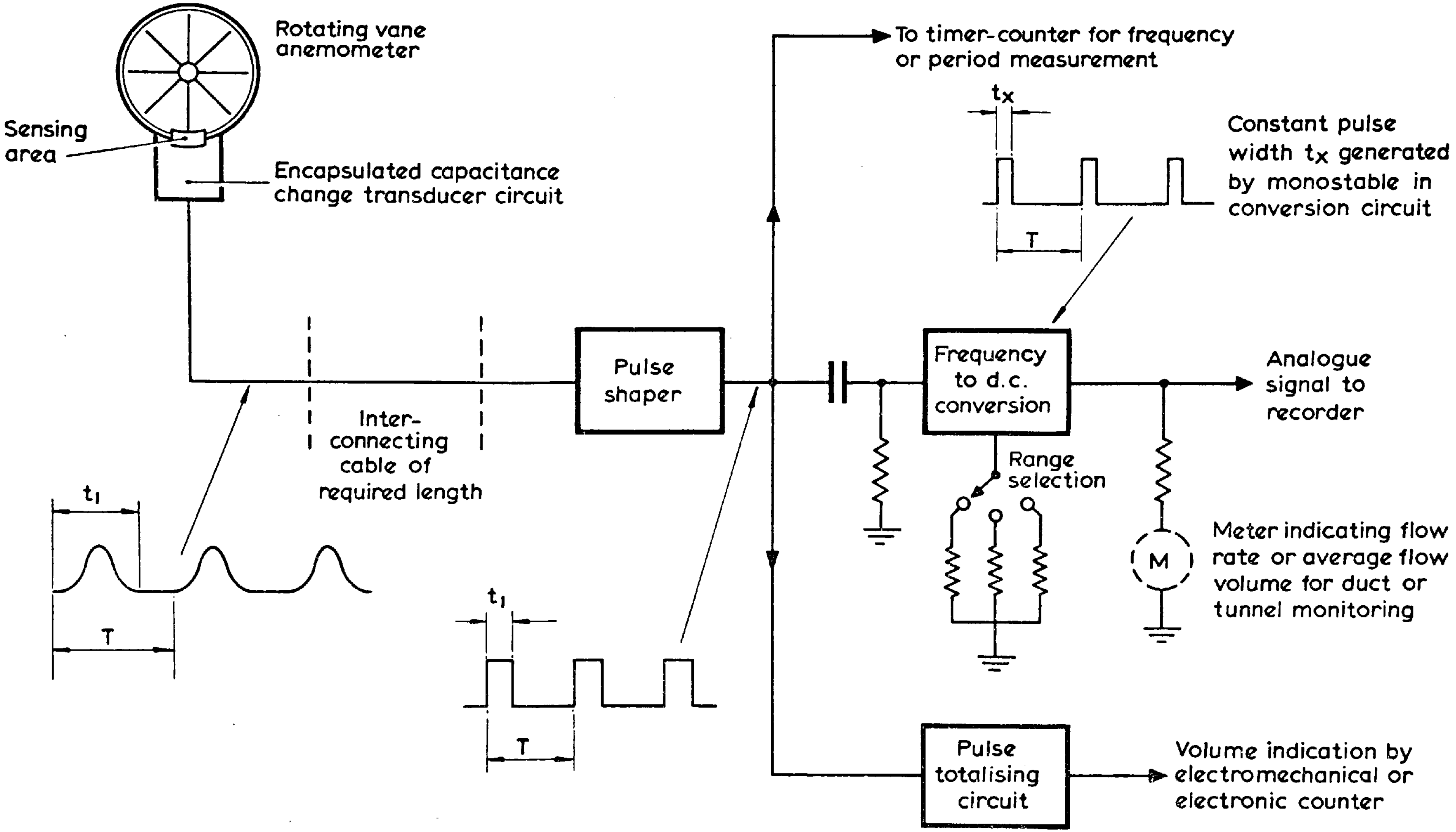


Fig. 3.1 Method for obtaining analogue and digital readout from the vane anemometer

satisfactory for low frequencies may obscure or delay the output when the flow rate fluctuates. The design of frequency to voltage converter circuits[41] is in practice complicated by the requirements for good linearity, low drift with temperature, output voltage ripple content and the transfer function phase lag. It is preferable in this application to employ a microcircuit to perform the digital to analogue conversion, particularly since the output time constant is usually less than 20ms in such devices. Under certain circumstances it may be necessary to further reduce this output response time, in which case specialised frequency conversion circuit designs must be adopted[42]. The measurement of a specific flow volume can be achieved by summing the pulses from the anemometer and then dividing (either manually or with electronic logic division) by the appropriate calibration factor. If it is required to measure the average flow volume (litres of air/min) in a duct or tunnel then the analogue or digital indicating instrument feed from the frequency to d.c. conversion circuit can be calibrated for the cross sectional area of the duct. For this measurement it is necessary to correctly locate the anemometer in accordance with the flow profile as discussed in 2.1 and in detail in Chap. VI of Ref. 3, and for the highest accuracy a number of measurement points should be used with a continuously recording anemometer at each location. Most practical flow measurement problems in ducts and tunnels do not however merit the complexity and expense of this technique and it is usual to either mount the anemometer in the centre of the duct or at the most convenient point in the tunnel. The electronic rotating vane technique illustrated in Fig. 3.1 can be readily extended to provide multi-point scanning of flow in tunnels, mines and similar locations. In addition, either the analogue or digital signal provided by the circuit can be used to initiate alarm circuits or be used to control automatically the flow rate, as discussed in 7.2. The use of microcircuits to perform pulse shaping and frequency to voltage conversion enables the circuit to be constructed[43,44] in a hand-held unit with meter readout, powered from a small dry cell with a current drain of less than 10mA.

3.2 Vane Anemometer Calibration

The anemometer calibration curve, i.e. the curve of indicated air speed against true air speed can be investigated theoretically by using Eiffel's equations for the aerodynamic reactions on a flat plate (see Ref. 3, Page 212). If, as an initial assumption, the mechanical friction is neglected then the rotational velocity of the vane N is directly proportional to the wind velocity V, i.e;

$$N = CV \tan \theta$$

where,

C = instrument constant and θ = the inclination of the vane (at rest) to the flow direction.

The ideal anemometer calibration curve is therefore a straight line passing through the origin. In practice, however, friction exercises an effect which is felt mainly at low speeds when the aerodynamic forces on the vanes are small. At high speeds, when the relative effect of friction is small then the calibration curve of the instrument theoretically approaches a linear relationship (see Ref. 3, Page 217).

Measurement of the linearity of the anemometer calibration curve is therefore an important indication as to the behaviour of the instrument over the required range of flow. Removal of the frictional restraints imposed by the gearing will improve the low speed performance for a given design or alternatively allow a more rigidly constructed blade assembly in conjunction with a non-contacting pick-off to achieve the same linearity and low velocity measurement capability. There are two advantages in adopting the latter approach, firstly the robust construction of the resulting instrument (as shown in Fig. 3.2a) widens considerably the possible areas of application, and secondly a rigid construction enables flow rates in excess of 20 m/s to be measured without causing mechanical damage to the anemometer.

To investigate the linearity of the calibration curve and the repeatability between instruments of the same construction, the performance of three anemometer heads (designated A, B and C) as shown in Fig. 3.2a have been measured in a wind tunnel. A pitot tube was used as a standard against which the rotating vane units were calibrated.* The anemometer readings in pulses per second at each wind reading were derived from the average of a number of pulse counts, each taken over a 10s interval. As shown in Fig. 3.2b the results indicate good linearity and repeatability between the anemometer's tested. In addition one of the heads was calibrated at certain angles of pitch and yaw in comparison with the normal position in which the results of Fig. 3.2b were obtained. A movement in "yaw" is designated as rotation of the head about the axis of the mounting stub and the movement in pitch as rotation about an axis at

*Appendix 3

Fig. 3.2.a Rotating vane anemometer with capacitance change transducer (vane angle 40°, dimensions as for fig. 2.1.a)

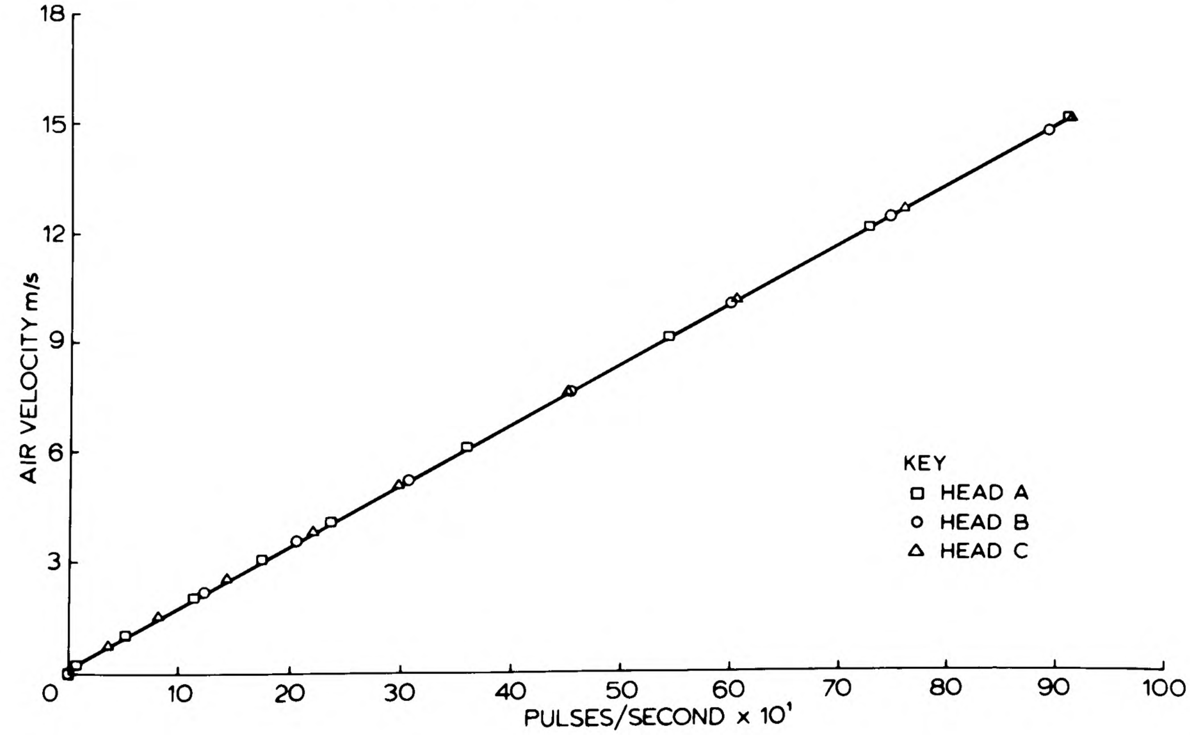


Fig. 3.2.b Rotating vane anemometer calibration curves

right angles to the instrument support (and to the wind direction).

Over the measured range of air speed from 1.5 to 12m/s negligible error in any of the anemometer readings was observed, for pitch angles of up to 7^{0} (forward and backward relative to the support rod), and for yaw angles of up to 10^{0}.

The calibration results indicate that the heads tested will function at air velocities as low as 0.2 m/s.

3.3 Anemometer Response Measurements

The response of a rotating vane anemometer to a change in air flow can be investigated by considering the equation[24];

$$2\pi I \frac{dn}{dt} - Q + T = 0 \qquad \ldots\ 3.1$$

where I is the moment of inertia of the rotor, Q the wind torque on the vanes, n the rotational speed of the blades, and T the frictional resisting torque.

From Ower's anemometer theory, the following equations also apply;

$$\frac{Q}{V^2 \rho D^3} = a + \frac{b\ n\ D}{V} \qquad \ldots\ 3.2$$

and:

$$T = K_1 V + K_2 \qquad \ldots\ 3.3$$

where,

V = instantaneous wind velocity

ρ = air density

D = diameter over blade tips

a, b, K_1 and K_2 are constants relating to the particular instrument under consideration.

Substitution of 3.2 and 3.3 into eqn. 3.1 to eliminate Q and T gives:

$$\frac{dn}{dt} + \frac{D^4 \rho\ b\ V\ n}{2\ \pi\ I} = \frac{(\rho\ V^2\ D^3\ a\ -\ K_1\ V\ -\ K_2)}{2\ \pi\ I} \qquad \text{.... 3.4}$$

This equation is of the form;

$$\frac{dn}{dt} + \alpha\ n = \beta \qquad \text{.... 3.5}$$

where α and β are constants depending on the anemometer construction and the air velocity.

The solution of eqn. 3.5 is;

$$n = \frac{\beta}{\alpha}\ (1 - \exp(-t/\gamma\ )) \qquad \text{.... 3.6}$$

where, $\gamma = \frac{1}{\alpha}$

If the anemometer is subjected to an instantaneous step in air velocity, from zero to V_0 then the output voltage v in the circuit of Fig. 3.1 (assuming instantaneous frequency to d.c. conversion) will take the form;

$$v = k_1\ V_0\ (1 - \exp(-t/\ \gamma)) \qquad \text{.... 3.7}$$

where k_1 is defined as the static sensitivity of the digital to analogue conversion.

From eqn. 3.4 the time constant is defined by;

$$\gamma = \frac{2\ \pi I}{D^4\ b\ V_0} \qquad \text{.... 3.8}$$

The variation of γ with V_0 is therefore affected by the changes that occur in the anemometer constants at various air velocities. It is however possible to account for these variables by using a relationship of the form;

$$V_0 = k_2\ \frac{1}{\gamma^x} \qquad \text{.... 3.9}$$

where k_2 is an instrument constant and x is an integer ≥ 1. For the step change in velocity V_0 the anemometer equation can therefore be written as;

$$\frac{dv}{dt} + \sqrt[x]{\frac{V_0}{k_2}} = k_1 V_0 \, . \qquad \ldots . \; 3.10$$

The results obtained for a rotating vane instrument of the type shown in Fig. 3.2a for various values of step input V_0 are shown in Fig. 3.3. The 'theoretical' curves have been obtained by using the measured value of time constant in eqn. 3.7.

Fig. 3.4 shows the variation of γ with V_0, which for the anemometer evaluated provides a value for x of 2.23. It is proposed that this parameter is of value in comparing the performance of rotating vane instruments to changes in flow rate. The decay of the anemometer signal from a steady state value is governed by the same equations as for the positive step response, although larger γ values are obtained under these conditions. The results obtained for a decay to zero output from a steady state condition are shown in Fig. 3.5.

Since eqns. 3.1 to 3.10 have been derived from Eiffel's general theory of vane aerodynamics the performance of all rotating vane instruments can be evaluated using identical techniques. In particular, it is theoretically possible to obtain similar results for flat vane respiratory flowmeters. Experimental verification of this assumption is presented in Chap. 4.

3.4 Conclusions

The anemometer performance data presented in this chapter shows

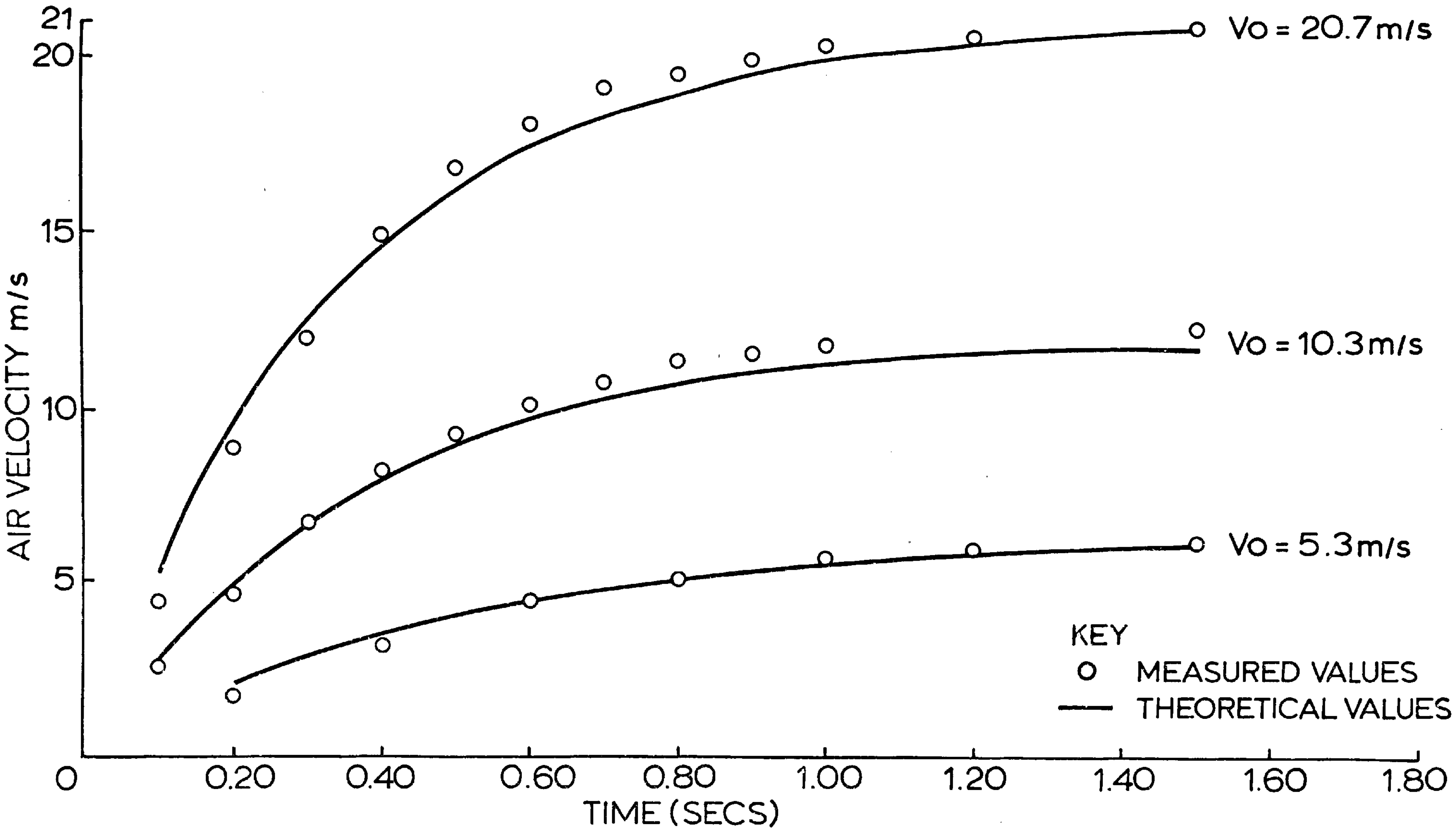


Fig. 3.3 Rotating vane response for step input

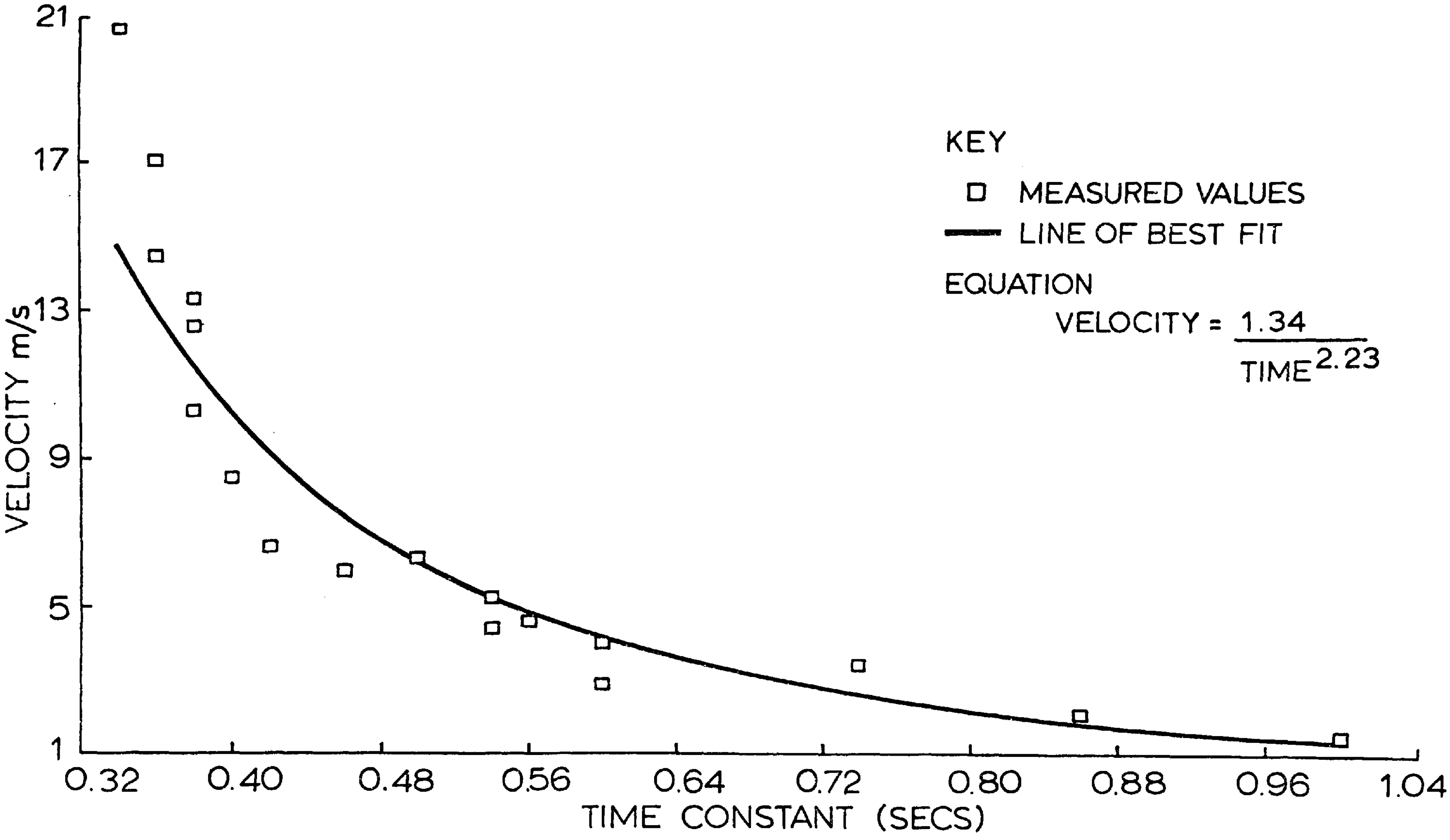


Fig. 3.4 Rotating vane time constant plot for step input

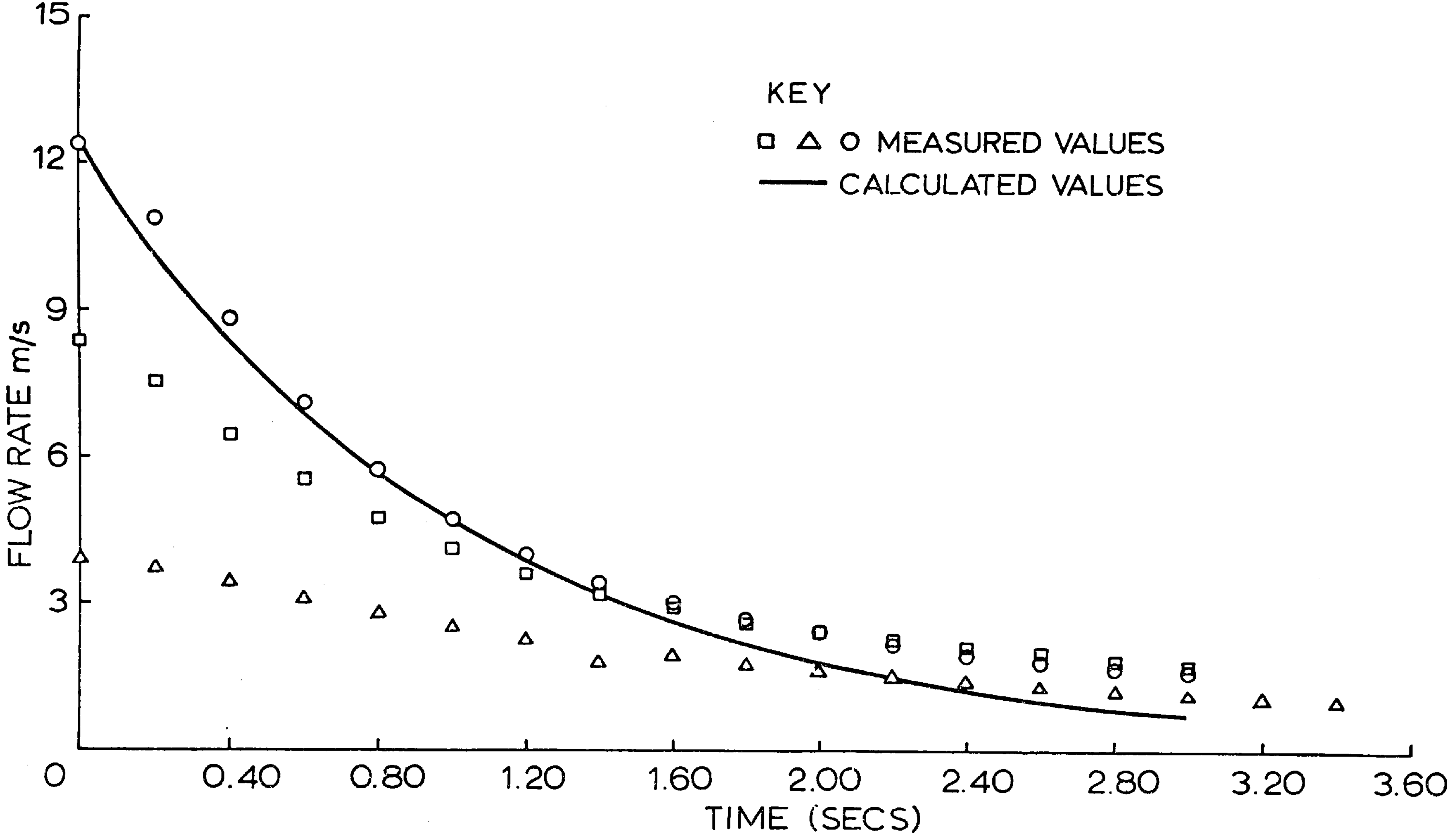


Fig. 3.5 Rotating vane decay from steady flow

that the rotating vane instrument is capable of providing consistent and accurate air velocity measurements.

Over the air velocity range 0.2m/s to 18m/s the results have shown a linearity and repeatability between identically manufactured instruments which is better than ± 1%.

It is of particular interest to consider the improvements obtained when comparing the performance with that of a rotating vane anemometer having a gear train readout mechanism. Firstly the calibration measurement of Fig. 3.2b shows that the instruments tested will function at air velocities as low as 0.2m/s. This favourable compares with Ower's value[32] of 0.15m/s which was obtained with a delicate instrument specifically designed for low air speed measurements. Ower has stated[24] that for mechanically coupled instruments: 'The ordinary anemometer is suitable neither for the measurement of very low wind speeds, nor for speeds in excess of 15m/s. For the former work special care in the design and construction is necessary if satisfactory performance is to be obtained.'

It may be concluded that the adoption of a non contacting vane sensing technique has extended the operating range of the instrument. For example it has been shown that a rigidly designed anemometer, as shown in Fig. 3.2a, can function over a range of air velocities which extends to the lowest value obtained by Ower on his very delicate low speed instrument. Furthermore the construction of this noncontacting vane instrument enables it to be employed for air velocity measurements up to and exceeding 25m/s.

Continuous running of the instruments evaluated has also shown that the calibration remains unchanged within the accuracy of the pitot tube reference used.

The time constant of the rotating vane instrument which has been measured as a function of the air velocity using a step response technique, has a typical value of 0.5s at 5m/s. The value of this parameter, which is mainly governed by the inertia of the rotating parts, shows an improvement on that quoted by Mahdi & McPherson[33] (1.5s at 4m/s) for an anemometer using a photo-electric pick-off.

It may be concluded that the integer x (eqn. 3.9) introduced in this investigation to denote the form of the time constant - velocity curve, is a parameter which is of value when comparing the response performance of rotating vane instruments.

CHAPTER 4

Rotating Vane Techniques Applied to Respiratory Monitoring

4.1 The Medical Requirement for Performing Respiratory Measurements

There are in general two clearly defined areas in which the measurement of lung function expiration and inspiration parameters is necessary[45]:

1. the determination of the respiratory minute and tidal volume is one of the essential parts of the monitoring of patients during surgery.[46] Furthermore respiration, as one of the two vital organ systems providing oxygen supply and carbon-dioxide wash-out of the tissues, should be supervised in every seriously ill patient. In postoperative or postanaesthetic conditions, as well as in patients with impending or existing respiratory failure, this supervision should be continuous.[47]
2. considerable assistance in the management of patients with respiratory disease, such as asthma,[48] is obtained when physiological tests of respiratory function are performed.[49] Pulmonary function tests have four main purposes;
    a. to assess the respiratory function in order to determine the progress of disease and the effect of treatment
    b. to permit early diagnosis of respiratory disease, e.g. to detect airway obstruction in patients who smoke before chronic bronchitis develops
    c. to make a diagnosis in the patient with breathlessness and to evaluate the extent of pulmonary disability

d. to assess the patient prior to lung surgery.

It is also essential that instruments are available for use in the respiratory screening of large groups of people.[50,51,52] Such measurements enable an analysis of the effect of industrial pulmonary diseases, such as Pneumoconiosis[53] to be made.

Furthermore, recent research indicates that it is very valuable from the point of view of the individual patient and from the wider view of the epidemiologist to have results of this kind which go as far back as possible in the history of any group under investigation. From an entirely different standpoint it is accepted medically that such data forms an important index of health and many investigations relating respiratory parameters to sociological factors such as academic achievement in schoolchildren,[51,52] physical fitness and athletic ability,[50] have consequently been undertaken.

For anaesthetic applications a ventilation measurement instrument should possess the following features:

1. achieve sufficient measurement accuracy under gas flow conditions where wide variations in density, temperature and humidity can occur. This must include satisfactory unattended operation over long periods of time during which considerable moisture deposition may occur.
2. be capable of measuring tidal (to and fro) gas flow. This may be achieved either by the instrument being sensitive to flow in one direction only, or by the instrument responding in a similar manner to flow in both directions.
3. have a fast speed of response to ensure accurate measurements under non-sinusoidal flow conditions. Such

conditions often occur in practice when lung ventilators are used to assist the patient in breathing.

4. the sensor used in the instrument must be robust and capable of being autoclaved. It must be applicable to all anaesthetic gas circuits and also be suitable for use with the patient breathing air without external assistance.
5. the sensor must possess a small dead space ($<30\mathrm{m}\ell$), and offer the minimum of resistance to breathing.
6. the measurement technique used should provide an electrical output which is a linear function of the parameter it is proposed to measure. The measurements should be accurate to within 1% to 5% of the true value,[54] depending on the application, and the time for registration of 95% of the response to a signal should be small in relation to the physiological fluctuations of the variable in question.
7. to obtain the basic lung function parameters* a measurement technique which is capable of providing a flow rate/time signal in addition to an expiration (or inspiration) volume/time signal is required.
8. the instrument should not require calibration before use, consume minimal current so as to improve on the portability of existing types, and be reasonably inexpensive.

* Respiratory parameters are defined in 5.1.1.

4.2 The Development of a Rotating Vane Respiratory Anemometer

In an attempt to attain the specifications listed in the previous section a rotating vane form of sensor has been developed during this investigation[55,56] (see also Appendix 2), for use in both anaesthetic and lung function measurement applications.

The sensor consists of a cylindrical anodised aluminium tube having British standard medical equipment taper as shown in Fig. 4.1a through which the flow to be measured is continuously passed. Within this tube is a flat kapton* vane as shown in Fig.1.4b of approximately 1.8 cm^2 surface area, mounted with its axis parallel to the direction of flow, in jewelled bearings journalled in the wall of the tube. The kapton vane, which has a weight of less than 0.03 gm, has been found to exhibit excellent rigidity characteristics. Furthermore, this type of material has been designed to remain serviceable at temperatures up to 250°C, thereby readily allowing the sensor to meet the necessary sterilisation requirements.

The unidirectional flow response of the sensor is achieved by means of a swirl plate Fig. 4.1c which is inserted within the cylinder and which allows the vane to rotate only in the predetermined direction. This plate converts the movement of the air or gas stream to be measured into a spirally swirling flow within the chamber containing the vane.[30]

The rotation of the vane is sensed by using the capacitance change transducer technique discussed in Chap. 2. To ensure adequate capacitance change as the vane edge passes the sensing probe the kapton vane is vacuum coated with an aluminium film. The sensing area is a circular conductive probe with a surface area of

* Kapton[57] is a heat resistant polymide film material manufactured by DuPont (U.K.) Ltd.

Fig. 4.1.a Sensor flow chamber

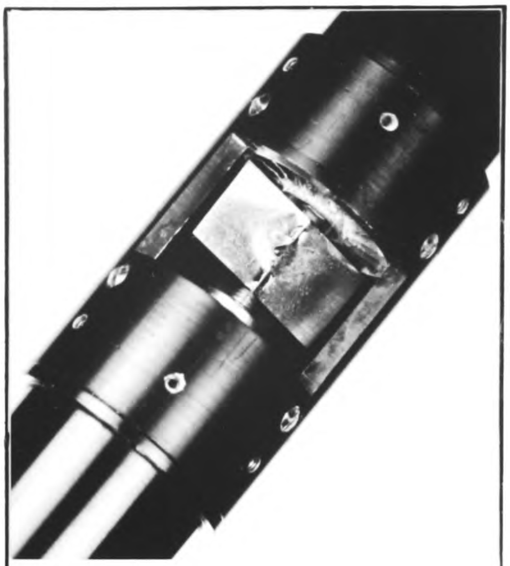


Fig. 4.1.b Kapton vane construction

Fig. 4.1.c Sensor swirl plate

Fig. 4.1.d Capacitance pick-up probe

Fig. 4.1.e Transducer arrangement

Fig. 4.1.f Complete respiratory anemometer

approximately 1.2 cm^2 mounted in the tube as shown in Fig. 4.1d. The probe is terminated in a screw socket connector which enables the sensor to be temporarily disconnected from the capacitance change transducer for sterilisation purposes. To allow the sensor to operate under conditions where considerable moisture deposits can occur, the sensing area probe is encapsulated in an epoxy resin coating. The capacitance change caused by the vane in this sensor passing the probe has been measured as typically 0.16pF with a residual capacitance value of 3.64pF. Under these conditions a 100mV signal is available from the transducer circuit which, as expected, is of a form identical with that obtained for an eight bladed rotating vane anemometer as shown in Fig. 2.5a.

The transducer circuit is encapsulated in a small rectangular block and housed in a circular metal tube, Fig. 4.1e. The complete respiratory anemometer is shown in Fig. 4.1f.

4.3 Evaluation of Respiratory Anemometer Performance

To enable a complete assessment of the performance of the respiratory anemometer to be undertaken it is necessary to consider operation under both continuous and intermittent flow conditions. In the former case the rotating vane anemometer theory outlined in Chap. 3 should equally well apply to this form of vane flowmeter, since the derivation is based on Eiffel's flat vane aerodynamic theory.

4.3.1. Continuous Flow Calibration and Step Response Measurement

The continuous flow performance of the flowmeter has been evaluated in a wind tunnel arrangement, in the same way as for the rotating vane anemometer instrument discussed in 3.2. Over the air velocity range 0.2 - 15m/s the respiratory anemometer has a linear calibration curve and measurements indicate good repeatability and long term stability for identically manufactured units (better than 1% assuming negligible pitot tube reading error).

As expected, the low mass vane considerably improves the response time for this form of rotating vane instrument to the extent that accurate step response measurements have been found difficult to achieve, since:

a. it is necessary to generate a step change in air velocity having a rise time less than that of the flowmeter under test. This requires the use of an electrically operated high speed mechanical valve.

b. the analogue to digital conversion circuit of Fig. 3.1 must have a response time considerably less than the anemometer time constant. This may be achieved in practice by using a specialised form of frequency conversion circuit.[42]

The flowmeter time constant measurements which have been obtained using a storage oscilloscope are shown in Fig. 4.2. These results show the marked similarity between the respiratory flowmeter and the vane anemometer (c.f. Fig. 4.2 with Fig. 3.4) although in the former case the time constant is measured in milliseconds rather than seconds. The decay time constant for this flowmeter is also considerably improved in comparison with that obtained for the rotating vane instrument (Fig. 3.5) being typically less than 200ms at 6m/s. These results are of value in that they indicate that the respiratory anemometer is capable of tracking fast changes in air flow and in

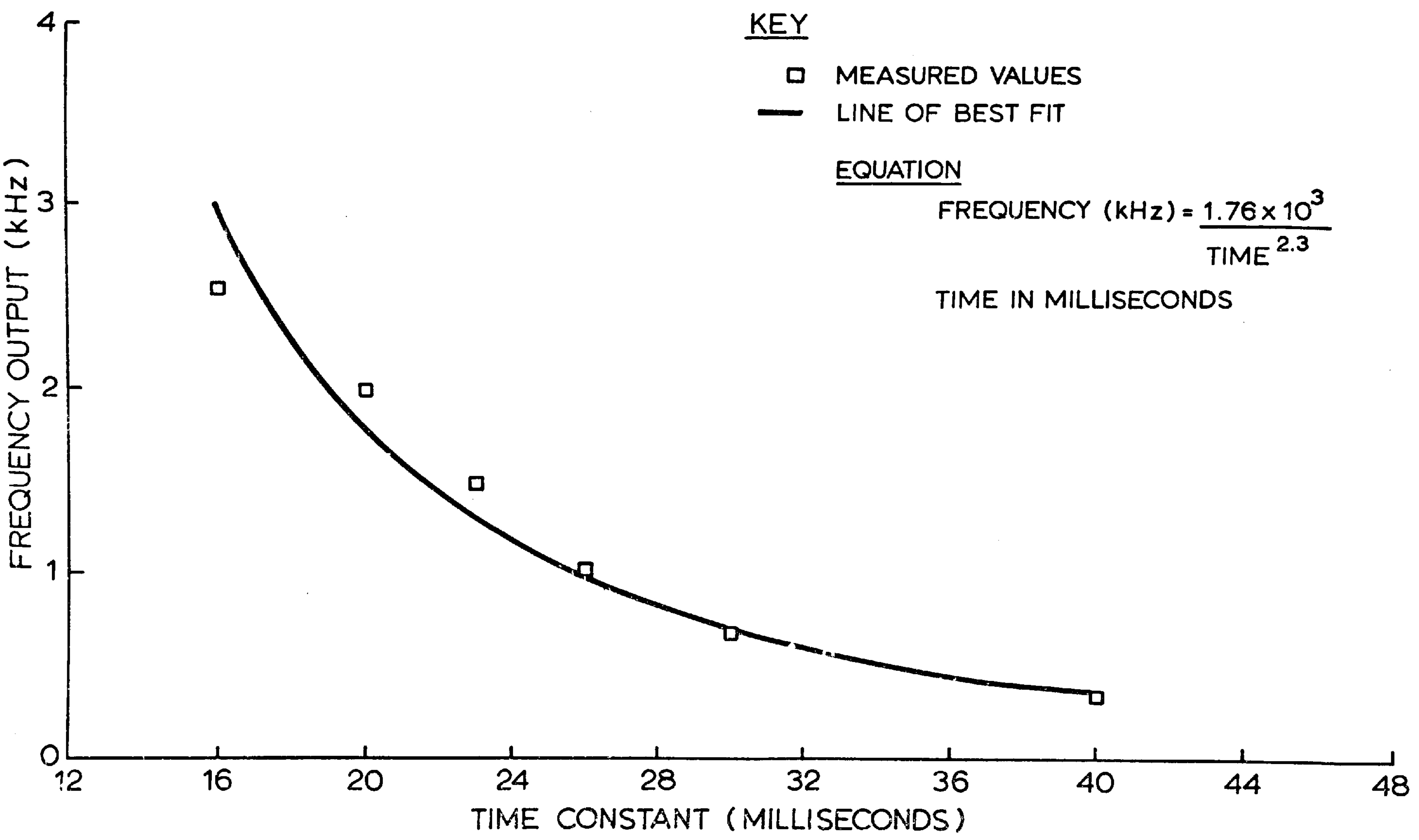


Fig. 4.2 Respiratory flow meter time constant plot for step unit

addition that it has a minimal vane 'run on' characteristic when the air flow either ceases or reverses direction.

4.3.2. Performance Under Intermittant Flow Conditions

One of the simplest intermittent flow tests, which is particularly relevant to the evaluation of a respiratory transducer, is shown in Fig. 4.3a. This arrangement uses an accurately constructed volume displacing piston which can be preset to discharge between 1 and 5 litres of air through the sensor under test. To verify the piston calibration accuracy a recording spirometer (Ohio displacement spirometer) is placed in series with the sensor. Both the total number of pulses produced by the sensor, for a specific piston displacement, and the time taken to achieve this displacement, are measured by electronic timer-counter instruments. The timer start and stop signals are obtained from an electronic circuit which senses the commencement and end of vane rotation respectively. (c.f. Fig 5.1a).

The volume/time waveshape can also be mechanically controlled to produce gas flow rates and volumes of exactly known physico-mathematical characteristics[58], for example sinusoidal displacement.

The results obtained from the apparatus* of Fig. 4.3a are summarised graphically in Fig. 4.3b and 4.3c. To obtain the results in Fig. 4.3b the piston displacement time has been used to calculate the equivalent number of expirations per minute. These results are of significance when considering the use of the sensor for measuring expiratory flow in lung ventilators. Firstly, over the normal operating range from

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*These measurements were made by the author in the Respiratory Laboratory at the Middlesex Hospital, London.

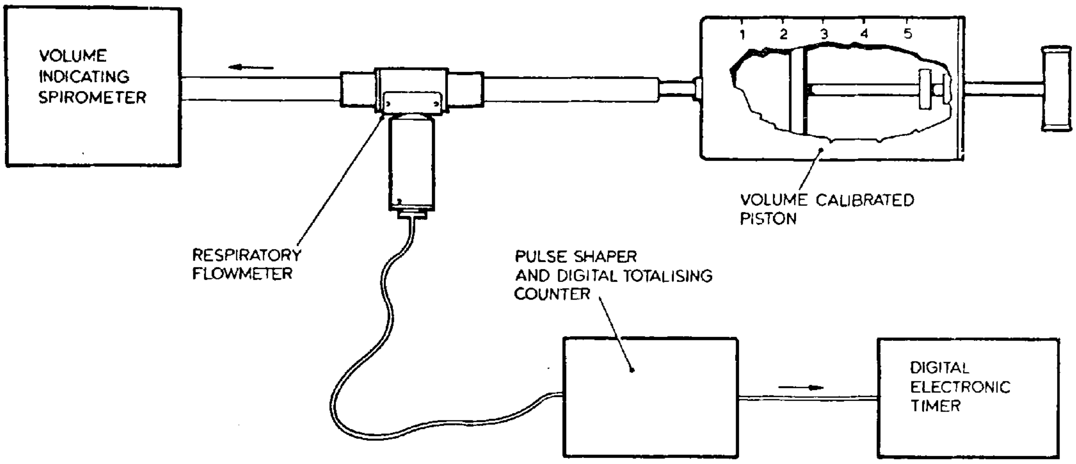

Fig. 4.3.a Apparatus for performing intermittent flow measurements

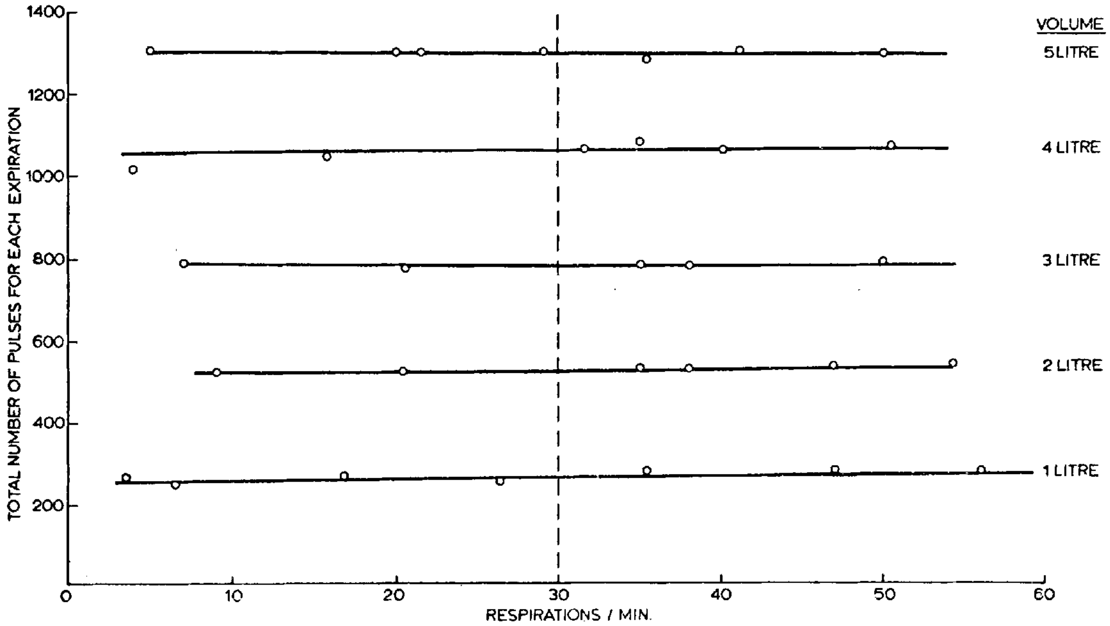

Fig. 4.3.b Intermittent flow calibration

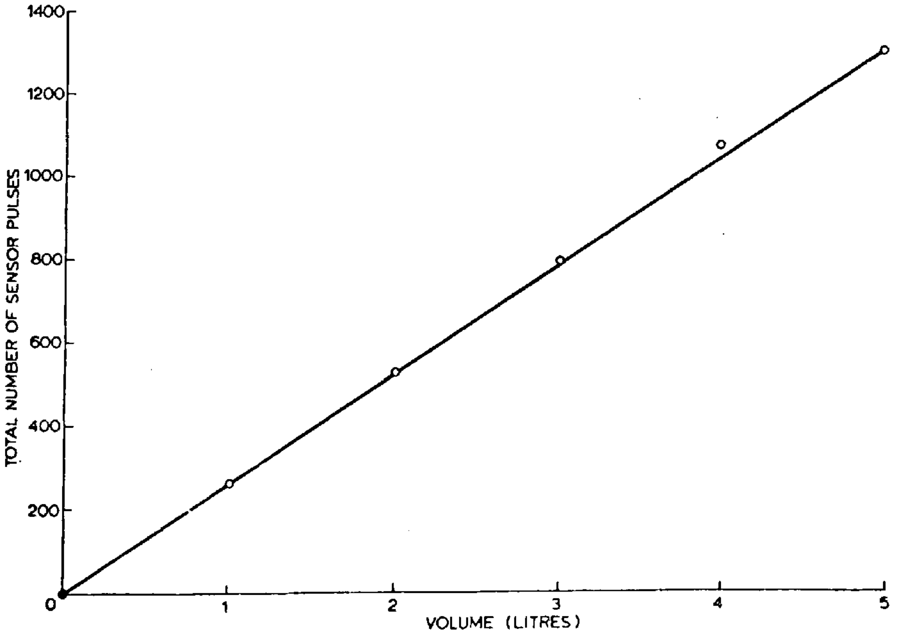

Fig. 4.3.c Sensor calibration at a fixed respiration rate of 30 per min

10 to 40 respirations/min., for a fixed volume of displaced air the anemometer provides consistent pulse totals i.e. the cycling rate has a small effect on accuracy (less than 5% variation over this range). Secondly, as shown in Fig. 4.3c the total number of pulses per expiration (at a fixed cycling rate of 30/min), is linearly related to the volume of air displaced through the sensor.

It is interesting to note that these results are applicable when the rate of piston displacement is manually varied, even in an irregular manner so as to produce 'peaky' volume/time waveshapes. This performance, provides a practical indication that a sufficiently fast response time can be achieved from an electromechanical anemometer under intermittent flow conditions. Furthermore the consistentaccuracy under high cycling rates with rapid flowrate fluctuations confirms that the sensor has minimal vane 'run on' under these difficult measurement conditions.

To investigate the sensor performance under continuous cycling operation similar to that found in practice on lung ventilator machines, the cylinder arrangement of Fig. 4.3a has been mechanically driven at a fixed rate to produce an approximately half cycle sine wave flowrate pattern. This form of apparatus can be compared in performance with that of a Starling Pump[59] as used by Lunn[60] who has evaluated the sensor independently. The results shown in Fig. 4.4a for cycling frequencies of 18 and 35 per min. indicate that the pulse per litre is virtually constant over the entire range of minute ventilation with a constant 5% discrepancy in pulse counts between the two cycling rates. The sensor exhibits a starting flow, i.e. the continuous flowrate of gas sufficient to initiate rotation of the vane,

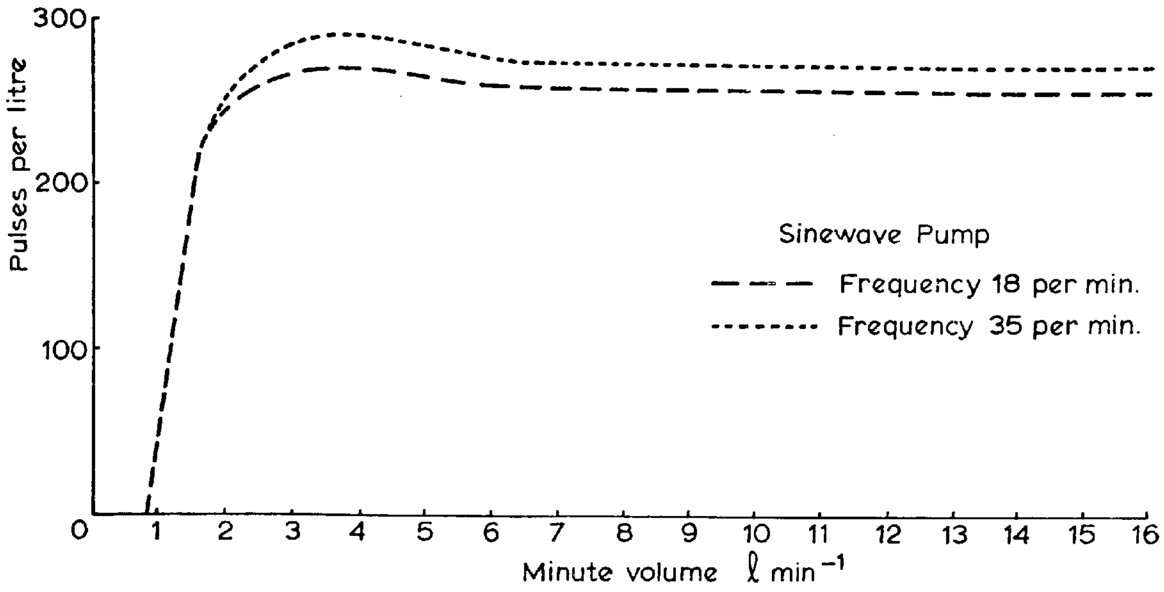

Fig. 4. 4a Spiroflo sensor performance under constant cycling conditions

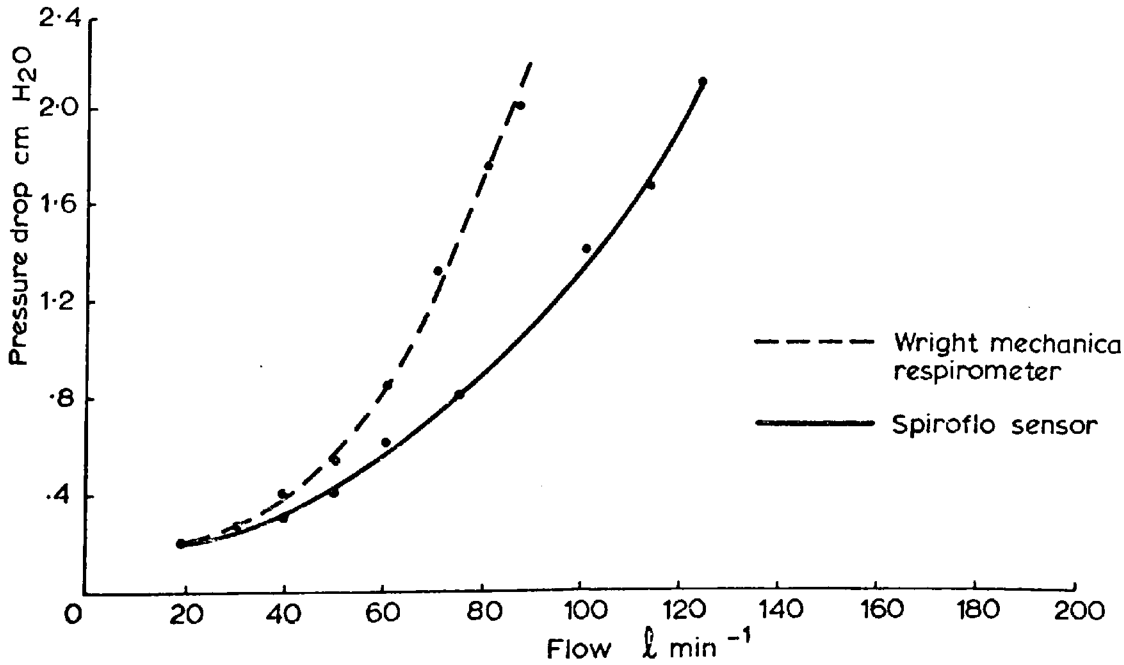

Fig. 4. 4b Sensor pressure drop measurements

of 1.2 ℓ/min. when the long axis of the sensor is vertical. When the long axis of the sensor is horizontal this value varies in different sensors between 1.5 and 2 ℓ/min.

To ensure that the respiratory anemometer has a resistance to flow of a sufficiently low value, the pressure drop across the sensor has been measured at various flowrates. The results, graphically presented in Fig. 4.4b, show that the pressure drop is as low as 2mmH$_2$O at a flow of 20 ℓ/min. This addition to the resistance to breathing, at normal ventilation, is of little significance except perhaps when the maximal voluntary ventilation[54] of the patient is under investigation. The sensor resistance can however be reduced by increasing the bore of the tube in which the vane is housed.

Lunn's investigation of the sensor performance has included measurements using both nitrous oxide and oxygen in addition to air. Over the minute volume range between 2 and 15 ℓ/min. the nitrous oxide causes the sensor to give a pulse per litre error less than 10% of that value obtained with oxygen or air (the latter two gases providing identical results). Over the range between 5 and 10 ℓ/min. this error reduced to less than 5%. Lunn has attributed this effect to the lower viscosity and higher density of the nitrous oxide gas.

Clinical tests* under operative anaesthetic conditions have shown that the sensor will perform satisfactorily under conditions of high gas moisture content. Whereas it is difficult to assess the extent of the measurement error caused by the water droplets impinging on the vane, long term use of the sensor has however shown that such

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*Tests performed by Dr. V. Keating, Consultant Anaesthetist, Queen Charlotte Hospital, London.

errors can at worst cause a deviation of less than 10% between the actual and indicated volume values.

Experience has shown that modifications to the swirl plate (affected by filing the fluted edges) can readily allow each sensor to achieve the same pulse per litre count (within 2%).

Under these conditions it is found that each sensor will then function in an identical manner with that of a 'standard' sensor.

4.4 Discussions on Sensor Performance

The respiratory anemometer design presented in this investigation which, for commerical purposes has been termed a Spiroflo sensor, has been shown to be capable of achieving the requirements for such a flowmeter listed in 4.1. The value of the technique can be assessed by comparing the results obtained with those achieved by alternative measurement methods.

4.4.1 Comparison with the Mechanical Wright Respirometer

At the present time the most widely used instrument for the measurement of minute volume is the Wright respirometer.[30] This consists of a miniature air turbine with moving parts of very low inertia. The revolutionsof the rotor are recorded by means of a gear train and dial of the type used in wrist watches. The instrument indicates directly on a dial the number of litres of gas which have passed between two successive readings. The respirometer responds to gas flow in one direction only and it may therefore be used with tidal flow. Whilst this type of respiratory anemometer has an accuracy which is adequate for clinical monitoring,[61] it suffers from two distinct disadvantages. Firstly, being entirely mechanical, the minute volume reading must be obtained with the aid of a stop watch. During anaethesia this calculation must be repeated frequently and under operative conditions this becomes a time consuming and often a difficult task to accomplish.[46] The second and most serious disadvantage of the Wright respirometer is its liability to damage, resulting for example, from being dropped inadvertently on to a hard floor. Such an accident can easily occur in practice due to the compactness of the instrument. The damage that usually results is in the gear train mechanism which couples the vane to the dial.[61]

The Spiroflo sensor can be considered as offering a number of advantages when compared to the Wright instrument;

a. the digital output signal provided by the transducer technique enables a continuous assessment of the minute volume value to be made.

b. the absence of a gear train mechanism and the use of a very low mass vane allows the sensor to withstand, without damage, considerable mechanical shock.

c. the steady state starting flow rate of the Spiroflo sensor is 1.2 ℓ/min. compared with the Wright's value of 2.5 ℓ/min.

d. as shown in Fig. 4.4b, the pressure drop across the Spiroflo sensor is lower than that of the Wright instrument, particularly at high flow rates.

e. under constant cycling conditions the Spiroflo sensor provides an improved overall accuracy particularly at minute volume values of less than 7 ℓ/min. Comparison with Nunn's results[61] show that the Wright respirometer has a tendency to give readings with progressively larger errors at minute volume values below 7 ℓ/min., whereas the Spiroflo does not show an increasing error until the minute volume is below 2.5 ℓ/min, as shown in Fig. 4.4a (c.f. Lunn's measurements,[60] using a dry gas meter as a standard, which verifies this statement).

f. the measurements performed by Lunn[60] on the Spiroflo sensor show that it is less sensitive than the Wright instrument to a change in gas density. For example, over the range of minute volumes encountered during anaesthesia the latter anemometer has an indicating error which can be in excess of 15% of the actual value compared with less than 5% for the Spiroflo.

g. a further operational advantage of the Spiroflo sensor is in the ease with which it may be autoclaved. Whereas the Wright respirometer must not be subjected to temperatures exceeding 70°C, the Spiroflo can readily withstand any practical sterilisation procedure.

The improvement in the performance of the Spiroflo sensor when compared with the Wright instrument is undoubtedly due to the elimination of a gear train in the readout mechanism. Furthermore the problem of the respiratory vane anemometer reading low at low minute volume values and reading high at high volumes[61] is reduced as a result of the non contacting vane sensing technique employed.

4.4.2. Comparison with Alternative Electronic Vane Respirometer Instruments

It is interesting to note that since the development and subsequent publication of information[55,56] (see also Appendix 2), relating to the sensor developed during this investigation, the British Oxygen Company (who market the mechanical Wright instrument) have introduced an electronic Wright respiration monitor which uses a light source and phototransistor to generate signal pulses which are proportional to the volumetric gas flow through the transducer head.

Detailed performance measurements have since been published for this instrument in conjunction with an independent evaluation for the Spiroflo sensor[62,*]. As a result of these measurements it has been stated that "in most of the tests performed the Spiroflo showed more accuracy (including a faster speed of response) than the electronic Wright respirometer." The quoted value for the flow resistance of this type of Wright instrument is 2cmH_2O as compared with the Spiroflo value of 1.4 cmH_2O at 100 ℓ/min.

From an operational stand-point the main disadvantage of the electronic Wright sensor is the necessity in a portable instrument for rechargeable batteries owing to the high current consumption of the lamp used in the transducer arrangement. In view of the widespread acceptance of and requirement for portable electronic spirometers[63] for use at the bedside, in clinics and in consulting rooms, it is considered that operation from non-rechargeable cells having a long operational life is a particularly important factor.

In addition to the electronic Wright respirometer two alternative 'electronic turbinemeter' designs have been commercially produced in recent years (U.S.A.). In the first, termed an Expirometer, the rotating blades reflect a light on a phototransistor

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[*] Measurements undertaken by Dr. M.D. Vickers, Head of Clinical Investigation and Research Dept., Dudley Rd. Hospital, Birmingham.

producing pulses that are counted by digital logic yielding a direct volume readout. Secondly in the Spirostat instrument, turbine vanes interrupt a light, and similar digital logic activates a stepping motor, which moves a light across a fibreoptic bundle; this, in turn, moves across a Polaroid film, producing a spirogram that is later analysed with an overlay.

Both of these instruments have been shown to exhibit considerable errors (± 20%) when used for lung function assessment purposes and their general adoption has therefore not been recommended[63]. Furthermore the performance data for these instruments which includes excessive 'run on' (2s) and high flow resistance (5 cmH_2O at 120 l/min.) with considerable non-linearity, eliminates their use for anaesthetic minute and tidal volume measurements.

4.4.3. Performance of Alternative Respirometer Instruments

An evaluation of two thermistor type spirometers has also provided very unsatisfactory results[63]. With these instruments poor accuracy[62] and excessive long term drift has been noted. Under anaesthetic and intensive care monitoring conditions such devices are considered unsuitable unless a measurement technique which eliminates the errors caused by moisture can be devised.

In addition to the mechanical Wright respirometer, both the Dräger volumeter[54] and the Dry gas-meter[54] continue to be used for anaesthetic applications, although neither of these instruments satisfy a number of the requirements listed in 4.1. The Dry gas-meter has a size which restricts its area of application and it is mainly used under laboratory conditions. It is however regarded as having reasonable accuracy and it is often employed as a means for calibration for alternative instruments.

In recent years the most widely used electronic respiratory air flow instrument has been the Pneumotachograph.[45] This device uses a wire gauze as a laminar resistor to create a differential pressure which is measured by a sensitive pressure transducer. Whilst this system is capable of good accuracy it suffers from the disadvantage of being expensive and rather bulky. In addition it is seriously affected by condensation of water vapour on the resistance gauze. This problem is overcome in practice by heating the resistance with an electric element which further reduces the portability in requiring a.c. mains operation. The Pneumotachograph has however found general acceptance as a laboratory instrument although it is rarely used for patient operative monitoring.

4.5 Sensor Calibration

The problem encountered in accurately performing respiratory flow measurements, particulary under anaesthetic conditions, inevitably causes calibration discrepancies. These difficulties arise since each measurement method that has been devised has a specific disadvantage and consequent inaccuracy under certain operational conditions. These inaccuracies generally occur because of the intermittent nature of the flow to be measured. Thus for a particular sensor, although it would be a simple matter to quote calibration information for different steady flow rates, it would be of little value to the user who requires to measure respiratory flows.

In the case of the respiratory vane anemometer type of instrument the requirement for the sensor to distinguish between the expiratory and inspiratory phase causes the sensor to rectify an alternating flow. This means that attempts to calibrate the instrument against actual respirations, using a gas meter and valves, can lead to erroneous results unless considerable care is taken, since most valves allow a certain amount of reflux; this will be subtracted from the gas meter readings but not from the anemometer readings.

It is an inevitable feature of vane anemometers, that the instrument calibration factor varies with the flow rate, due to the pressure difference between the two sides of each blade. This is caused by the blades moving slower than the air stream, i.e., there is 'slip' present. This will cause the instrument to give a low reading. The magnitude of this slip is fairly constant and so the error introduced will decrease with increasing gas flow rate and the calibration factor will tend towards a maximum value. The effect of slip on the Spiroflo sensor can be observed in Fig. 4.4a, where a 10% error in the indicated value occurs at approximately 2 ℓ/min. Under similar conditions the Wright respirometer indicates 10% low at 3 ℓ/min.[61]

When an alternating flow is measured a different calibration factor can theoretically occur at each point along the flow-rate curve corresponding to the particular flow-rate. The average flow-rate and thus the overall calibration factor for a particular alternating flow will vary with the shape of the flow-rate curve (wave form) for a given minute volume. For the same minute volume the maximum flow-rate will be much higher than with a steady flow and so the graph of the minute volume against calibration factor will approach the maximum value more quickly. In general for a vane flowmeter the inertia of the mechanism causes it to 'run-on' when the gas flow ceases. This causes the instrument to give a high reading, the magnitude of the error increasing with the frequency of alternation. Nunn's results[61] for the Wright respirometer show that this'run-on' effect gives rise to a response which has a linear rising slope between 5 and 15 ℓ/min. causing a 5% indicating error over this range at 46 respirations/min, with sinusoidal flow. The extremely low inertia of the Kapton vane in the Spiroflo sensor virtually eliminates this error over the minutevolume range up to 16 ℓ/min., as shown in Fig. 4.4a.

Owing to its non-linear response to flow rate, the calibration of the respiratory vane anemometer type of instrument is affected by the wave form of respiratory flow. For instance, a short sharp breath will theoretically register a higher reading than a long slow breath of the same volume. Another important effect, when measuring minute volumes is the type of respiration. If there are fairly long pauses between breaths, the flow rate, while respiration is occuring, may be much higher than when respiration is practically constant. This effect is important in anaesthesia where in many cases, at low minute volumes, the actual respirations are relatively rapid but at rather long intervals.

The flow rate linearity of the Spiroflo sensor over the range of minute volume values encountered in practice can be expected to provide a reasonably consistent performance under various respiratory wave form conditions. This assumption has been verified by Lunn[60] who had found that Spiroflo sensor indicated with less than a 5%

variation in pulse counts over a minute volume range between 3 and 15 ℓ/min. when a sinusoidal flow is mechanically modified to provide an exponential flow rate/time variation. It is important to consider this latter condition when evaluating respiratory sensors since an exponential form of expiratory flow occurs in practice during intermittent positive pressure ventilation of a patient.

It may be concluded that the variations in calibration rate for the sensor are in general not significant in clinical work, but it is possible that they must be taken into account in accurate physiological or similar studies. The Spiroflo sensor has the advantage that the calibration errors, as previously discussed, tend to occur in a regular and ofter linear manner. It is therefore feasible to consider the application of automatic electronic error compensation circuits to enable a high degree of accuracy to be achieved. Such techniques may include compensation for the variation in temperature between the inhaled and exhaled air volume measured. This error can be further reduced in practice by using valves, so that the sensor is not exposed to the wide fluctuations of air temperature occurring in to-and-fro respiration.

Owing to the calibration difficulties, it is essential to stipulate the conditions under which the instrument calibration has been achieved. For example, the British Oxygen Company supply the electronic Wright instrument calibrated with a Sine Wave Pump giving a 1 to 1 inspiratory/expiratory ratio at a frequency of 20 respirations per min. It has however been suggested by an eminent authority in anaesthetic measurements[*], that a more appropriate

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[*] Personal communication with W.W. Mushin, Professor of Anaesthetics, University Hospital of Wales.

calibration method is achieved by measuring the discharge volume from a model lung charged via a lung ventilator (see Chap. 5).

4.6 Conclusions Relating to Areas of Application for the Spiroflo Sensor

The Spiroflo sensor performance data presented in 4.4 and 4.5 is sufficient to envisage the technique being applied in the following areas of medical application;

1. the monitoring of both tidal and minute volume under both operative and intensive care conditions. In this latter context the sensor technique offers the facility that when several patients have to be supervised simultaneously and/or a number of additional parameters have to be monitored for the same patient, then a simple method for monitoring the respiration electronically exists. It has been stated[47] that such a requirement is virtually essential in modern hospitals where such conditions occur in post operative recovery rooms and intensive care wards. Furthermore the sensor can be incorporated in a small battery driven instrument for use in the operating theatre.
2. for the measurement of flow from lung ventilator machines where it is essential[59] to incorporate some type of ventilation meter, particularly in cases of long-continued ventilation. In this application it is preferable to locate the sensor as close as possible to the patient in the expiratory circuit, so that the volume of gas measured is that which has actually been transferred from the lungs of

the patient. It is therefore essential that the sensor is not seriously affected by the condensation of water within its mechanism.

3. for the measurement of lung function parameters the portable electronic direct readout spirometer can facilitate rapid diagnosis under both bedside and consulting room conditions. It has been suggested[62] that the ease with which such an instrument can be applied to patient respiratory analysis enables a nonspecialist physician to detect asymptomatic pulmonary disease and to measure the degree of pulmonary impairment.

   Mechanical spirometers suffer from the disadvantage of being bulky and they often present sterilization problems. Furthermore considerable time and effort is required for tracing analysis, particularly in the screening of large groups of people.

CHAPTER 5

Electronic Circuit Techniques for the Evaluation of Respiratory Parameters

5.1 Introduction

5.1.1 Respiratory Parameter Definitions

Among the basic pulmonary tests are those designed for determination of lung volumes and capacities. These parameters, which are a function of an individuals physical characteristics and the conditions of his breathing mechanism are defined as:

1. the tidal volume (TV), or normal depth of breathing, is the volume of gas inspired or expired during a normal, quiet, respiration cycle.
2. the inspiratory reserve volume (IRV) is the extra volume of gas that a person can inspire with maximal effort after reaching the normal end inspiratory level. The end inspiratory level being the level that is reached at the end of a normal, quiet inspiration.
3. the expiratory reserve volume (ERV), is that extra volume of gas that can be expired with maximum effort beyond the end expiratory level. The end expiratory level is the level reached at the end of a normal, quiet expiration.
4. the residual volume (RV) is the volume of gas remaining in the lungs at the end of a maximal expiration.
5. the vital capacity (VC) is the maximum volume of gas that can be expelled from the lungs by forceful effort after a maximal inspiration. It is actually the difference between

the level of maximum inspiration and the residual volume, and it is measured without respect to time. The vital capacity is also the sum of the tidal volume, inspiratory reserve volume, and the expiratory reserve volume.

6. the total lung capacity (TLC) is the amount of gas contained in the lungs at the end of a maximal inspiration. It is the sum of the vital capacity and the residual volume.
7. inspiratory capacity (IC) is the maximum amount of gas that can be inspired after reaching the end expiratory level. It is the sum of the tidal volume and the inspiratory reserve volume.
8. the functional residual capacity (FRC) is the volume of gas remaining in the lungs at the end expiratory level.

In addition to the static volumes and capacities listed above, several dynamic measures are used to assess the breathing mechanism. These measures are important because breathing is of course a dynamic process, and the rate at which gases can be exchanged with the blood is a direct function of the rate at which air can be inspired and expired.

A measure of the overall output of the respiratory system is the respiratory minute volume. This is a measure of the amount of air inspired during one minute at rest. It is obtained by multiplying the tidal volume by the number of respiratory cycles per minute. A number of forced breathing tests are used to assess the muscle power associated with breathing and the resistance of the airway. Among them is the forced vital capacity (FVC), which is in effect a vital capacity measurement taken as quickly as possible. A measure of the maximum amount of gas that can be expelled in a given time is called the forced expiratory volume (FEV), and the maximum rate of airflow attained during such an expiration is termed the peak flow rate (PFR).

The relative contributions to a change in the ventilatory capacity of a rise in the airway resistance or a fall in the stroke output of the lungs may be examined by expressing the ventilatory capacity as a function of the stroke output.[54] For this purpose the ventilatory capacity is assessed as the forced expiratory volume, and the stroke output as either the vital capacity or the forced vital capacity. The resulting ratio is termed the FEV% index:

$$\text{FEV\% index} = \frac{\text{FEV}_{1.0}}{\text{FVC}} .100\%$$

The ratio is low when the airway resistance is high, since this causes a disproportionate reduction in the forced expiratory volume.[54] The assessment of patient breathlessness, which may be caused by lung disease or by heart disease of congenital or rheumatic origin, is achieved in practice by the measurement of the maximum breathing capacity (MBC) which is also used in the determination of the dysponeia index.[54] The MBC is determined by calculating the total expiratory volume under maximum breathing conditions over a specified period of time (typically 15s). This parameter is obtained in practice with the subject performing at least twenty respirations over the fifteen second measurement period.

5.1.2 Electronic Circuit Requirements

From the definitions in 5.1.1 it can be seen that the respiratory parameters which are capable of external measurement relate the volume and/or the flow rate to a specific interval of time during the measurement period. Electronic circuit techniques are therefore required which display simultaneously both the volume and velocity of flow as a function of time. Current medical practice[63] requires that the variations of both volume and flow rate with time must be provided as continuous and permanent records. This latter requirement is also essential for the calculation of certain respiratory parameter such as the maximal midexpiratory flow time (MMFT)[64], because the total expiration time must be known before the calculation can be made. Since this time is not known until the expiration has been completed, it is essential to have a continuous and permanent volume/time record to determine the parameter.

When it is necessary to determine the inspiratory/expiratory time ratio, as in the monitoring of lung ventilator machine performance, the Spiroflo sensor can be used in conjunction with an electronic timing circuit. Under certain conditions, such as in the plotting of flow/volume loops (see 5.3.5), it is required to obtain information on both the inspiratory and the expiratory cycle of the patient. This can be achieved by placing two Spirflo sensors of opposite flow polarity in series. It is envisaged that for such measurements the sensors could be engineered as a combined system without adversely affecting performance.

5.2 Design of an Anaesthetic Respiration Monitor

The Spiroflo sensor has been used as the basis for the design of an instrument for measuring both the tidal and minute volume (TV, MV) under operative and intensive care conditions.

The techniques developed have also been extended to provide a method for monitoring the performance of lung ventilator machines. From the viewpoint of an anaesthetist* such an instrument is required to be portable and capable, unlike mechanical instruments such as the Wright respirometer, of providing a continuous scan of both the tidal and the minute volume. With an instrument of this type the anaesthetist can obtain immediately an indication of both of these important parameters. In addition the respiratory 'trend' of the patient, which is indicated by changes in the tidal volume during the progress of surgery, can be readily observed and a chart recording obtained if required.

Following the introduction of MOS logic microcircuits the design of a portable digital readout respiration monitor can be readily achieved using an LED or liquid crystal display. To conserve the battery power the display can be switched on periodically (one second in every four say) and the contents latched to prevent readout flicker. It is possible to incorporate in the design a read and store mechanism for the tidal volume indication so that the preceeding value is always available, whilst the subsequent expiration is being calculated. In conjunction with a 10s timebase (say) a similar facility can be incorporated for the minute volume calculation. In view of the consistent pulse per litre performance of the sensor (as shown in Fig. 4.3) the digital display can be programmed to indicate directly in litres.

* a viewpoint expressed during discussions with D. Allen, Professor of Anaesthesiology, Children's Memorial Hospital, Chicago, U.S.A.

Probably the most important practical feature of this type of instrument design is that in conjunction with the Spiroflo sensor* a rapid evaluation of the minute volume value can be achieved, i.e. within 10s, and also trends in this parameters can be readily observed.

In view of the requirement for a chart recorder readout facility, particular emphasis has also been placed during this investigation on the design of an analogue indicating instrument.

5.2.1 Start and Stop Pulse Circuit

The design of an analogue readout instrument requires a circuit which performs a digital to analogue conversion on the sensor signal. For the measurement of tidal volume this circuit must be initiated by the vane commencing to rotate, and reset when the vane ceases to rotate. The circuit developed to fulfil this requirement is shown in Fig. 5.1a. This arrangement uses an N type field effect switching transistor Tr_3 which is biased into the conducting state i.e. with zero gate voltage when the vane is not rotating. When the vane commences rotation the rectangular waveform from the pulse shaper circuit causes Tr_1 and in turn Tr_2 to conduct, thereby applying a negative gate voltage to Tr_3 which causes it to switch to the non-conducting condition. The circuit time constant C_1R_1 is chosen so that the switching action takes place just before the vane ceases rotation, i.e. at flow rates less than 0.5 l/min. This ensures that

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* this view has been expressed by Dr. B.M. Wright at the Clincial Research Centre, Northwick Park Hospital, Middlesex, during discussions relating to the application of the Spriroflo sensor.

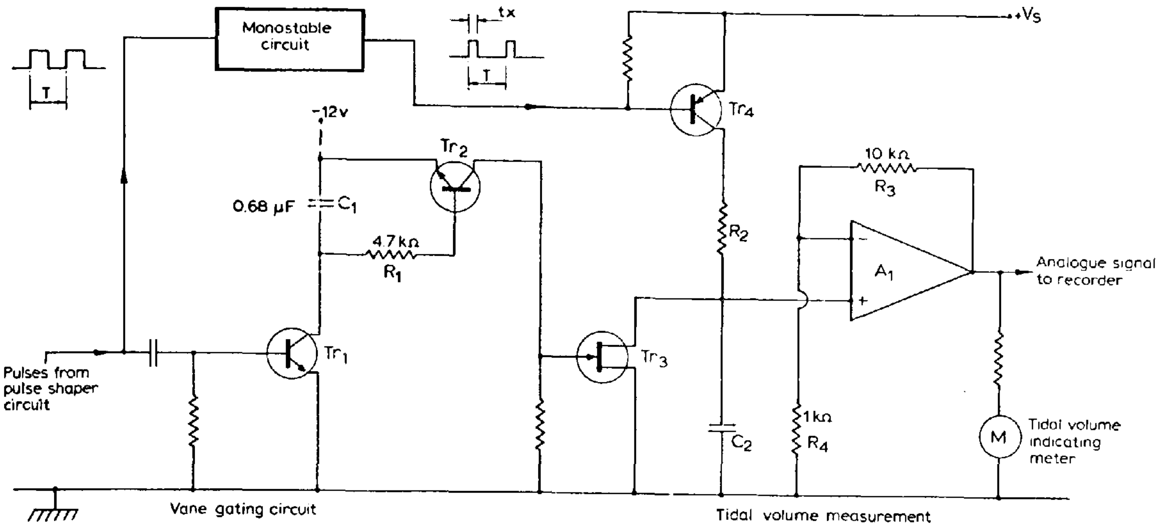


Fig. 5.1a Circuit for tidal volume analogue display

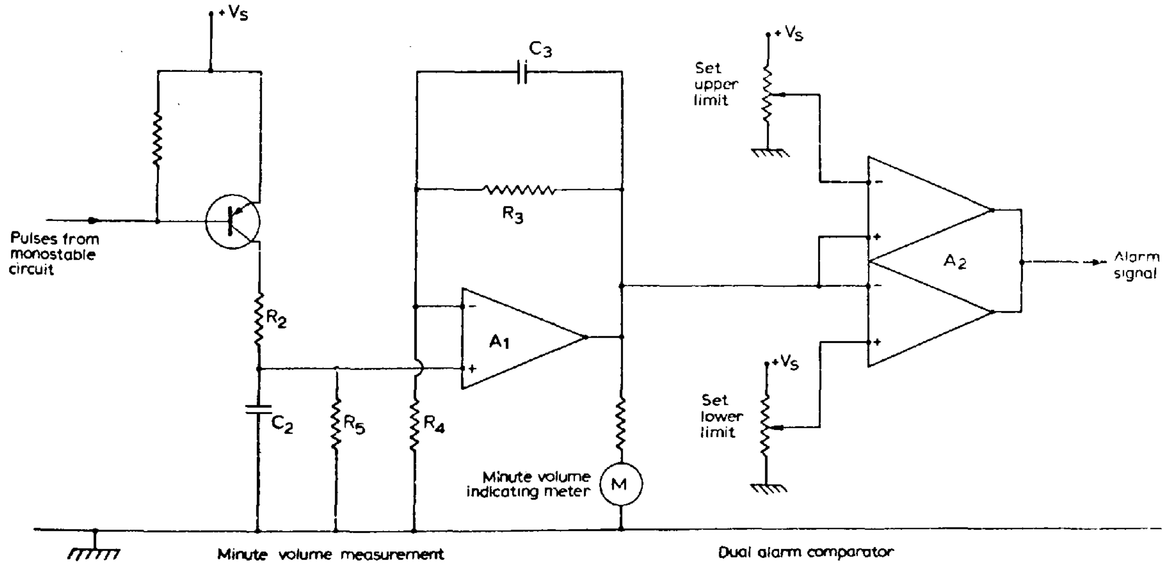


Fig. 5.1b Circuit for minute volume analogue display with alarm facilities

the tidal volume measurement circuit will not respond to possible vane 'run on' which may be caused by a leaky valve or a similar system fault. This is an important measurment consideration particularly under high respiratory cycling rates, i.e. greater than 40 respirations per min., since the maximum possible circuit reset time between successive tidal volume readings is less than 0.5s if an inspiratory/expiratory ratio of 1 : 2 is assumed.

5.2.2 Analogue Readout Circuit for Tidal and Minute Volume

To achieve an analogue readout for tidal volume it is necessary to perform a digital to analogue conversion, with hold and reset facilities, on the sensor signal. The technique developed to fulfil this requirement is shown in Fig. 5.1a. The leading edge of the rectangular waveform from the pulse shaper circuit is used to trigger a monostable circuit, having a pulse width t_x smaller than the lowest period that can occur in practice for the sensor signal, i.e. t_x<0.2ms. The circuit of Fig. 5.1a has been designed to enable each tidal volume reading to be displayed and then reset before the following expiration, i.e. the analogue output signal rises to the tidal volume and then is cancelled to await the following value. An alternative form of this circuit can incorporate a store and hold facility which indicates the previous tidal volume value and which is only updated when a new value has been obtained. With this arrangement a measurement value is continuously available for assessment.

Integration of the monostable output waveform is achieved by using a single grounded capacitor arrangement C_2 as shown in Fig. 5.1a. Such an arrangement is preferable to the conventional integrator (in which amplifier feedback is applied from the output to the inverting input through a capacitor) since the reset condition is readily achieved by using the switching action of Tr_3 across C_2.

The monostable pulses are used to switch Tr_4 into the conducting state, and for each period t_x the capacitor C_2 is charged through R_2 from the stabilised supply V_s. To achieve better than 1% linearity of rise of voltage across C_2 the maximum tidal volume reading is restricted to a voltage of $0.02V_s$, i.e. 100mV. The operational amplifier A_1 in Fig. 5.1a enables this voltage to be increased to approximately 1v to enable a meter or recorder readout to be obtained. It is necessary for A_1 to have a low input bias current so as to reduce the loading effect on C_2. In addition it should possess a low offset drift under these circuit conditions. The circuit performance has proved accurate and stable over long periods of time even when a high value (1000 μf) tantalum capacitor is used for integration. Such a high capacitance value has the advantage that the amplifier A_1 can have an input bias current of at least 25nA without affecting circuit performance. The long integrating time involved in this parameter calculation (up to 3s typical) precludes the use of a polycarbonate type of integrating capacitor unless an expensive amplifier having the lowest possible bias current is used (i.e. 0.4pA as in electrometer FET input type amplifiers).

Calibration of the tidal volume circuit is achieved by adjusting R_2 to provide the necessary full scale value (2 l typical). The circuit reset time is governed by the time constant $C_2 r_{ds}$ (on), where r_{ds}(on) is the small signal drain-source resistance with zero gate-source voltage for Tr_3. A typical value for r_{ds} (on) is 25Ω, thereby providing a reset time constant of 25ms for a C_2 value of 1000 μf. This time constant is adequate in practice for high respiration rates even with low inspiratory/expiratory ratios. The performance of the circuit of Fig. 5.1a has been evaluated by using a constant frequency sinusoidal waveform as an alternative to the sensor signal. An X -Y recorder (Hewlett Packard 2100A) has been used to determine the linearity of the rise of output voltage (up to 1v) over a wide range of input frequencies, i.e. between 50Hz and 3kHz, and results indicate a linearity of better than 1%. The minute volume calculation requires time integration for a readout in litres per minute. This can be achieved by generating a 10s (or similar) timing period, with hold and reset facilities. It has been suggested (c.f. 5.2) that this is a sufficiently adequate sampling time and one which will provide a rapid determination of the minute volume value from the instant of switch on. That is, the minute volume reading will not normally differ significantly during each 10s interval over a period of one minute.

An an alternative to the generation of a specific timing signal a waveform averaging arrangement has been considered, and comparative measurements have indicated that good accuracy can be obtained from the circuit shown in Fig. 5.1b. This form of integrator[65], which behaves as an RC filter having a time constant R_3C_3 is ideally suited for use in a portable and inexpensive anaesthetic monitor. This circuit has the disadvantage that unless an excessively large time constant is used, the output signal will fluctuate from the mean value by an amount dependent upon the respiratory frequency and the inspiratory/expiratory ratio. Experience has shown however that under normal operating conditions, about 20 respirations/min, with a time constant R_3C_3 of 7s the cyclic variation about the mean is less than 5% of the indicated value. This time constant value does however require a 30s waiting period from switch on before an accurate assessment of the minute volume can be achieved. To further reduce the cyclic variation of the mean value the vane gating circuit is replaced by R_5 which provides a 1s discharge time constant for C_2 during the inspiratory phase.

As shown in Fig. 5.1b the minute volume signal is used to feed a dual comparator circuit which can be preset to trigger an alarm circuit which is initiated under conditions of over and under ventilation. Such a facility is of particular value when monitoring patients who are in intensive care units under mechanially assisted respiratory conditions. The failure or misadjustment of a lung ventilator machine is rapidly indicated by this arrangement.

5.2.3 Evaluation of Instrument Performance

The circuits discussed in 5.2.1 and 5.2.2 have been combined in the development of a portable instrument which is shown in Fig. 5.2. For operation from dry cells the total current consumption can be reduced to less than 10mA by using a micropower operational amplifier and MOS logic circuits. The instrument performance has been evaluated* by the method discussed in 4.5, using the test and calibration arrangement shown in Fig. 5.3. The variable respiratory resistor and reservoir volume can be regarded as a model lung[59] in which the compliance consists of two five gallon oil drums connected in parallel.

* these measurements were performed by the author at the research laboratories of Air Products Ltd., Allentown, Pensylvania, U.S.A.

Fig. 5.2 Anaesthetic Respiration Monitor
for measurement of tidal and minute volume.

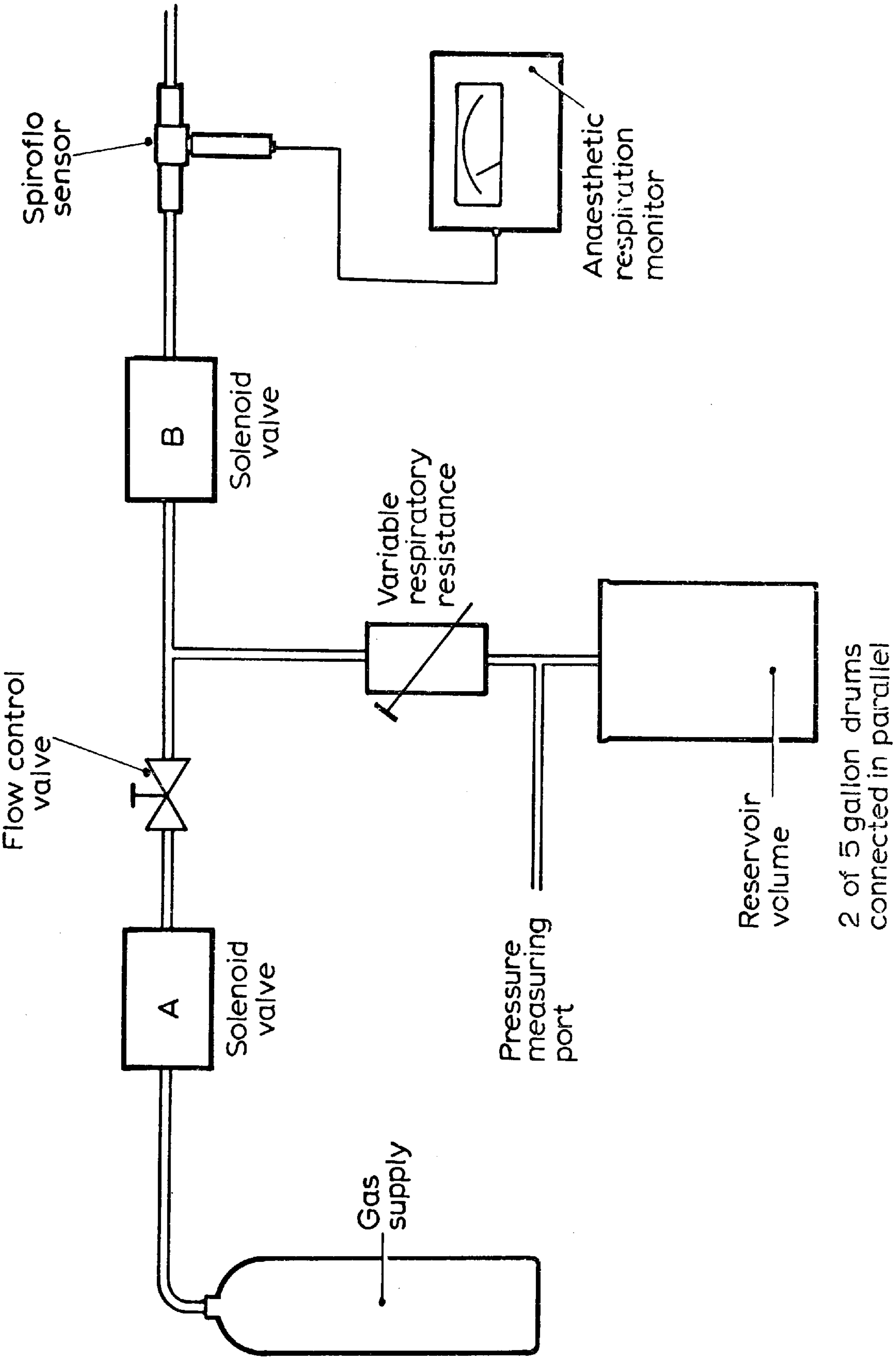


Fig. 5.3 Test and calibration arrangement for anaesthetic respiration monitor

By clamping the inlet to one of the drums the compliance can therefore be halved. The solenoid values A and B are arranged to oppose each other and the compliance is calculated by charging the model lung to a nominal volume V of one litre. Measurement of the pressure P under zero flow conditions therefore enables the system compliance C to be determined since:

$$C = \frac{V}{P}\ \ell/\text{cmH}_2\text{O}$$

The flow resistance R is obtained by measuring the flow rate Q (typically 1 l/s) through the variable resistance, together with the pressure P relative to the atmospheric value:

$$R = \frac{P}{Q}\ \frac{\text{cmH}_2\text{O}}{\ell/\text{s}}$$

Calibration of the instrument is achieved by discharging the charged reservoir volume through the Spiroflo sensor for a particular system time constant value:

$$CR = \frac{V}{P} \cdot \frac{P}{Q} = \frac{V}{Q}\text{s}$$

The variations of both the indicated tidal and minute volume with the lung time constant are shown in Fig. 5.4a and 5.4b respectively. The time constant range over which these measurements were undertaken (0.05 to 1.2s) embraces the values encountered under virtually all patient ventilation conditions, viz from 0.8s for a neonate to 0.1s for an adult. The results show a variation of 8% in the indicated value for both the tidal and minute volume readings over the range of time constant values measured. This error occurs as a result of the variation in the waveform of the flow from the model lung (c.f.4.5), which is characterised in this arrangement by the variation in the

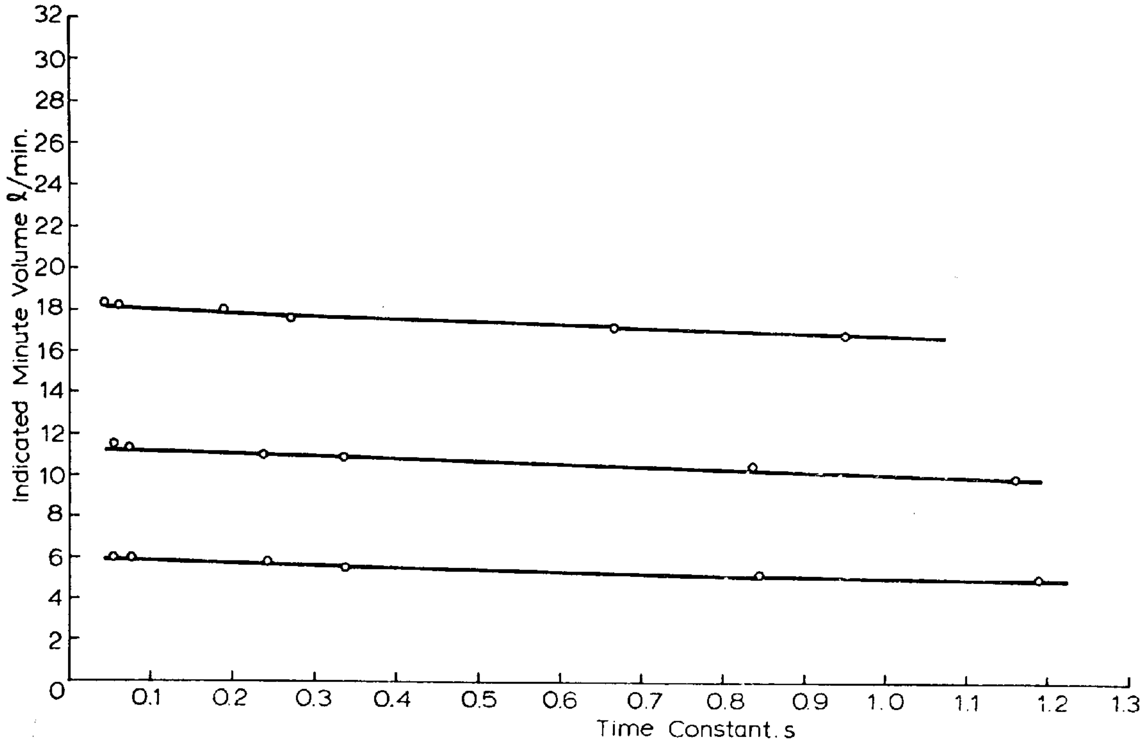


Fig. 5. 4a Variation in minute volume with time constant
(at a constant cycling rate of 20 respirations / min.)

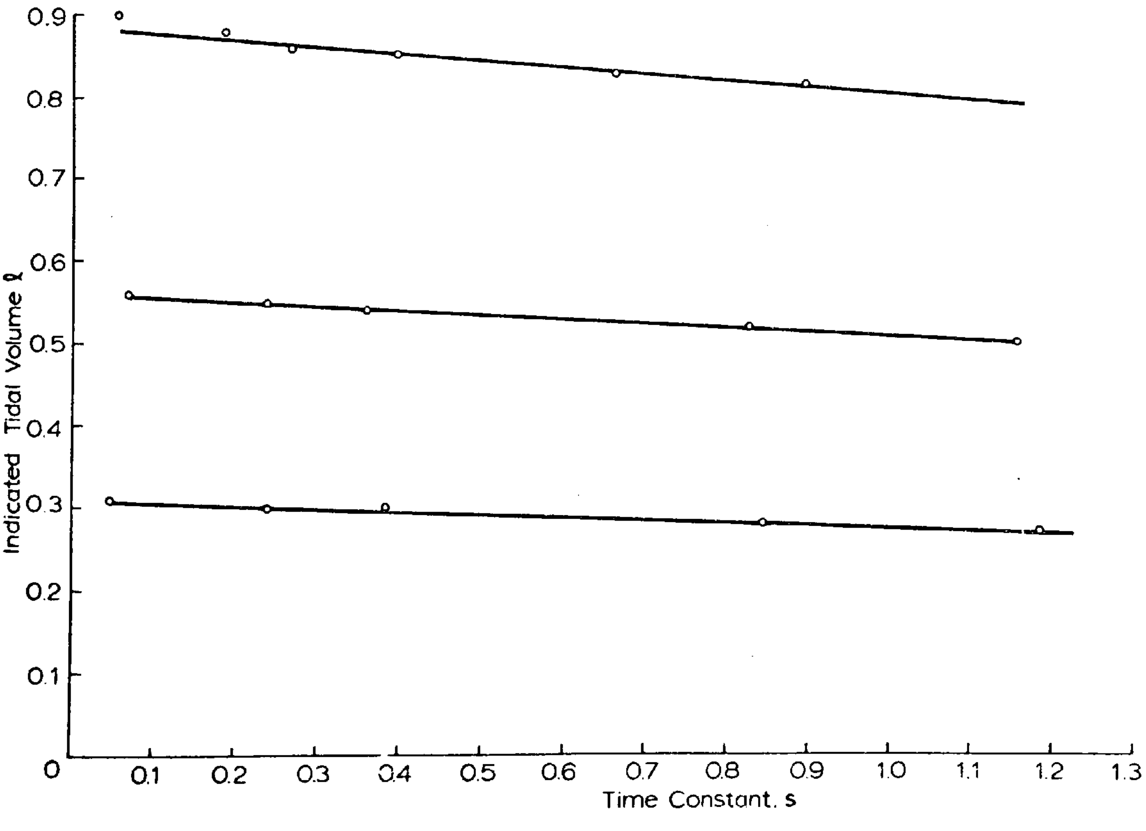


Fig. 5. 4b Variation in tidal volume with time constant
(at a constant cycling rate of 20 respirations / min.)

time constant value.

The change in the minute volume with the breathing rate has also been investigated using this apparatus, and the results show that an error of less than 2% in the indicated value over the range 9 - 48 respirations/min. occurs.

The instrument performance has also been independently evaluated by Lunn[60] (c.f. 4.5) and by the Mechanical Development Department of Vickers Medical Ltd.[66] (Measurements undertaken at the Westminster Hospital, London). In the latter case air was supplied by a Blease "Manley" ventilator to a test lung having a compliance of approximately 0.5 ℓ/cmH_2O. Expired air from the test lung was passed through the Spiroflo sensing head to an Ohio 840 Spirometer which was used as a calibration standard. The quoted results shown that minute and tidal volume values obtained were "very accurate" and that "the measurement discrepancies were probably within the experimental error of the standard used".

Long term clinical use of this instrument has been undertaken by Keating (c.f. 4.3.2). Experience has shown that the continuous monitoring of tidal volume is of particular value during neurological surgery, since under such conditions a deterioration in the condition of the patient is rapidly indicated by a change in this parameter.

5.3 Measurements of Lung Function Parameters

The Spiroflo sensor has been used for the measurement of lung function parameters in conjunction with the circuit arrangement shown in Fig. 5.5.

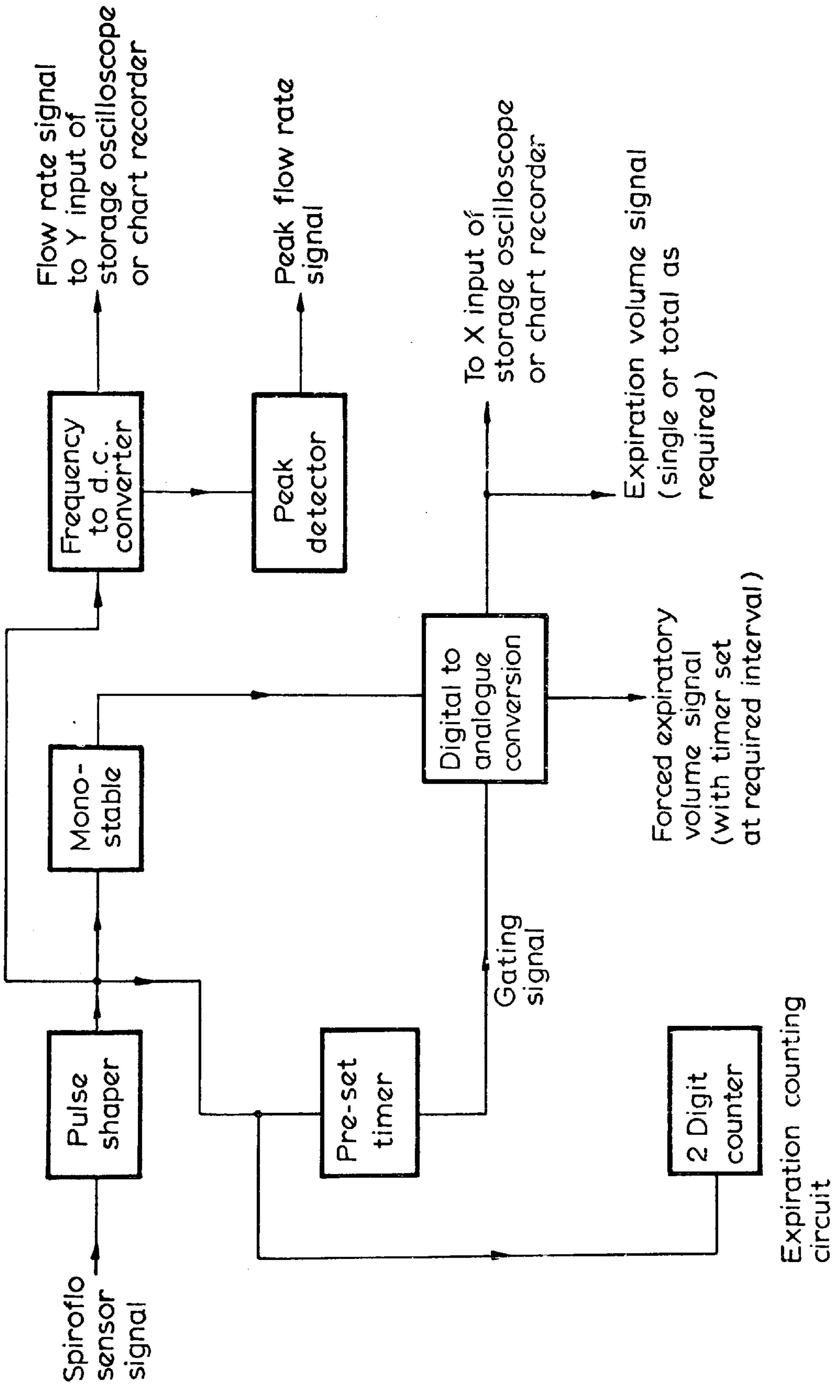


Fig. 5.5 Circuit arrangement for measuring lung function parameters

5.3.1 Measurement of Peak Flow Rate (PFR)

The expiratory PFR is the maximum flow which can be sustained for a period of 10ms during expiration from a position of full inspiration. Calculation of this parameter is achieved by using a peak detector circuit[65] to detect the maximum flow rate signal obtained from the frequency to dc converter microcircuit during the expiratory period. The shape of the flow rate/time curve (for a normal male) obtained on a storage oscilloscope, is shown in Fig. 5.6a and 5.6b, where each time division respresents 0.2s and 0.1s respectively and each vertical division represents 120 ℓ/min. The maximum flow rate indicated by these measurements is approximately 600 ℓ/min.

It is of considerable value in practice to display the flow rate time curve, since it is possible for an abnormal subject to generate reasonable peak values which are sustained only for a very short period of time i.e. a 'peaky' curve occurs. It is regarded as unsatisfactory[67] to rely merely on analogue or digital readout of the peak value, since the volume of air represented by quite a large change in peak level is very small (particularly for 'peaky' curves), so that it is unlikely to have physiological significance. As can be seen in Fig. 5.6b the rate of rise of the flow rate time curve is such that it is preferable to use a storage oscilloscope rather than a chart recorder since the latter would require a paper speed of at least 10cm/s.

The provision of a high speed readout arrangement also enables the forced mid-expiratory flow FMF, which is the average flow rate over the middle half of the forced vital capacity, to be obtained. This parameter is, however, not normally measured when investigating

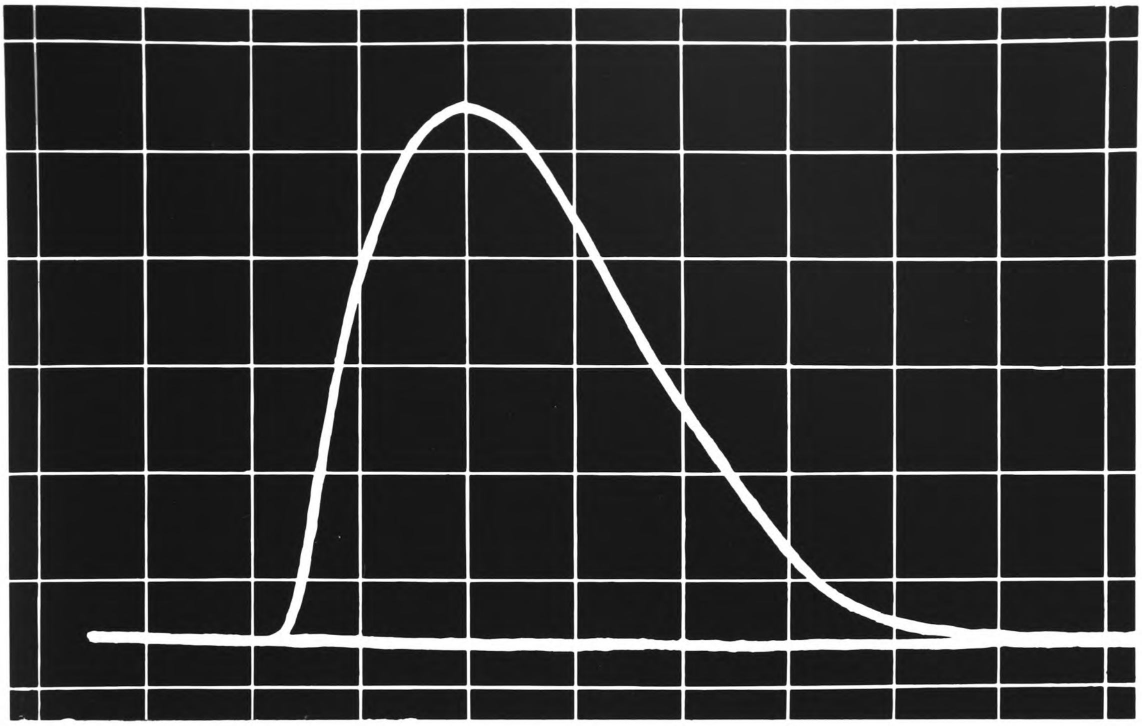


Fig. 5. 6a 0. 2s / div.

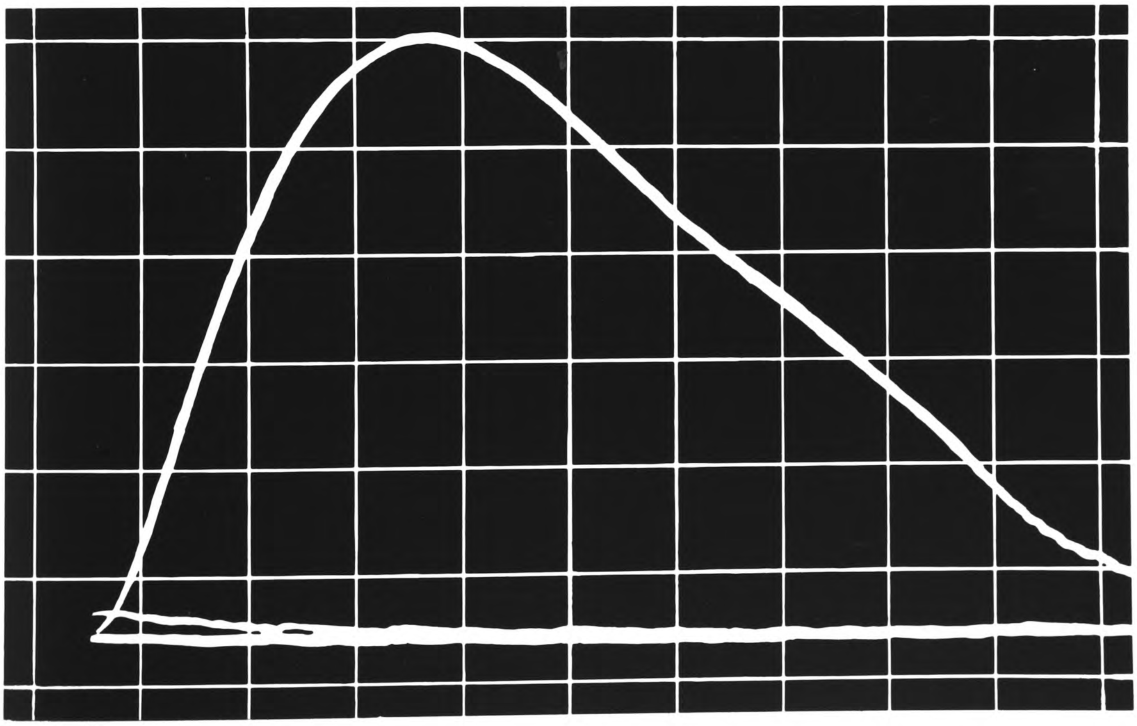


Fig. 5. 6b 0.1s / div.

Fig. 5. 6a/b Forced expiratory flow rate-time curves.

lung disorders, since it is highly correlated with other indices, such as the forced expiratory volume, which are more readily calculated.

5.3.2 Measurement of Forced Expiratory Volume and Vital Capacity

The forced expiratory volume is the measured volume of gas expelled over a given period of time, e.g. forced expiratory volume 1 second or $FEV_{1.0}$. As shown in Fig. 5.5, this parameter is obtained by using an electronic timer circuit which is initiated by the commencement of rotation of the vane. At the duration of the preset time period the volume signal is fed into a store and hold circuit which is driven from the digital to analogue convertor.

To measure the forced vital capacity the signal representing the total volume of expiration is fed into a store and hold circuit.

The measurement of both the forced vital capacity and the forced expiratory volume for a normal male is shown in Fig. 5.7a. The results have been obtained by using a storage oscilloscope, where each time division represents 0.2s, and each vertical division represents one litre ($FVC = 4.5\ \ell$ and $FEV_{1.0} = 4\ \ell$).

The FEV% index can readily be calculated from the results obtained from Fig. 5.7a since:

$$FEV\% = \frac{FEV_{1.0}}{FVC} \cdot 100\%$$

$$= \frac{4.0}{4.5} \cdot 100\% = 89\%$$

This ratio, which may be calculated by using an analogue divider circuit arrangement,[65] has a typical value in the range 51% to 99% for a normal male, depending on age. If the output signal from the

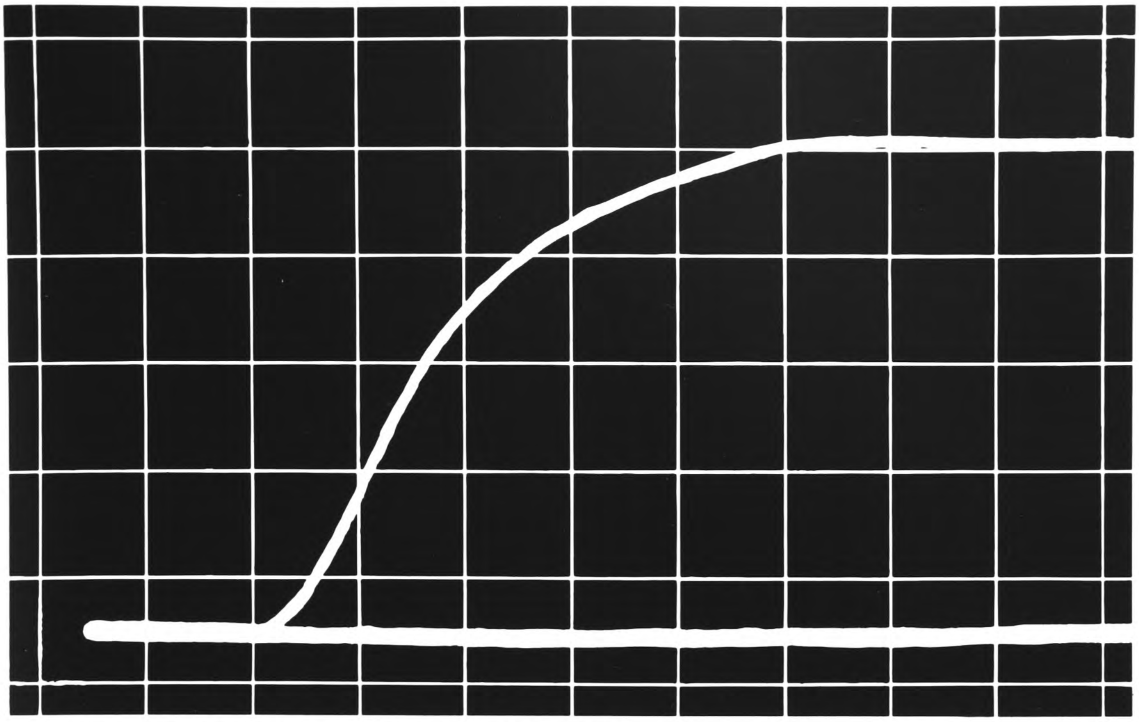


Fig. 5.7a FVC and FEV measurement curve. 0.2s/div.

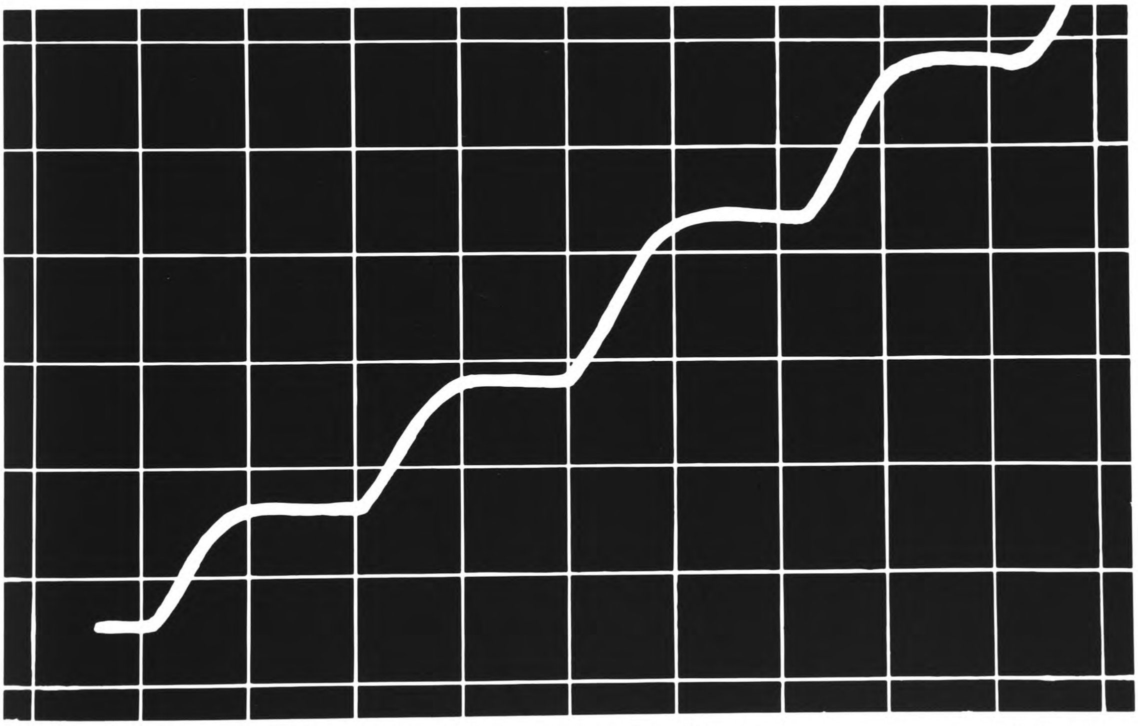


Fig. 5.7b Calculation of the total expiratory volume over a given time period. 1s/div.

digital to analogue conversion circuit is not reset at the end of each expiration period, and held in a peak detector circuit, then the total expiratory volume for a given time period can be calculated as shown in Fig. 5.7b where each vertical division represents four litres.

The circuit shown in Fig. 5.5 also enables the maximum breathing capacity of a subject to be obtained. This measurement, which is commonly made during voluntary hyperventilation for a period of 15s, is termed the maximum voluntary ventilation (MVV). Since the MVV is a function of the breathing rate it is necessary to calculate the total number of expirations over the measurement period. This is achieved with a digital or electromagnetic readout arrangement in the circuit shown in Fig. 5.5.

5.3.3 The Maximal Expiratory Flow-Volume Curve

A major advance in understanding forced expirations came with the work of Hyatt, Schilder and Fry[68] who described the maximal expiratory flow volume curve (MEFV). This curve is obtained during a forced vital capacity expiration when instantaneous expiratory airflow is plotted against lung volume instead of time (as for FEV determination). This measurement indicates that flow increases rapidly at the commencement of the expiration reaching a maximum at approximately 80% of the vital capacity. The flow then decreases to zero at the residual lung volume. The curve can be shown to consists of an effort-dependent portion above about 75% of vital capacity, and an effort-independent portion below 75% of vital capacity.[69]

To obtain the maximal expiratory flow volume curve it is necessary to use a storage oscilloscope or X-Y chart recorder with the expiratory volume and flow rate signals feed to the X and Y axis respectively, as shown in Fig. 5.5. The results obtained on an oscilloscope for a normal male subject are shown in Fig. 5.8. These measurements were obtained by requesting the subject to perform a series of vital capacity expirations of graded effort, varying from a very slow breath out, to one of maximal speed and effort (vertical axis 0 - 600 ℓ/min., horizontal axis 100% - 0% of vital capacity).

The intersection of the curves of Fig. 5.8 with a vertical line can be used to determine the flow rate obtained as the subject passes through a specific lung volume, for example 50% of vital capacity. These flow rate volumes can then be plotted against the simultaneous values for transpulmonary pressure so as to obtain the isovolume pressure / flow curve.[68] Such information is of considerable value in the design of mechanical lung analogues which are used in the study of lung mechanics, particularly under forced expiratory conditions. It is of particular interest to note that for numerous measurements under maximal forced expiratory conditions, the MEFV curve has been found to be very repeatable for a given individual. Such an observation is in accordance with medical knowledge, which predicts a characteristic shape which occupies typically 80% of the total flow rate / volume area.

The inspiratory flow/volume curve is readily obtained by reversal of the Spiroflo sensor in relation to the subject. By using two such sensors in series, it is therefore possible to obtain the complete flow/volume loop for the subject. This is an important feature of the sensor, since current medical practice requires the plotting of such loops[70] as pulmonary diseases produce characteristic flow/volume loop abnormalities. The visualization of abnormalities and the

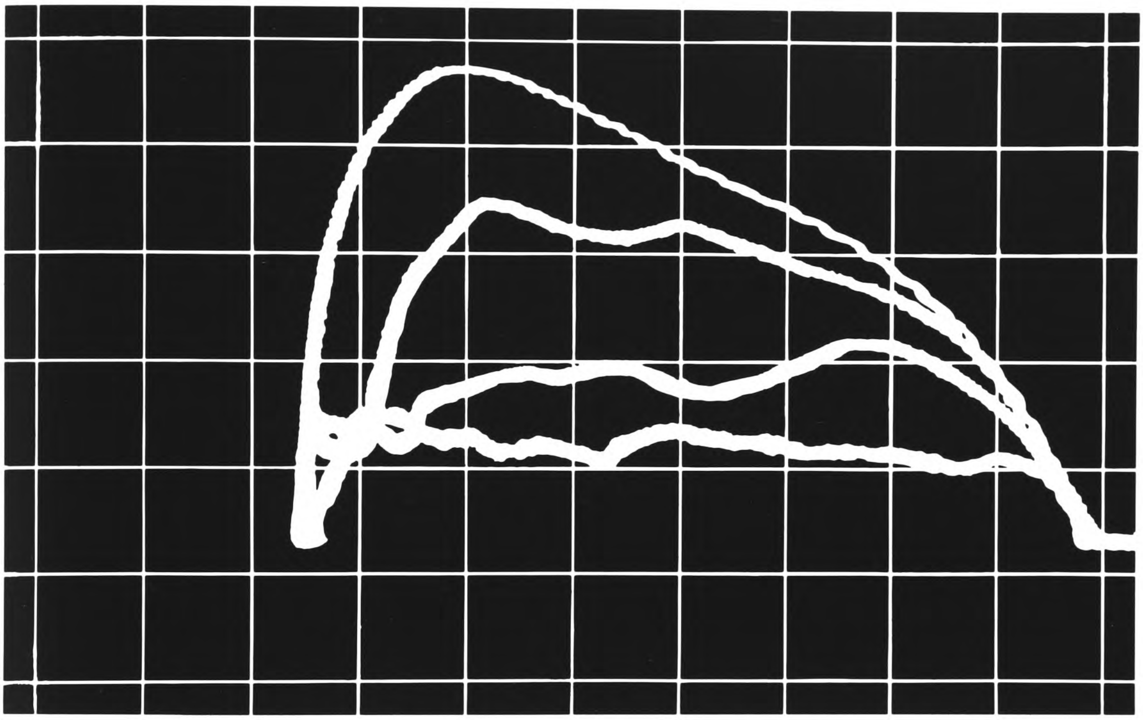


Fig. 5.8 Instantaneous expiratory airflow plotted against lung volume (using the same subject to perform various graded efforts.)

calculation of instantaneous flow rates at specific lung volumes therefore make this test invaluable for screening in pulmonary disease, for assessing the pulmonary effect of drugs, and for observing the progression or regression of pulmonary disorders.

5.4 Performance of Alternative Lung Function Measuring Instruments

At the present time the majority of respiratory function measurements are achieved using instruments which are entirely mechanical in operation. The measurement of forced lung function parameters requires an instrument which is capable of a high speed of response. For this reason wet spirometers are not normally used in this application[54] and dry spirometers, such as the vitalograph[71] have been developed to measure VC and $FEV_{1.0}$. In this instrument the movement of a wedged-shaped bellows is recorded on a chart which runs, at the commencement of expiration for 6s. The vitalograph has the advantage of being lightweight, portable and robust, and is often used for medical survey work. The main disadvantage of this technique is that flow-rate dependent parameters cannot be measured (without being computed from the slope of the resulting trace) and so the peak flow rate and the maximal flow volume curve has to be obtained using an additional instrument, from a separate measurement exercise (parallel connection of measuring devices must be avoided to maintain minimum resistance to flow).

The peak flow rate can be measured by a pneumotachograph (c.f. 4.4.3), although a more portable and useful clinical instrument is the Wright peak flowmeter.[54] This is a variable area orifice form of meter and is capable of measuring flows up to 1000 ℓ/min, with the imposition of only a small resistance to gas flow. The main disadvantage of this instrument is its inability to record the flow rate/time curve.

In many respiratory laboratories the pneumotachograph, although bulky and expensive, is used to provide the peak flow rate from a forced expiration exercise by the patient. To obtain the vital capacity electronic integration is used and the maximal expiratory flow volume curve can then be displayed on a storage oscilloscope.

Although a number of electronic spirometer designs (both thermistor and turbine meter types) have been commercially introduced in recent years c.f. 4.4.2, their use in lung function assessment has not been recommended[63] since considerable errors have been shown to occur, particularly when they are used to measure the forced expiratory volume and the peak flow rate.

5.5 Conclusions Relating to the use of the Spiroflo Sensor for Lung Function Measurements

Respiratory performance measurements with the Spiroflo sensor have shown that:

1. it is capable of accurately measuring parameters such as the forced vital capacity, the forced expiratory volume, the peak flow rate, and the maximal expiratory flow volume curve over a wide range of values, i.e. from the patient with chronic lung disease to the athlete in training.
2. the Spiroflo sensor has been shown to have a performance which may be compared with that obtained by using a pneumotachograph. It has the additional advantage of being

small and portable so that it can be readily transferred from the laboratory to the bedside of the patient and into an industrial environment for survey measurements to be undertaken,

3. the physical construction of the sensor enables it to be of value in measuring lung function parameters under difficult conditions, i.e. mountain climbing or athletic training. Problems associated with the availability of a suitable sensor have previously restricted such measurements to the exercise laboratory. The digital signal provided by the sensor is ideally suited to such applications and can be used to modulate a telemetry transmitter. At the receiving site the signal can be recorded on a cassette type of recorder[72] for future analysis.
4. for use on peak flow rate measurements it is envisaged that the sensor resistance could be reduced in value by constructing the vane in a larger volume air chamber (similar to the Wright Peak Flowmeter).

5.6 Use of an On-Line Digital Computer Facility for Lung Function Assessment

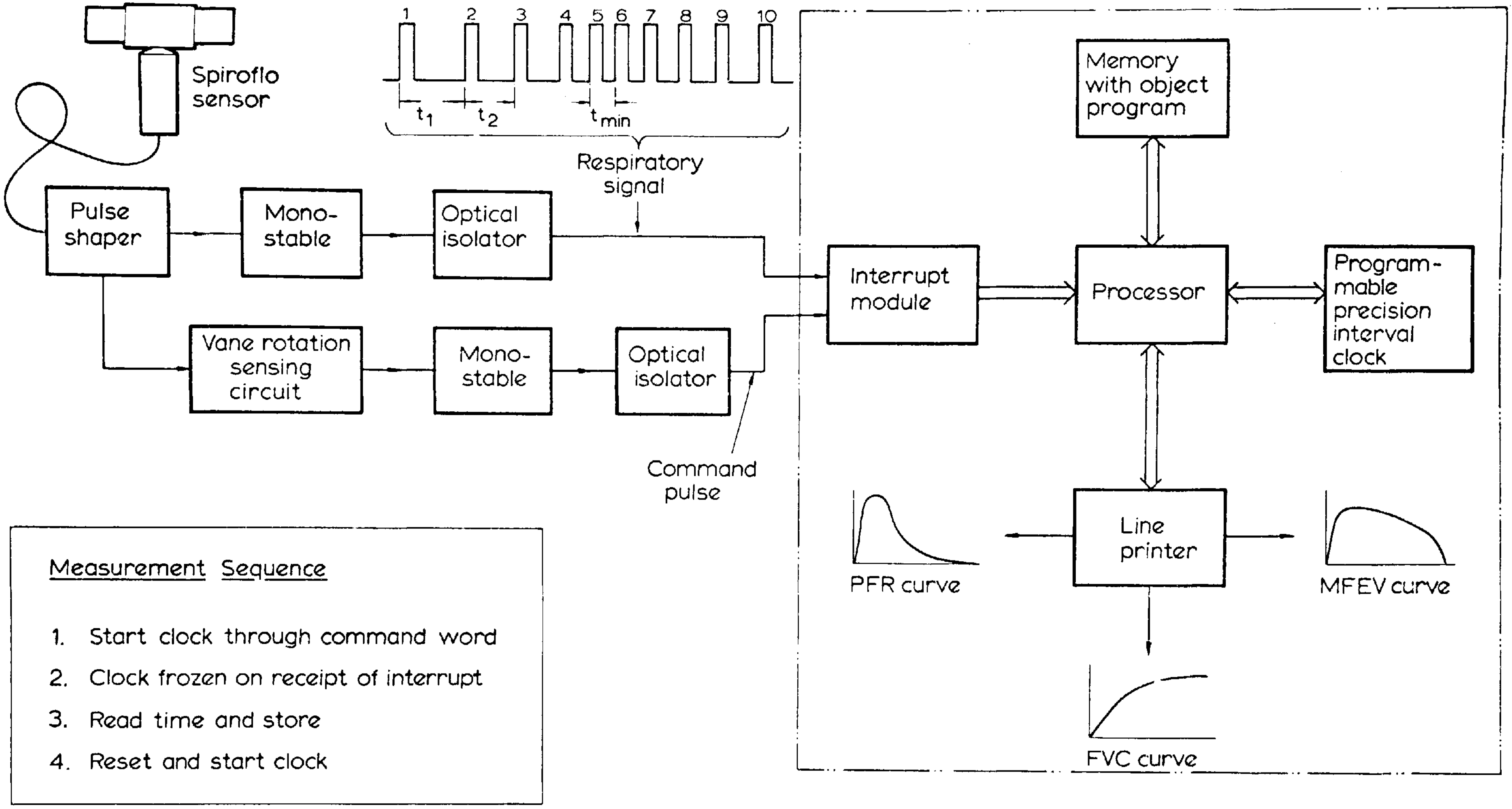
It is considered that an on-line computing facility for the analysis of lung function data will prove of considerable value, particularly as a diagnostic aid.

Digital computer techniques have previously been applied to process information which has been collected off-line to enable statistical pulmonary data to be compiled. For example Knight, Hughes and Field[73] have produced a detailed computerized statistical analysis of records produced by the Vitalograph Spirometer. Such investigations are of value since:

1. spirometer records can exhibit considerable variation from subject to subject from day to day and even among several records made serially by the same subject on the same occasion. For this reason the patient is usually allowed two attempts at a forced expiration before counting valid attempts, with a resting period between each attempt. It is therefore necessary to investiage statistically the repeatability and reproducibility of such measurements.
2. in an attempt to limit the number of measurements of respiratory data many investigations have been undertaken to obtain correlation between the various parameters[64,74,75,70]. Computing facilities can assist in the rapid analysis of such data and provide empirical equations which interrelate the parameters.

To investigate this technique the digital signal produced by the Spiroflo sensor has been interfaced with an Interdata 80 Digital Computer to provide an on-line respiratory analysis system. The method developed, which is shown in Fig. 5.9, uses the sensor signal to provide an interrupt signal which is serviced by a software programme. By using a programmable precision interval clock, having a 1ms resolution, the time interval between each successive input pulse (t_1, t_2, t_3 ------t_{min} etc) can be measured and stored. The clock arrangement in this instance is a hardware facility of the computer.

For a typical forced expiration, from a healthy male subject, the



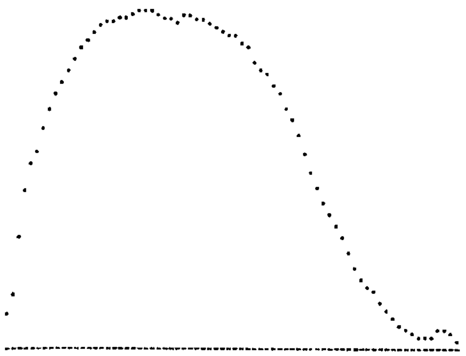
Measurement Sequence

1. Start clock through command word
2. Clock frozen on receipt of interrupt
3. Read time and store
4. Reset and start clock

Fig. 5.9 On-line digital computation of respiratory data spiroflo sensor produces approximately 1500 pulses with a PFR corresponding to a t_{min} of 0.5 ms, i.e. a frequency of 2kHz. The computer is therefore required to store 1500 time intervals and to calculate the variation of the volume and flow rate during the expiratory time period. The software programme has been written to enable the average value of both the volume and flow rate for each 20 ms period of the expiration to be computed. Graphical representation of the data is then provided by the line printer which is fed with the average value signals. The results obtained for a healthy male subject are shown in Fig. 5.10 for a maximum inspiratory test, and Fig. 5.11 for a forced expiratory test. For each test the flow rate/time, volume/time and flow rate/volume graphs are produced. In addition the calculated values for the PFR and $FEV_{1.0}$ are printed, together with any further parameters that are requested when the appropriate code number is entered on the teletype keyboard.

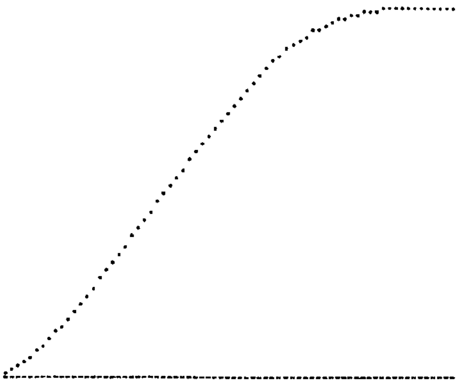
Comparison with the results previously obtained in Fig. 5.6, 5.7, and 5.8 illustrates the improved resolution provided by this digital storage and analysis technique. Since rapid changes in flow rate are not integrated out by digital to analogue conversion, the graphical information processed by the computer will reflect such changes. The Sprioflo sensor signal is therefore ideally suited to this form of processing since the measured time constant (Fig. 4.2) has a typical value of less than 20 ms.

To illustrate the performance of the method during discontinuous flow rate conditions, forced expiratory measurements have been undertaken with an externally produced throat obstruction. The result shown in Fig. 5.12 have been obtained by varying the degree of obstruction

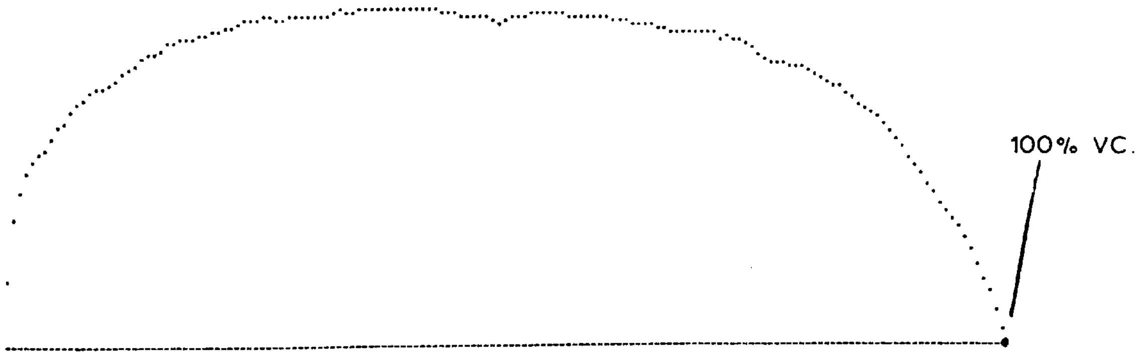


```
TEST NUMBER 0013
MAX FLOW RATF 2083 PULSES PER SECOND
TOTAL VOLUME  1585 PULSES
FEV 0.75  0074
FEV 1.0 0093
```

a. FLOW RATE – TIME. Sampling point at each 20ms interval during inspiration.

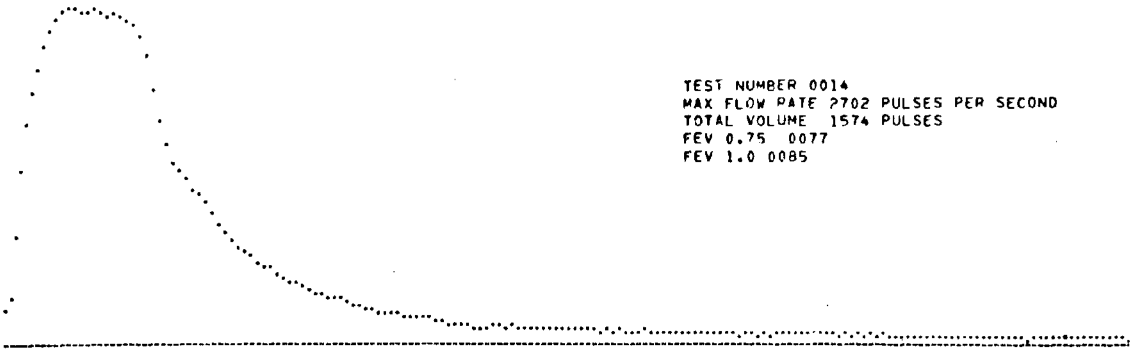


b. VOLUME – TIME. Sampling point at each 20ms interval during inspiration.



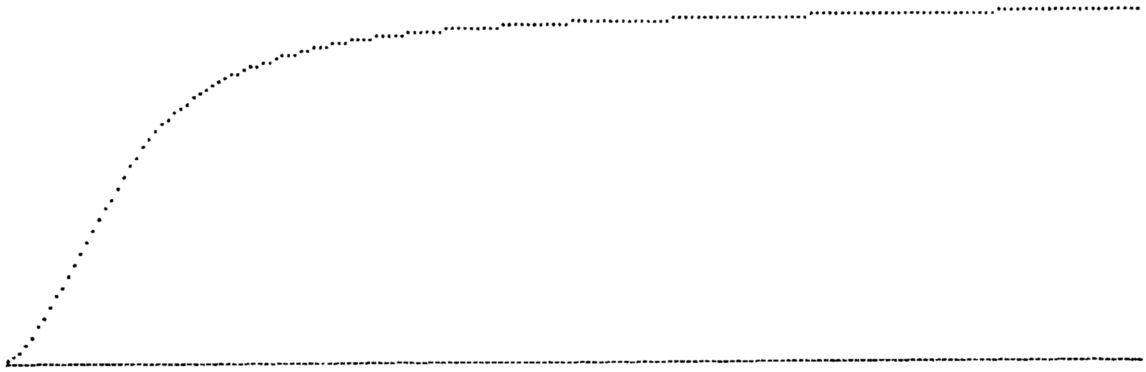
c. FLOW RATE – VOLUME.

Fig. 5. 10 Digital computer analysis for a maximum inspiratory test.

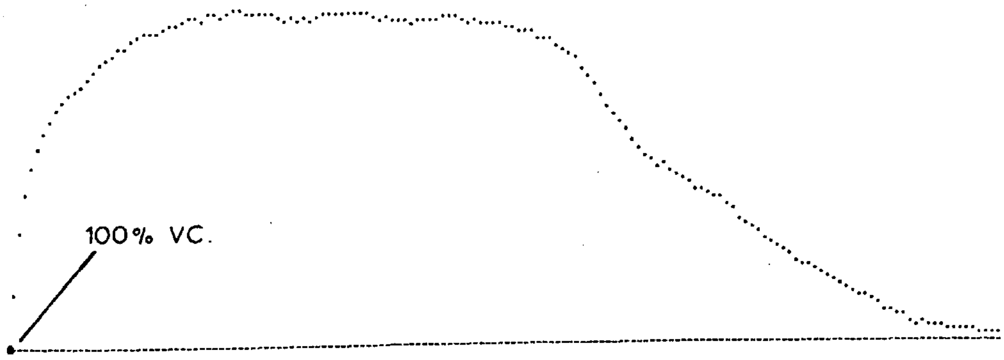


```
TEST NUMBER 0014
MAX FLOW RATE 2702 PULSES PER SECOND
TOTAL VOLUME  1574 PULSES
FEV 0.75  0077
FEV 1.0 0085
```

a. FLOW RATE – TIME. Sampling point at each 20ms interval during expiration.

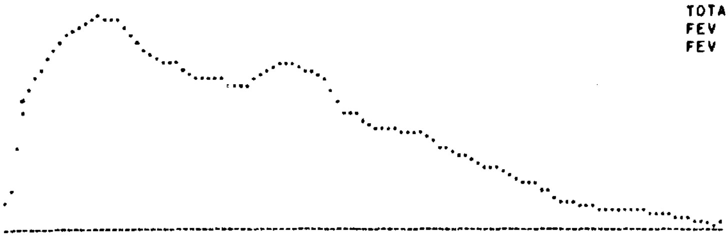


b. VOLUME – TIME. Sampling point at each 20ms interval during expiration.



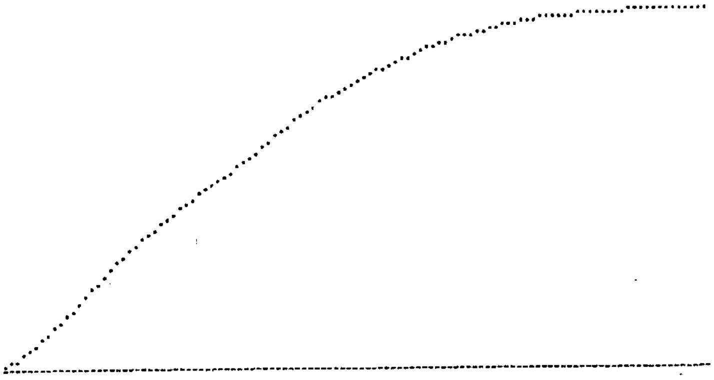
c. FLOW RATE – VOLUME.

Fig. 5.11 Digital computer analysis for a forced expiratory test.

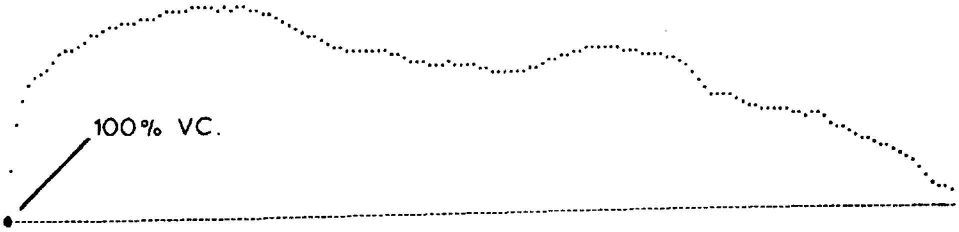


```
TEST NUMBER 0016
MAX FLOW RATE 2564 PULSES PER SECOND
TOTAL VOLUME  1507 PULSES
FEV 0.75  0054
FEV 1.0 0071
```

a. FLOW RATE – TIME. Sampling point at each 20ms interval during expiration.



b. VOLUME – TIME. Sampling point at each 20ms interval during expiration.



c. FLOW RATE – VOLUME.

Fig. 5. 12 Forced expiratory computer analysis with externally applied throat obstruction.

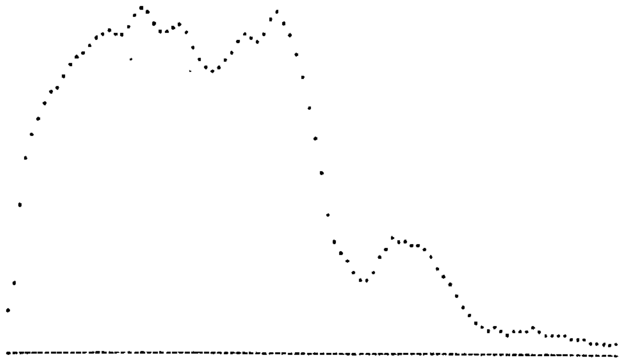
during the expiratory period. These measurements indicate the importance of monitoring the forced expiratory flow rate-time information in addition to that of the volume-time. The results illustrate that even under such extreme measurement conditions the volume-time graph remains continuous. An instrument not providing continuous flow rate information (such as the Vitalograph[71]) will therefore only indicate that the subject has a below average forced expiratory volume value.

The results obtained from a maximum inspiratory test under discontinuous gasping conditions are shown in Fig. 5.13.

It has been proposed by Vickers & Sykes[76] that flow rate information may be obtained from the slope of the volume/time curve from an instrument such as the Vitalograph. The results shown in Fig. 5.12 and 5.13 demonstrate that this assumption is incorrect and should not be adopted for the diagnosis of lung disorders.

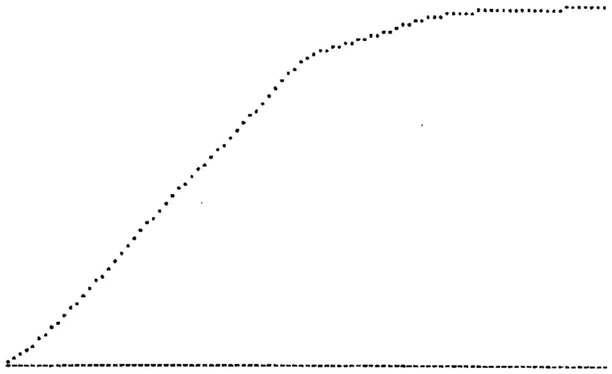
It is considered of particular interest to apply this improved resolution measurement technique to verify the repeatability of the shape of the maximum expiratory flow volume curve for a given individual,[69] as discussed in 5.3.3. The complete inspiratory-expiratory MEFV loop for a normal male subject is shown in Fig. 5.14. Preliminary experiments have indicated good repeatability for the same subject during day to day measurements, i.e. each subject appears to produce a distinctively shaped curve. As would be expected, during periods of ill-health the curve shape is not maintained - notably the effort-dependent portion of the expiratory cycle. Similar observations have been made by Laszlow*using a pneumotachograph in conjunction with

*personal communication with Dr. G. Laszlow, Middlesex Hospital, London.

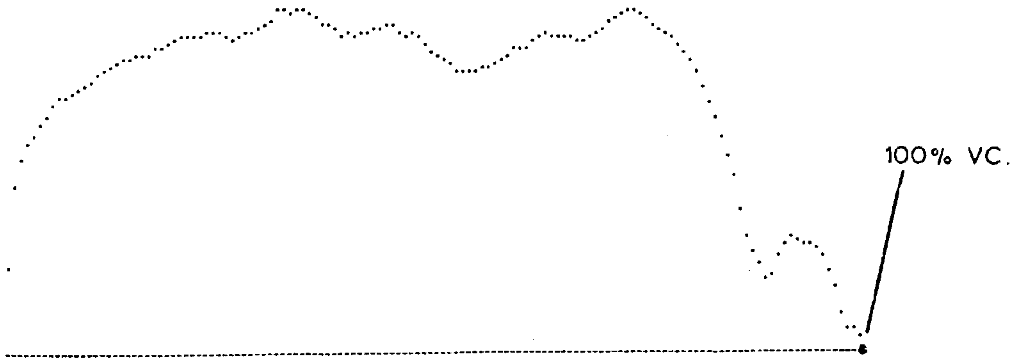


```
TEST NUMBER 0007
MAX FLOW RATE 1587 PULSES PER SECOND
TOTAL VOLUME  1353 PULSES
FEV 0.75  0065
FEV 1.0 0085
```

a. FLOW RATE – TIME.   Sampling point at each 20ms interval during inspiration.

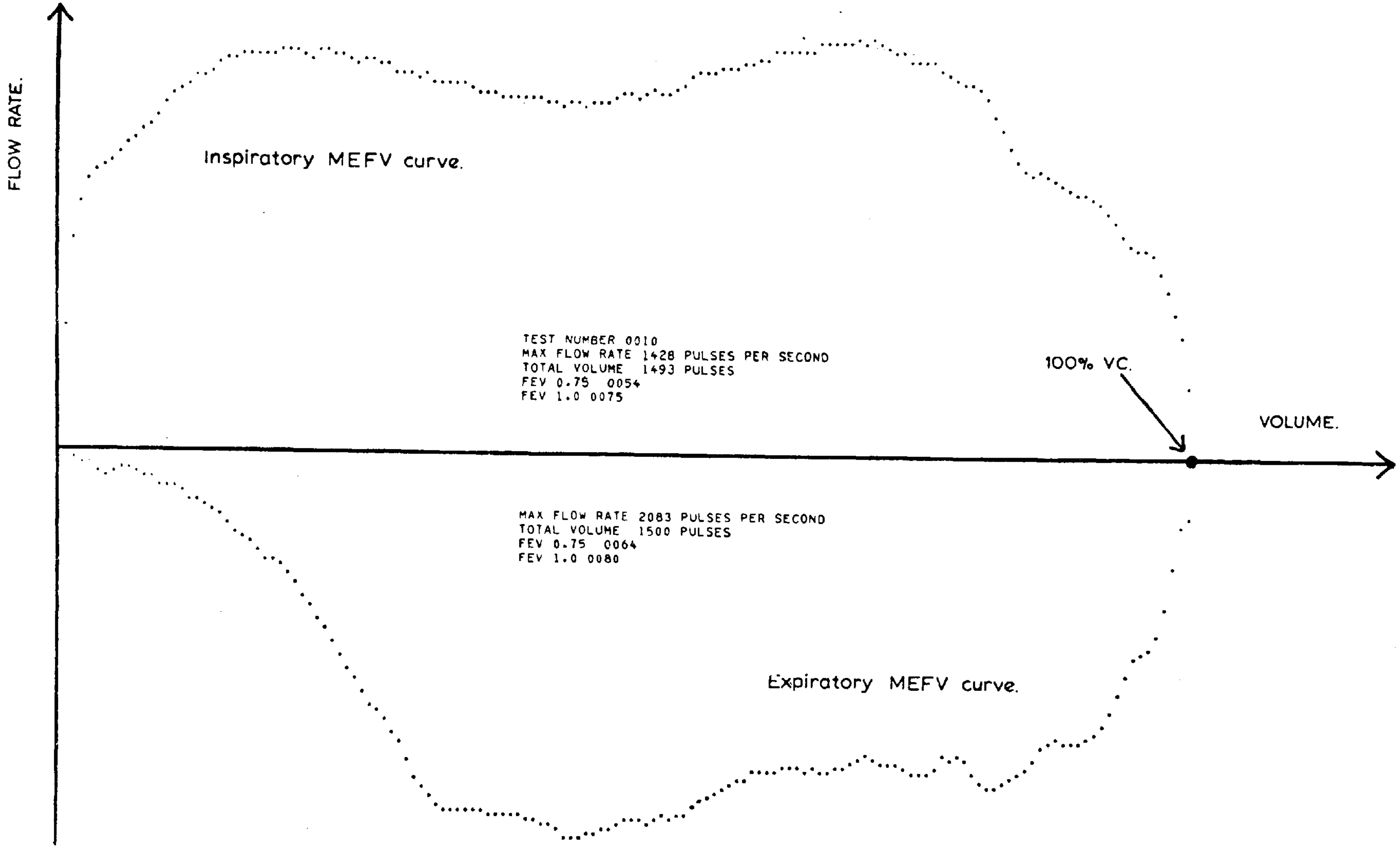


b. VOLUME – TIME.   Sampling point at each 20ms interval during inspiration.



c. FLOW RATE – VOLUME.

Fig. 5. 13 Computer analysis under inspiratory gasping conditions.



```
TEST NUMBER 0010
MAX FLOW RATE 1428 PULSES PER SECOND
TOTAL VOLUME  1493 PULSES
FEV 0.75  0054
FEV 1.0 0075
```

```
MAX FLOW RATE 2083 PULSES PER SECOND
TOTAL VOLUME  1500 PULSES
FEV 0.75  0064
FEV 1.0 0080
```

Fig. 5. 14 Digital computer analysis providing a complete flow rate – volume loop.

a storage oscilloscope. At the present time detailed medical knowledge relating to such occurrences does not appear to be available. The results discussed above illustrate the versatility and value of an on-line digital computing facility. The techniques can be extended to provide comparitive diagnostic information by using nomogram respiratory parameter data[77] which relates the predicted value for a subject in terms of age, sex, height, weight and body surface area. It is possible to store this information and to programme the computer so that the measured parameters are compared with the standard normal values. The results are then displayed as a percentage of the normal.

Recent research has been undertaken[70] into obtaining the normal standards for the flow volume loop, and to determining the repeatability of its characteristic shape for a particular abnormality in chronic obstructive pulmonary disease. To obtain this information requires considerable patient screening, for example to obtain a standard flow volume loop. Bass has measured 149 normal male adults. It is envisaged that the digital computer analysis technique would prove of considerable value in formulating such information, particularly since the Spiroflo sensor can be used to collect data with a cassette type recorder. It is of interest to note that whilst an Interdata 80 Digital Computer system has been used to obtain the on-line measurements for this investigation, a relatively low cost microprocessor system can be programmed to provide the same analytical information.

In view of modern developments in the microprocessor area,[78] a respiratory laboratory could be equipped with an on-line computing facility at a cost comparable with that of a pneumotachograph and an associated storage oscilloscope.

CHAPTER 6

Monitoring Flow in the Underground Environment

6.1 Introduction

In underground conditions the speed of the air is a most important environmental factor because of its primary function of providing energy for turbulent mixing and removal of gas. The higher the velocity the greater the degree of turbulence and the more rapid the mixing process. In gassy mines such mixing is essential to prevent the formation of a methane layer at the roof level. Air velocity has the effect of diluting and removing other gases, dust and water vapour. Consequently it is considered[79] that air velocity measurement must assume a high priority in the several conditions which require monitoring.

The history of underground explosions from gas shows that in many instances an inadequate air velocity was a contributory factor.[79] It follows that this primary safeguard against dangerous methane concentrations must be maintained at a suitable value, and that continuous air velocity monitoring is essential. Whilst many mines throughout the world do not suffer from the possibility of the formation of concentrations of methane and other explosive gases, there are other problems and hazards which necessitate the monitoring of air flow. For example, in the mining of fluorspar in Newfoundland there exists a radiation hazard caused by uranium deposits. Although these deposits are not present in mineable quantities, there is often a sufficient concentration to present a serious risk to health. The effective radiation of α particles, which have a half life of 19 minutes, is greatly increased in such mines by the presence of water, which leaches the uranium particles from the rock. To overcome this problem a very high purge rate of ventilation air is used to carry particles away and so reduce the concentration to a safe level.

A further reason for the maintenance of suitable air velocities is the provision of suitable comfort conditions, and air velocity is one of the factors which are important when determining an acceptable effective working temperature with minimum dust concentrations. It has been estimated[80] that substantial portions of the operating costs that are incurred in ventilating a mine are wasted because of air loss between the intake and the working faces. Many such losses can be minimized,[80] and the efficiency of the system can be improved if air velocity monitors are placed strategically to enable disturbances in ventilation to be measured and corrected.

An investigation has been undertaken into the use of the Rotating Vane Anemometer, of the type discussed in Chapter 2, for measuring air flow in the underground environment. In the first instance an analogue transmission system for use in gassy mines has been developed in conjunction with the National Coal Board.* Secondly, a remote reading multi-channel system with tone scanning has been designed for use in large mine complexes.

6.2 Development of NCB Air Flow Measuring System

The NCB single-headed air velocity monitor system has been designed during this investigation to satisfy detailed specifications drafted by MRDE,[81] for use in routine monitoring and for special

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*National Coal Board Mining Research and Development Establishment (MRDE), Stanhope Bretby.

investigations. The instrument is comprised of three main units:

1. a small sensing head powered from a dc supply and producing a standard output signal in the range 0 to +2.0v dc relative to the zero reference potential of the power supply. The output signal is required to be linearly related to air velocity, with 0.4v corresponding to zero velocity and 2.0v to maximum velocity. The 0.4v zero offset is necessary to distinguish between zero air flow and supply failure. Three air velocity ranges are required, 0 - 2m/s, 0 - 5 m/s and 0 - 10 m/s, and range changing must be effected by a simple adjustment whilst the unit is underground.
2. a terminal unit containing an air velocity indicating arrangement, a visual system in the form of a flashing red light and relay contacts for operation of a remote alarm. It is required that the alarm is initiated when the air velocity falls below a preset level. The lamp flashing sequences are as follows:-
   a. under normal operating conditions the lamp must flash once every 16s.
   b. under alarm conditions the lamp must flash at a frequency of 1Hz.
   c. under the majority of practical fault conditions the lamp must fail to flash.
3. a chart recorded unit using pressure sensitive paper, i.e. non-ink writing, to obtain a continuous record of air velocity.

It is required that the complete system must operate from an intrinsically safe rechargeable battery supply having an open circuit voltage in the range 12 to 15v. Under normal operating conditions the battery is continuously charged, but under power failure conditions the system is required to operate satisfactorily for a period in excess of three days. Particular emphasis has been placed in achieving the required system performance with minimum energy consumption. This ensures that the air velocity in the mine can be monitored during shut down periods, such as weekends and holidays.

The instrument specification follows a transducer system design philosophy initiated by MRDE which attempts to achieve a standardisation in underground measuring systems. It is proposed that the output signal from each type of instrument, i.e. methane concentration, air velocity, air temperature and humidity etc., is transmitted to the surface on a digital telemetry system for overall monitoring, analysis and control, using a digital computer facility.

At the present time the NCB consider the electronic rotating vane anemometer as the most practical instrument for measuring air flow underground.[82] Hot-wire, thermistor or thermocouple anemometers have severe intrinsic safety problems associated with their operation. In addition to being non-linear devices they require careful protection from moisture and dust. Initial experiments[83] with a vane anemometer of the type discussed in Chapter 2, have shown that under the most severe conditions of dust and humidity the calibration remains within ± 1% over a period of 10 weeks. Without correcting for air density, the total error has been estimated as less than 3% depending upon the air pressure, temperature and velocity. It has consequently been concluded that this type of sensor is capable of providing a basis for a continuous monitoring system.

6.2.1 Sensing Head Design

The sensing head circuit has been developed from the basic rotating vane instrument technique shown in Fig. 3.1. In view of the requirement for a 0.4v zero offset voltage, it is essential to incorporate a positive voltage regulator in the head unit. The low output impedance specified for the signal circuit is achieved by using an operational amplifier arrangement following the frequency to dc conversion microcircuit. To satisfy intrinsic safety regulations all electrolytic capacitors used in the circuit are encapsulated, with a series resistor to provide current limiting.[84] Zener diode protection is also used on each capacitor to eliminate the hazard that could arise from an overvoltage fault condition. To ensure that localised and temporary disturbances in the air velocity do not operate the alarm circuit, the output signal from the sensing head is damped with a selected time constant of either 10s or 20s. The evaluation of this instrument under wind tunnel conditions (in conjunction with MRDE, Bretby) has verified the performance data previously obtained with the basic rotating vane instrument (Fig. 3.3).

6.2.2 Terminal Unit Design

The Terminal unit circuit arrangement is shown in Fig. 6.1. A low pass filter circuit is used on the signal input to reduce the inevitable disturbance caused by the pulsed relay and lamp circuit. In particular, transients caused by energising the relay coil cannot be eliminated by adequate decoupling, because of the intrinsic safety requirements. Furthermore the dc supply to the system has to be

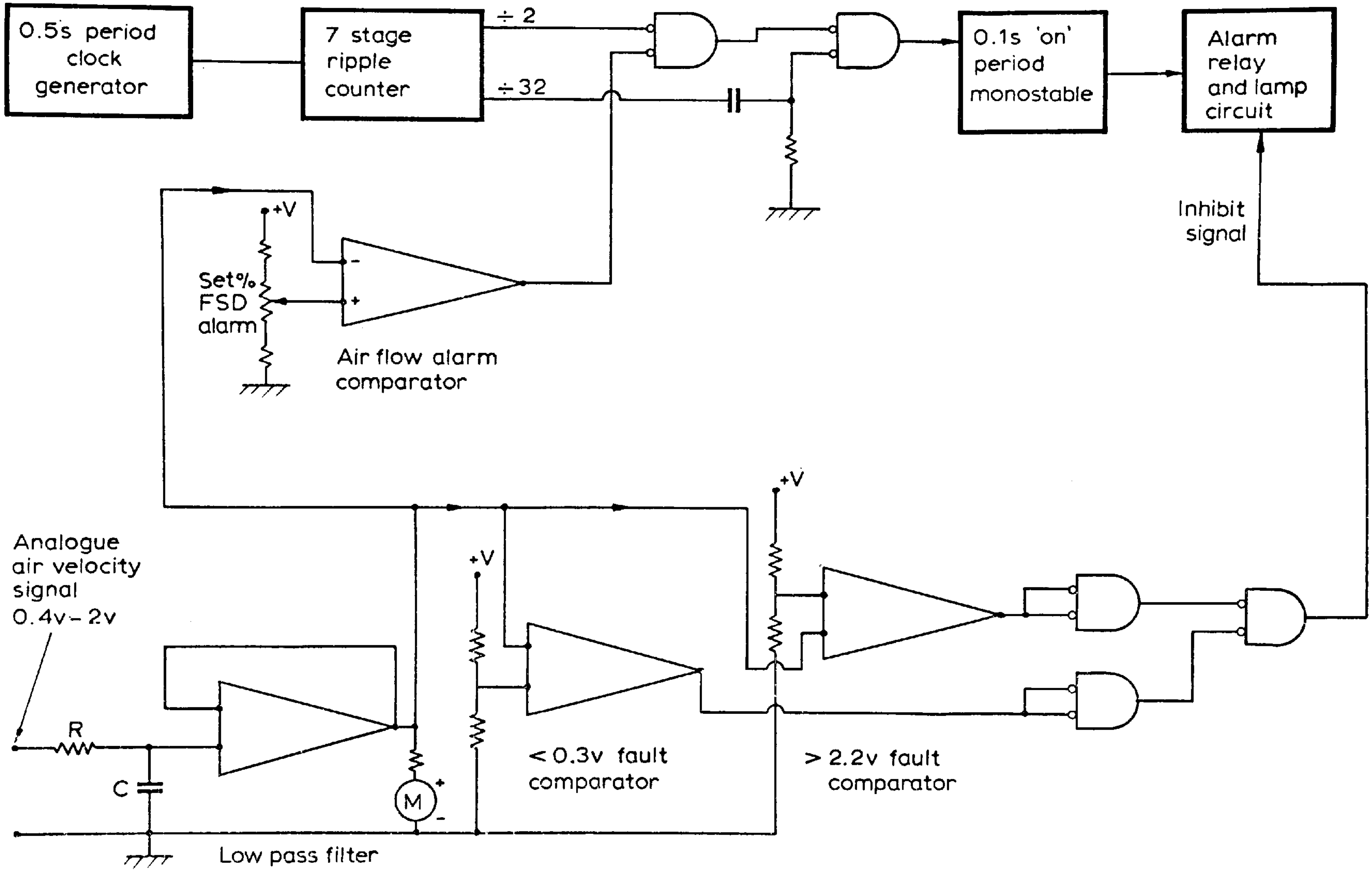

Fig. 6.1 NCB Terminal unit circuit arrangement.

current limited with a series resistance.

The alarm circuit has been designed using MOS logic to provide the maximum fail safe protection for the system. An integrated circuit timer is used as a clock generator providing 2 pulses per second into a 7 stage ripple counter. Under 'normal' air flow velocity conditions the 2^5 output from the counter triggers a monostable circuit to provide a 0.1s period pulse every 16s, which is used to drive the lamp and relay circuit. If, however, the air velocity falls below the preset level, the alarm comparator enables the 2^1 output from the counter to trigger the monostable to provide the required 1Hz alarm signal. Two further comparators are used to detect either a <0.3v or >2.2v condition and to thereby inhibit the flashing sequence under the majority of fault conditions that may occur in practice.

The construction details of both the Sensing head and the Terminal unit are shown in Fig. 6.2. The circuit design has been certified by SMRE* as suitable for operation in the presence of Group 1 gases (BS 1259) and these systems are currently being introduced by the NCB for use in mines throughout the United Kingdom.

6.3 Multi Channel Air Flow Monitoring System

As an alternative to the NCB instrumentation a multi channel tone scanning air flow monitoring system has been designed for use in large mine complexes. The ideal ventilation monitoring system must be capable of measuring the air velocity from a number of locations below ground using a single multi-core cable for signal transmission

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* Safety in Mines Research Establishment.

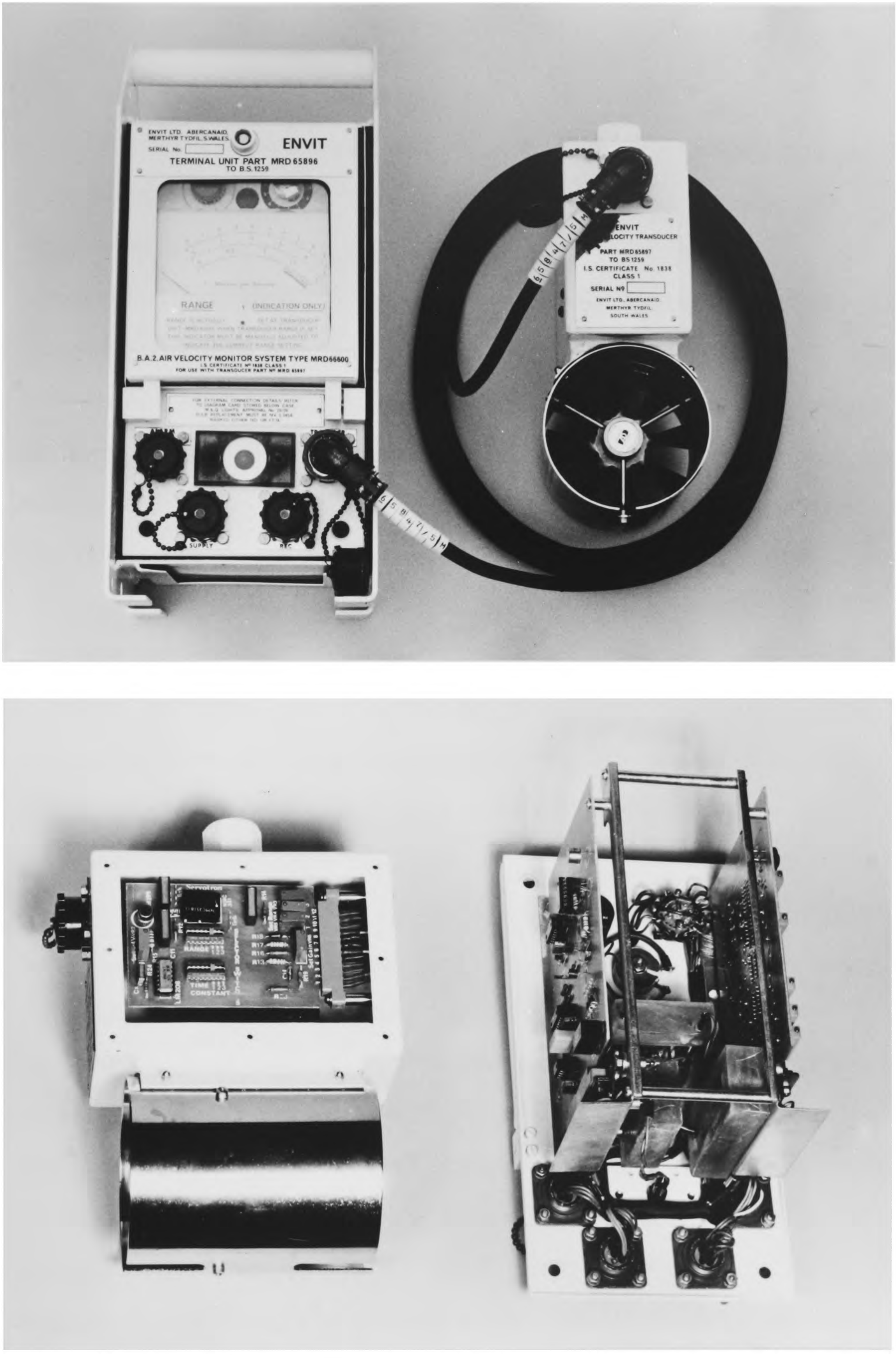

Fig. 6.2 NCB Air-flow monitoring system.

with readout and alarm monitoring on the surface.

The development technique uses tone scanning to obtain the air flow reading from each of the monitoring points in sequence. All anemometer sensing heads are connected in parallel to a single four core cable (tone signal, flow signal, positive supply and common) which connects them with the terminal unit located above ground. Each vane anemometer circuit is equipped with an MOS tone switch which is triggered by the programmed frequency and which connects the positive supply to the transducer and its associated line driving amplifier. The terminal unit arrangement which has been designed using MOS logic is shown in Fig. 6.3. A crystal oscillator is used as the basis for the tone generation and each of the channels provided is scanned for a preset 'on' time, with the tone frequency being selected by logic controlled division. A band pass active filter is used to provide a sinusoidal tone signal which feeds the line from a low output impedance amplifier.

In this type of system design it is essential to ensure that a definite air flow alarm exists before triggering the audible or visual alarm indicator. Both high and low air velocity values can momentarily occur underground, for example when ventilation doors are opened temporarily, so that it is necessary to use a time delay mechanism on the alarm circuit. To achieve this a decade counter is used with the alarm comparator acting as a clock source. Each time a particular channel is scanned and found to be in either a low or a high alarm condition, the counter is advanced by an alarm comparator signal. Following a specified number of scans the main alarm indicator is triggered, assuming that similar alarm conditions exists

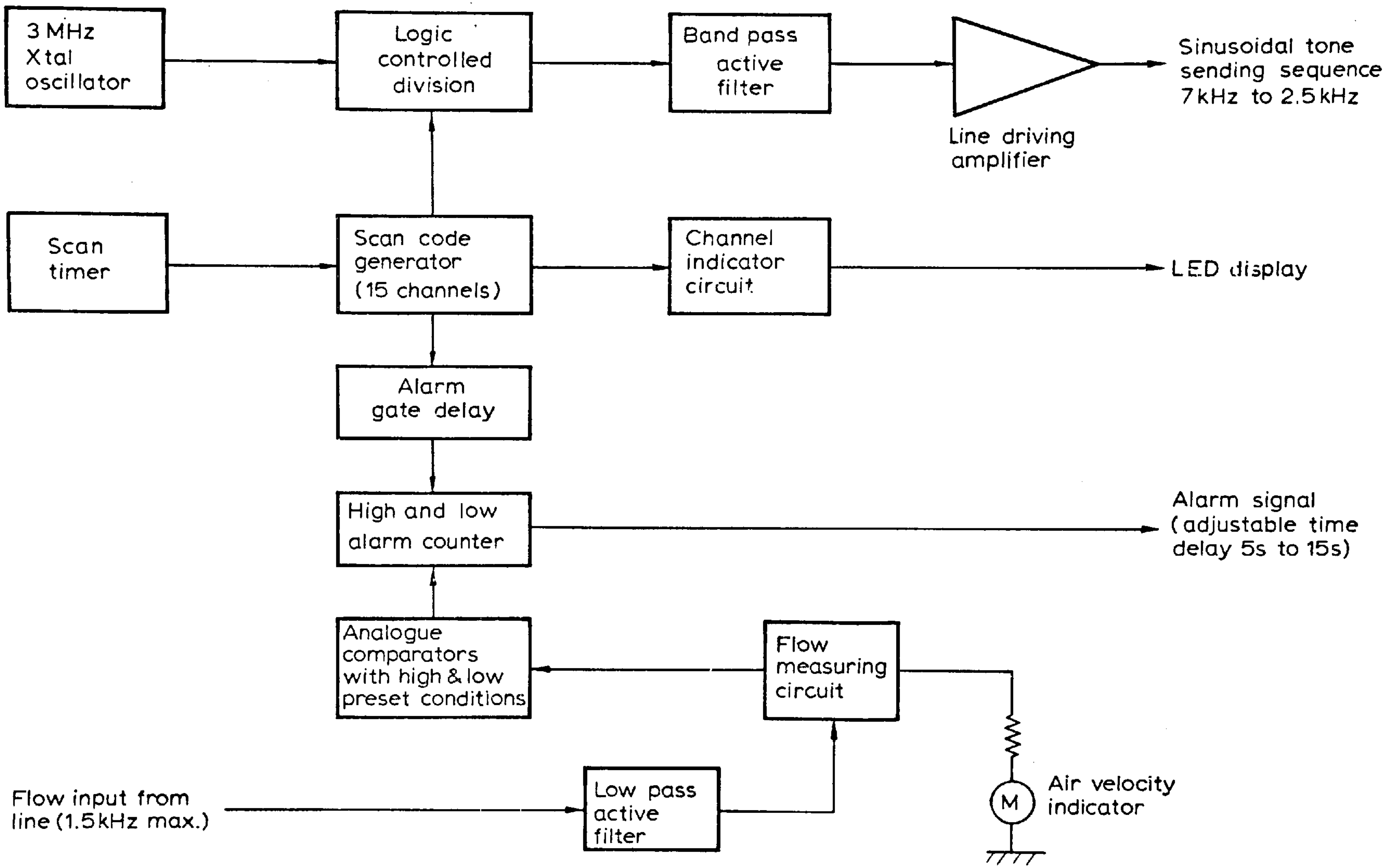

Fig. 6.3 Sequential tone scanning air flow monitoring system.

during each interrogation period. If a normal air velocity condition occurs during one of the scans, the counter is reset to zero. This arrangement therefore provides an alarm delay time which can be switched manually between 5 and 15s. The longer delay times are required during underground maintenance and shift changing periods. Manual overide is provided on each channel to enable a rapid assessment of the overall effect of any alarm condition. To eliminate the possibility of capacitively coupled tone signals from the long cable system operating the flow measuring circuit, a 2kHz low pass active filter is used on the signal input circuit of the terminal unit.

To conclude this investigation a dual 15 channel system as shown in Fig. 6.4 has been designed and installed in the Alcan Fluospar Mine in Newfoundland. In this installation the measurement and alarm circuits have been interfaced with a teleprinter to provide a continuous record of any alarm condition that may occur. This form of air flow monitoring system has provided a detailed knowledge[80] of how alarm conditions arise. In particular it has enabled dangerous conditions of under-ventilation to be rectified very quickly.

Experience with this technique has also verified[80] that the rotating vane system is capable of providing long term reliable operation in an underground environment where the humidity is 100%.

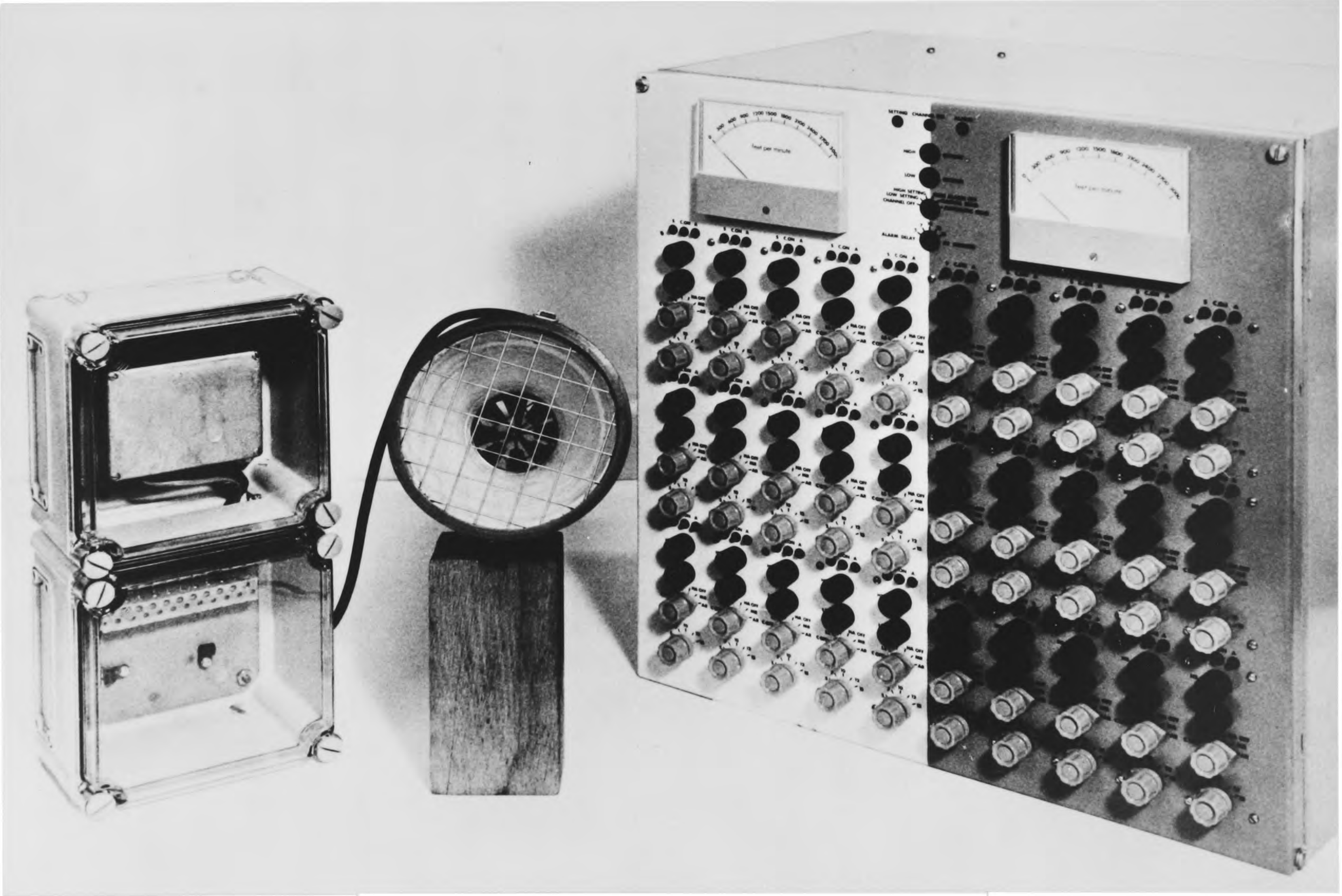

Fig. 6. 4 Multi-channel air flow monitoring system.

CHAPTER 7

Further Applications of Rotating Vane Instruments

7.1 Direction Indicating Rotating Vane Anemometer

A non-contacting method for sensing the direction of vane rotation has been developed during this investigation,[85,43] by using a pair of capacitance change transducers mounted on the periphery of the vane assembly. This enables the anemometer to measure air flow in either direction, i.e. it can distinguish the flow rate or volume for one direction of flow relative to the other.[86] The principle of the technique is shown in Fig. 7.1a where the transducers are mounted such that their positions are not coincident with those of a pair of blades or exactly mid way between adjacent blades. If both of these conditions are observed then other variations of relative positions are immaterial to operation, and both transducers can either be encapsulated in the same mounting block or separately mounted as required.

As shown in Fig. 7.1a each transducer output is fed into a pulse shaper circuit to obtain square wave signals which are used to drive the 'set' and 'reset' inputs of a bistable circuit. Assuming clockwise rotation of the vanes, then at $t = 0$ (say) a set pulse is obtained from blade No.1 on transducer No.1. However, at a very short interval t_1 later, depending on the position of transducer No. 2, the bistable circuit is reset from blade No. 2 on transducer No. 2. The output pulse train from the bistable circuit is therefore as shown in the first waveform of Fig. 7.1b. When the blades rotate in the opposite direction a set pulse from blade No. 1 still sets the bistable circuit, but it will not now be reset until blade No. 1 reaches transducer No.2.

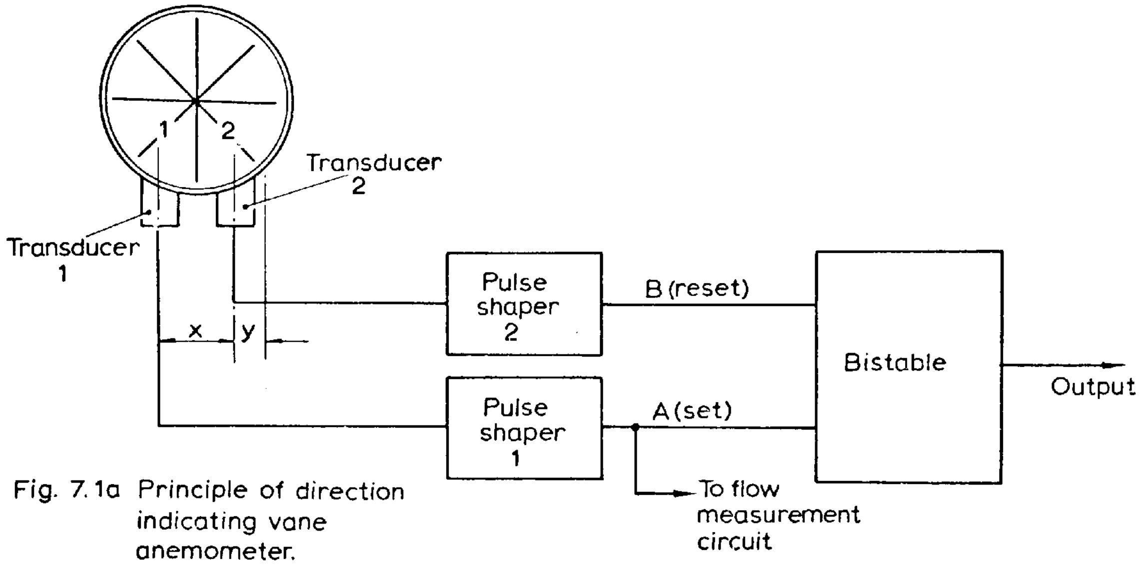

Fig. 7.1a Principle of direction indicating vane anemometer.

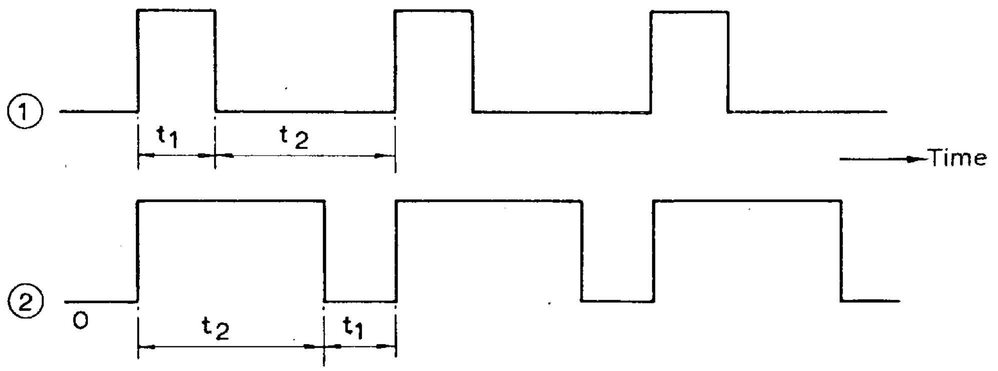

Fig. 7.1b Bistable waveforms.

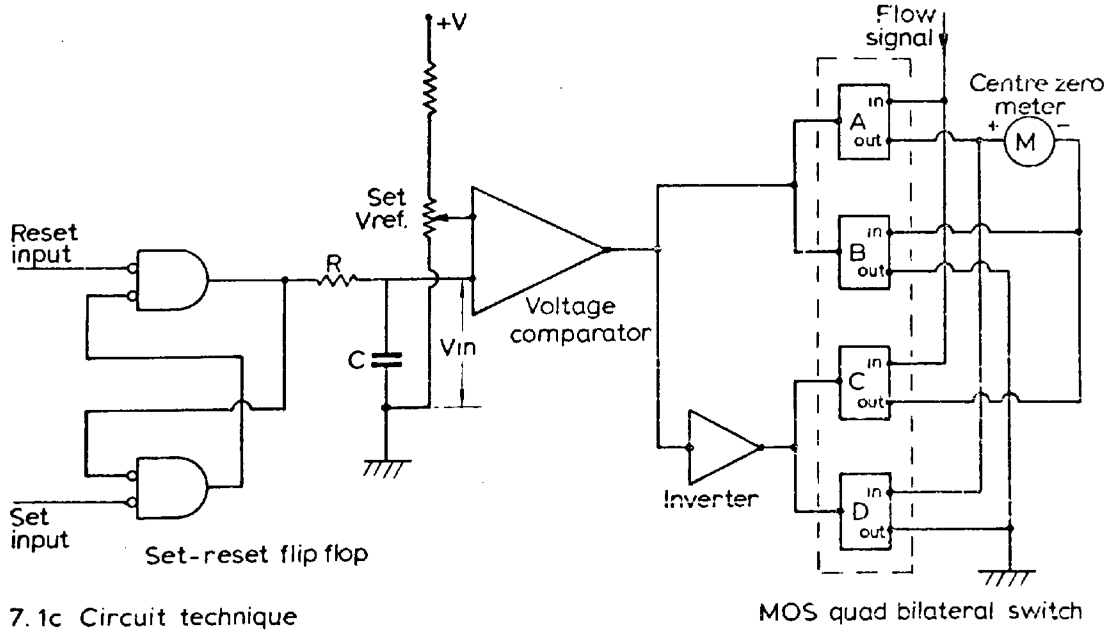

Fig. 7.1c Circuit technique for direction indication.

If the transducers are mounted as shown in Fig. 7.1a, where the distance x is greater than y, then the output pulse train from the bistable circuit will be as shown in the second waveform in Fig. 7.1b, where t_1 is proportional to y and t_2 is proportional to x. The direction of rotation is therefore obtained by using a circuit, as shown in Fig. 7.1c, to detect the difference in the average dc level of the two waveforms shown in Fig. 7.1b. To enable the technique to be applied to a portable battery driven instrument MOS logic gates are used to provide the bistable arrangement. The bistable output signal is integrated and applied to an analogue comparator which drives an MOS quad bilateral switch. The flow rate is indicated on a centre zero meter with the signal polarity governed by the direction of flow. With this circuit arrangement the direction of rotation signal is maintained until the vane reaches virtually zero rotational velocity. The techniques shown in Fig. 7.1 have been incorporated in a commercially produced instrument, designed by the author, which has been used in the study of air flow problems in ducts and tunnels and in particular in the London Underground Railway. This instrument uses a chart recorder with an event marker facility to indicate a reversal in flow direction.

7.2 Closed Loop Air Flow Control

An investigation has been undertaken into the application of the electronic rotating vane instrument in a closed loop air flow control system, for use in ducts and wind tunnels.

The circuit arrangement designed for this application is shown in Fig. 7.2a. The vane anemometer signal is converted into a 0 - 1v

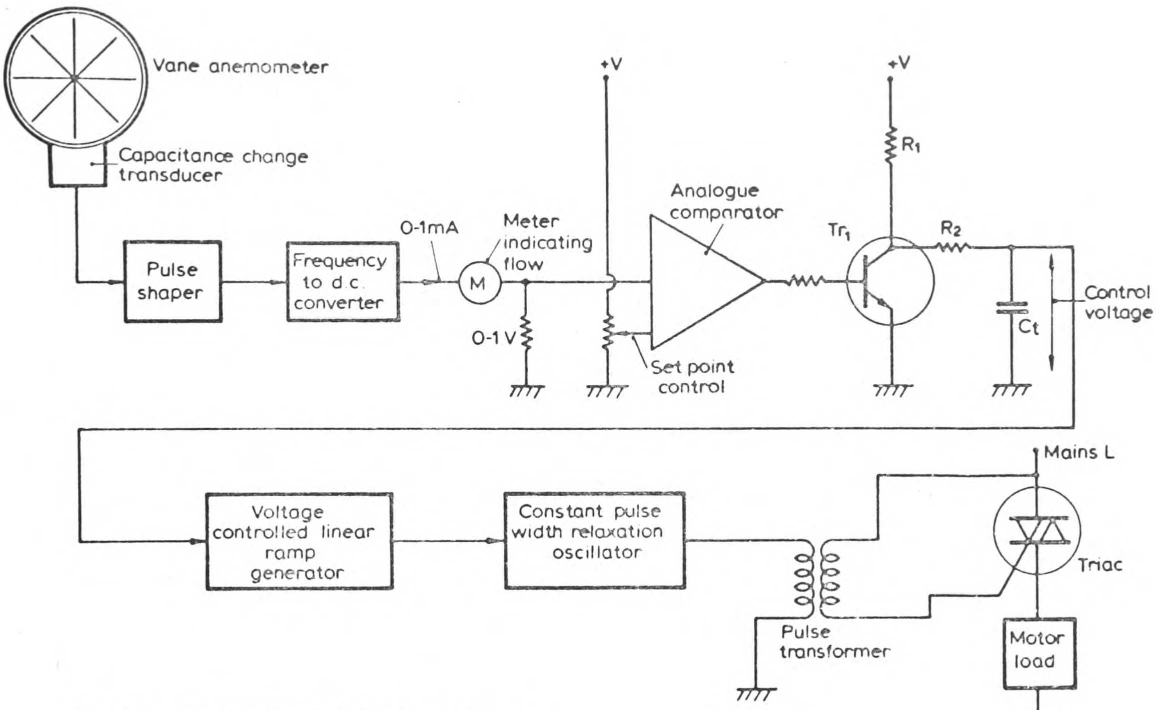

Fig. 7. 2a Closed loop air flow control system

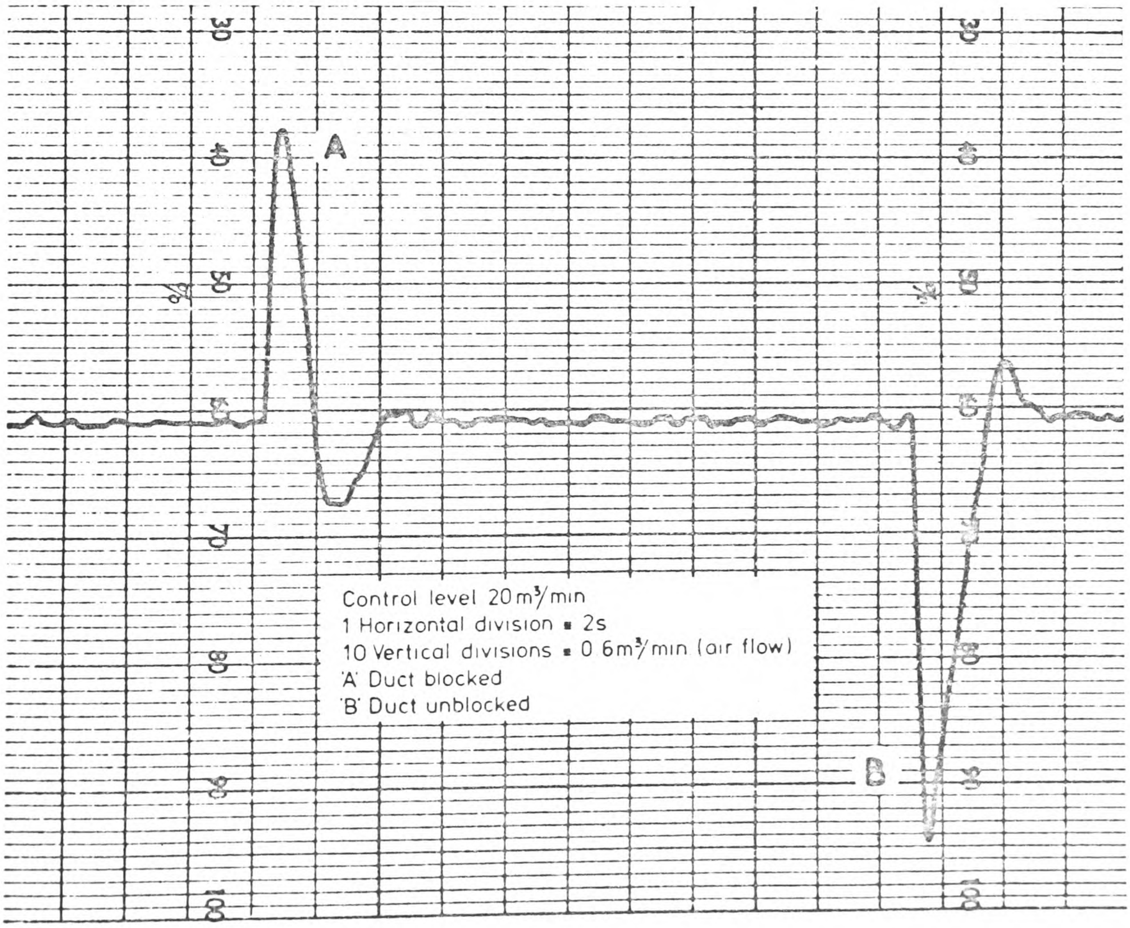

Fig. 7. 2b Control system step response characteristics

dc voltage and applied to an analogue comparator which triggers a switching transistor Tr_1 to provide a charging voltage for C_t. This voltage is used to control a linear ramp generator, having a charging time longer than the discharge time, which drives a pulse generator incorporating a Schmitt trigger circuit. The circuit is designed so that the magnitude of the ramp, with zero input control voltage, is just less than the input trip level for the pulse generator, so that with zero control voltage across C_t no output pulses are produced. As the control voltage is increased, the mean dc level of the ramp is increased, and pulses are generated when the ramp voltage reaches the input trip voltage. The greater the control voltage, the earlier in the cycle the ramp voltage exceeds the trip voltage, and the greater the length of the pulse train generated in the half cycle of the mains power supply to the motor. Thus by varying the control voltage[87], the length of the output pulse train and hence the conduction angle of the triac can be varied in synchronism with the mains supply.

The control point is set manually by a potentiometer on the comparator reference input. When the air velocity falls below the set level the comparator switches off Tr_1, and C_t charges via R_1 and R_2 to provide a subsequent increase in the motor speed. The corresponding increase in air velocity causes Tr_1 to conduct and C_t discharges through R_2. The charge and discharge time constants ($C_t(R_1 + R_2)$) and C_tR_2 respectively are chosen to provide the required control performance.

This closed loop air flow technique has been utilized* in the design of sterile nursing enclosures which are required for patients

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*in conjunction with AERE Harwell

at high risk of infection, including those undergoing organ transplants or intensive chemotherapy for cancerous conditions. Many of these patients require sterile protection for long periods and it is therefore necessary to minimise the risk of infection from the environment. To achieve this, it is essential[88] that sterile air is supplied at constant volume and pressure. To do this with certainty and accuracy requires a means for controlling the speed of the ventilation fan so that it responds automatically to variations in the air volume throughput. For example, as the air becomes contaminated the resistance to airflow increases and the air volume falls. To maintain the volume at a constant level the fan-speed must therefore be increased to compensate for the increased resistance.

The air flow control performance has been investigated in this application[89] by artificially blocking a duct having an air throughput of 20 cubic metres/min. By using a chart recorder fed from the anemometer signal, the response of the system to the sudden removal of the blockage is obtained, as shown by the curve 'A' in Fig. 7.2b. The response, which approximates to that of a second order system, has a recovery time of 4s, with a 30% overshoot (corresponding to a damping factor of 0.35). Curve 'B' in Fig. 7.2b indicates a similar response when the duct is again blocked.

7.3 Further Applications Utilizing the Capacitance Change Transducer

In view of the continued sensitivity of the capacitance change circuit in the presence of relatively large residual capacitance values, as shown in Fig. 2.4b, it is possible to detect the capacitance change occuring at the far end of a length of screened cable (1m typically). As a result of this performance it has been found possible to design an insertion type miniature vane flowmeter, as shown in Fig. 7.3a. In this instrument the vane sensing area is connected to a rigidly supported conductor which together with the outer metal supporting rod forms a transmission line for transfering the capacitance change to the transducer circuit located at the far end of the rod.

This form of vane flowmeter can be readily designed to be intrinsically safe and is therefore ideally suited to explosive gas flow measurements by insertion through a valve in the pipe. As shown in Fig. 7.3a a portable instrument which contains a chart recorder for long term metering applications has been designed for use with this type of flowmeter. The capacitance change transducer has also been utilized in the design of a cup anemometer as shown in Fig. 7.3b. In this arrangement the rotation of the vertical shaft supporting the cup assembly is sensed by the transducer, which therefore replaces the bulky and restrictive tacho-generator normally employed. Performance data obtained with this anemometer[90] shows an improved speed of response and a lower wind velocity measurement capability than that achieved by a conventional tacho-generator type instrument. This form of cup anemometer has been evaluated* and applied in an investigation on the long term effects of meteorological conditions on buildings.

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*Dept. of Architecture, UWIST, Cardiff.

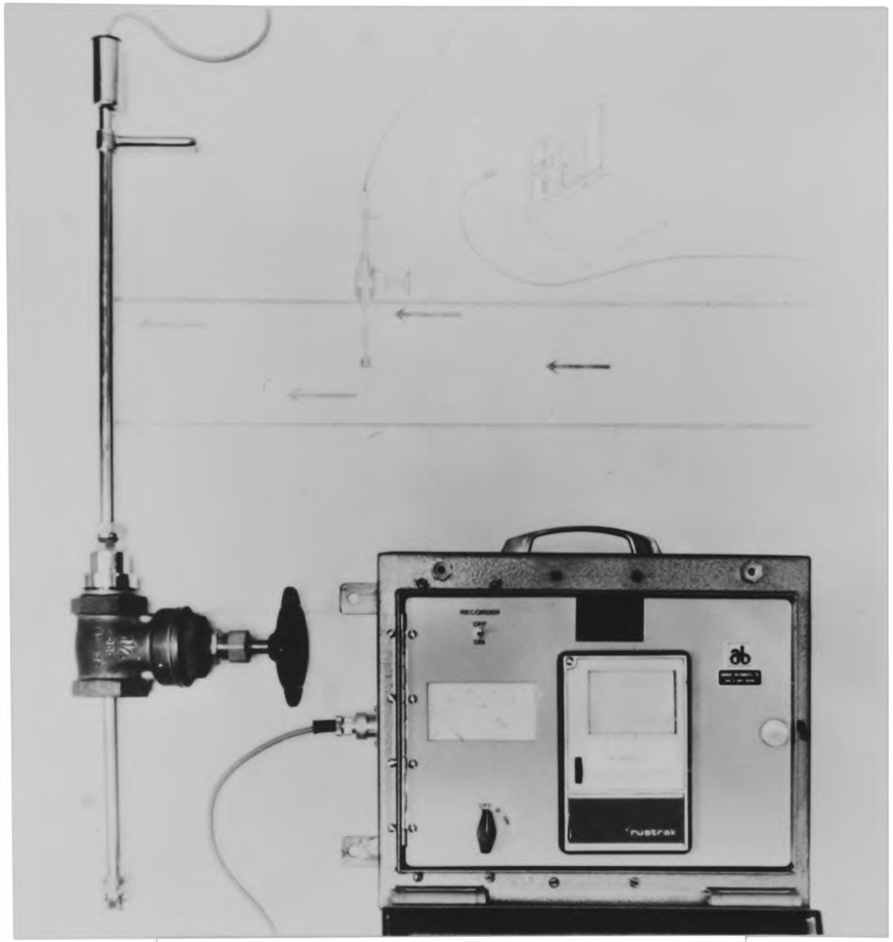

Fig. 7. 3a Insertion vane flowmeter instrument.

Fig. 7. 3b Cup anemometer utilising capacitance change transducer.

CHAPTER 8

Conclusions and Future Work

This investigation has broadly demonstrated the versatility of the vane anemometer for measuring air and gas flow under difficult environmental conditions. In particular the performance of a vane flowmeter, developed for use in respiratory monitoring, has indicated that good accuracy under discontinuous flow conditions can be achieved. The resulting electronic instrument design has been introduced commercially and authenticated by various medical authorities,[60,62,66] and is now widely applied in the measurement of tidal and minute volume under both operative and intensive care conditions.

The rotating vane system design developed for use in underground conditions, has obtained full approval and certification from the National Coal Board, whilst the sequential tone scanning method is used in Nickel and Flourspar mining in Canada.[80] The vane anemometer has also been developed to indicate the flow direction and to provide closed loop control of air flow in sterile units designed for immunosuppressive drug treatment and transplant surgery.[89]

A number of proposals for future work have arisen during this investigation, mainly as a consequence of the industrial support and medical involvement which arose during the development of the Spiroflo sensor. For example, it has been suggested by Dr. V. Grant et.al (Prince of Wales Hospital, N.S.W, Australia) that the respiratory vane flowmeter technique could be applied in the development of an instrument for use in paediatric medicine. The measurement of ventilation in infants and children during anaesthesia is considered to be particularly difficult because of the requirement for a sensor having a very low dead space, with good sensitivity and a high speed of response. Under these conditions it is necessary to measure the to-and-fro gas flow at the termination of the endotracheal tube in the mouth of the infant. Initial experiments have been undertaken with a Kapton vane sensor occupying a volume less than 3 cm^3 housed in a lightweight heat resistant material. The capacitance change caused by the vane has been transferred over a 1m length of screened cable to the transducer circuit, which is mounted in small enclosure remote from the patient. Initial results indicate that the technique appears feasible and it is envisaged that clinical tests will now follow.

At the present time the author is collaborating with the Clinical Research Centre (Division of Bioengineering, Harrow, Middlesex) on the application of the Spiroflo sensor in an oxygen consumption meter for the measurement of the inspiratory air flow. This instrument is designed to measure the oxygen intake in subjects under exercise conditions. Initial experiments have indicated that this form of sensor provides good accuracy and an improved performance when compared with alternative techniquessuch as the Wright Electronic Respirometer. In this application however it is often required to measure respiratory flow rates up to 80 ℓ/min with peak flow rates as high as 200 ℓ/min, and it is therefore necessary to develop a sensor with a pressure drop lower than that achieved with the Spiroflo design. It is proposed to construct a sensor having an increased diameter flow chamber, and to transfer the capacitance change from the face-mask fitting to the remotely located instrumentation to reduce the flowmeter size and weight.

With the advent of sophisticated digital integrated circuits it has now become possible to consider linearising the output from vane flowmeters which produce an output in serial digital form. The linearisation technique could then be used in pulmonary function analysis to enhance the flowmeter performance at low and high flow rates. A recently published method[91] for achieving this form of correction employs a decade rate multiplier in conjunction with a clock counter and read only memory (ROM). The ROM is programmed in accordance with the flowmeter error curve to enable the rate of pulses emerging from the linearising network to have both a linear and normalised relationship with the gas flow. It is considered that this technique may be of particular value in improving the performance of both the Spiroflo sensor and the proposed peadiatric sensor at low flow rates.

It is considered that the techniques presented in 5.6 for the on-line digital computation of respiratory data will be of considerable value in pulmonary function research applications. For example, it has been suggested by a consultant in respiratory diagnosis (Dr. G. Laszlo, Middlesex Hospital, London) that this technique may be applied to determine the effectiveness and progress of drugs in the treatment of pulmonary disease. It is envisaged that the Spiroflo sensor, in conjunction with a cassette recorder, may be used by the patient at home. Under these conditions the subject is relaxed and capable of producing consistent results. The information, in the form of a forced expiration, is collected on a regular basis during the treatment period. The computer is used to analyze the data from the recorder and to provide graphical results which will indicate the trend in parameters such as the forced expiratory volume, vital capacity and peak flow rate, over the treatment period. An interesting proposal regarding the application of the Spiroflo sensor for measuring lung ventilator flow performance has been made by R. Cavallo, Laboratories of Robert et Carriere, Paris. The ideal theoretical location for monitoring the flow from the ventilator is as close as possible to the mouth of the patient. In practice however, all known sensors eventually fail in operation because of excretions and excessive moisture deposits. To eliminate this problem it is necessary to remove the sensor and to locate it as far as possible away from the mouth of the patient (typical distance of 1.5m). However in this position the sensor will also measure the volume of gas in the connecting tubes from the ventilator in addition to that expired from the patient's lungs. To obtain an accurate measurement of the expiratory volume it is therefore necessary to subtract, for each respiratory cycle, the volume of compressed gas in the ventilator tubes from the total signal produced by the sensor. It is considered that this compensation may be achieved by deriving a pressure signal which is proportional to the volume of the compressed gas in the tubing. The corrected tidal volume value is obtained by subtracting from the indicated tidal volume reading a signal which is proportional to the peak to peak pressure developed in the system. To obtain the corrected minute volume reading it is necessary to multiply this pressure signal by a voltage which is linearly related to the ventilatory respiratory frequency. An analogue multiplier circuit may be employed to obtain this product, and the resulting signal is then subtracted from the indicated minute volume reading to obtain the corrected value. Initial experiments (in conjunction with Laboratories of Robert et Carriere, Paris) have verified these assumptions, and it is therefore proposed to fully investigate and implement these techniques using analogue computing methods.

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APPENDIX 1

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Capacitance-change transducer applied to rotating vane anemometry and tachometry

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Indexing terms: Anemometers, Capacitance, Tachometers, Transducers

Abstract

Electrical transducing methods for use in rotating-vane anemometry and tachometry are discussed and the advantages to be gained from a capacitance-change pickoff are outlined. Both a theoretical and practical analysis for the capacitance variation in such systems is given, leading to the conclusion that the resulting change, when converted into a voltage-time signal is ideally suited to cable and telemetry transmission. A simple transducing-circuit technique is then presented with measured results indicating that changes of less than 0·01 pF can readily be resolved. In addition, the circuit performance with high residual-capacitance values is investigated, the results of which have led to the development of an insertion-type flowmeter. The paper is concluded by illustrating the application of the techniques in a respiratory-flow transducer.

List of symbols

ϵ = permitivity of medium
$K(k)$ and $K(1-k^2)^{\frac{1}{2}}$ = elliptic integrals of the first kind
ω = angular frequency of input waveform
$T(s)$ = circuit transfer function in the s plane
v_{in} and v_{out} = circuit input and output voltages, respectively
Δv_{out} (d.c.) = change in d.c. component of circuit output voltage
ΔC_x = capacitance-change component
C_x = residual capacitance
C_{max} = maximum capacitance value
K = circuit constant

1 Introduction

1.1 Sensing techniques in rotating-vane anemometry

The adoption of a noncontacting method for sensing blade rotation in a rotating-vane anemometer enables the instrument to be employed in a number of important flow-measurement situations. An example is in the monitoring of air flow in underground environments, particularly in gassy mines, where dust deposits and intrinsic safety requirements preclude the use of hot-wire and thermistor methods.

If the sensing technique is relatively insensitive to moisture the spinning vane attains considerable value in respiratory monitoring where present instruments tend to use mechanical readout arrangements.

The development of the miniature germanium photocell provided the means for the first electrical method of vane pickoff[1,2] and a similar principle has been used in a recently developed commercial flowmeter for monitoring anaesthetic parameters.

Although the use of modern optoelectronic devices can improve upon earlier designs, the severe problem of dust and moisture deposits remains. These difficulties, particularly in relation to portability and simplicity of mechanical design, restrict the areas of possible application of such instruments.

The use of an inductive change caused by the vane passing through the airgap in a coil has been utilised in a transducer designed for monitoring flow in respiratory ventilating machines. A circuit is brought into oscillation by the increased mutual coupling caused by the vane, and the demodulated signal is then shaped to provide a square wave whose frequency is proportional to the flow rate.

While this technique offers many advantages over the optical one, the mechanical design is still complicated by coil alignment and construction.

1.2 Noncontacting sensing techniques in tachometry

Optical methods, which are extensively used in this context, require reasonable access to the rotating machines to obtain an interruption or reflection of the beam.

Since dust, vibration, and the presence of liquids can seriously disturb operation, such techniques are usually restricted to portable instruments.

For inbuilt systems the magnetic-pickoff method predominates although this does give rise to poor low-speed performance which requires the addition of a toothed wheel to the shaft to provide a consistent signal.

In practice, there are tachometry applications which are difficult, if not impossible to attain using either of these methods. For example, when measuring parameters such as shaft torque,[3] retardation time[4] and speed ratio, considerable shaft access is necessary to allow for the addition of specially constructed discs or toothed wheels. When very confined and hostile environments are concerned the measurement problem becomes acute, for instance when measuring torsional vibration[5] inside fuel-injection pumps and engine governors.

1.3 Advantages in capacitive sensing

It will be apparent from the previous comments that the need exists in both areas of application for a noncontacting sensing technique that fulfils the following requirements: (*a*) insensitive to moisture, dirt and interfering vibrations and suitable for use under conditions of extreme pressure, temperature and humidity; (*b*) the method must occupy minimal space and in tachometry systems it must demand only minor modifications to the rotating mechanism to which it is being applied; and (*c*) to achieve a consistent signal the magnitude and waveshape generated must not be a function of the rate of cutting of field lines, as in the magnetic method.

It is proposed that these specifications can be simply achieved by the use of a capacitance-change form of sensing technique. Investigations have shown that this method provides an extremely sensitive, stable and accurate solution to the problems outlined.

2 Capacitance variation analysis

When considering the sensing of a capacitance change, which ideally will be reproduced by the chosen circuit configuration, the form of this change is of fundamental importance to the suitability of the technique.

The form of the capacitance variation between a vane of the type used in anemometry and a sensing area which is located on the periphery of the circle swept out by the vane edge, Fig. 1A, can be investigated using transformation techniques. The capacitance per unit length of unequal coplanar strips has been evaluated using elliptic functions[6] as

$$C = \frac{2\epsilon K(1-k^2)^{\frac{1}{2}}}{K(k)} \tag{1}$$

where $K(k)$ and $K(1-k^2)^{\frac{1}{2}}$ are elliptic integrals of the first kind and

$$k^2 = \frac{(U_b - U_c)(U_a - U_d)}{(U_a - U_c)(U_b - U_d)} \tag{2}$$

It can be shown by transformation from the z-plane in Fig. 1B to the w-plane in Fig. 1C that

$$U_a = (h\cot\alpha - \tfrac{1}{2}d)^{\pi/\alpha} \qquad U_b = (h\cot\alpha + \tfrac{1}{2}d)^{\pi/\alpha}$$
$$U_c = \{h\,\mathrm{cosec}\,\alpha - \tfrac{1}{2}(L - L^1)\}^{\pi/\alpha} \quad U_d = -(h\,\mathrm{cosec} - \tfrac{1}{2}L)^{\pi/\alpha} \tag{3}$$

where the transformation is valid over the range

$$0 < \alpha < \cot^{-1}\frac{d}{2h} \tag{4}$$

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If a typical vane and sensing area dimensions are considered then a graph of capacitance change with vane angle can be drawn, within the confines of eqn. 4.

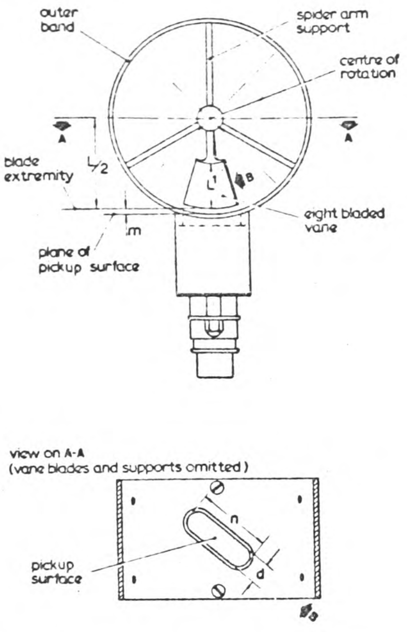

Fig. 1A
Typical vane construction and dimensions

$\frac{L}{2}$ = 3.25 cm L^1 = 1·63 cm d = 0·60 cm m = 0·08 cm n = 2·4 cm

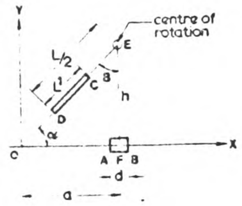

Fig. 1B
Theoretical z-plane vane equivalence

$h = \frac{L}{2} + m$

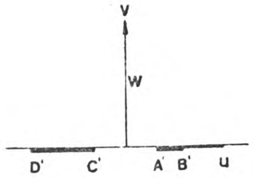

Fig. 1C
Transformation to the w-plane

The results, shown in Fig. 2, predict a capacitance change of approximately 0·4pF as the vane sweeps past the sensing area. Intuitively, the values for α (eqn. 4), over which eqn. 1 is invalid, can be assumed to give reasonably constant capacitance values, since the vane is then passing over the region of the sensing area.

Static measurements on a vane anemometer having approximately the same dimensions as the model of Fig. 1 have been used to verify the theoretical approach. To obtain accurate values for the vane angle a magnified screen projection of the mechanical arrangement was used. The results obtained are shown in Fig. 3, and as can be observed, a curve of the same general shape is obtained.

Difficulty has been found in comparing actual and predicted capacitance values since the curved aerodynamic design of the vane obviously cannot be represented in all respects by this simple model. In addition, the inevitable static capacitance of an actual system is difficult to predict however comprehensive the theory. If capacitance change values are considered however, then reasonable agreement is achieved, typically within 0·1pF.

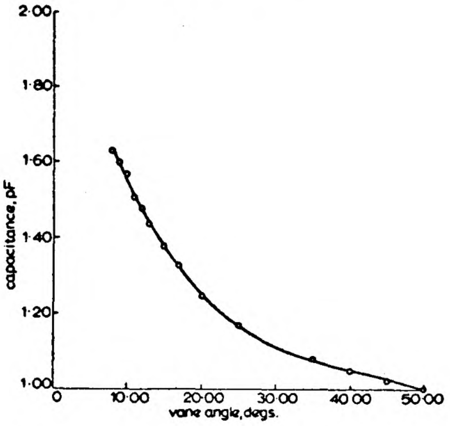

Fig. 2
Theoretical capacitance variation for vane-anemometer configuration

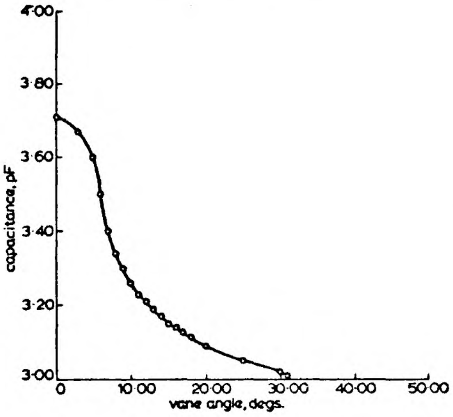

Fig. 3
Measured capacitance variation for vane-anemometer configuration

If suitable circuit techniques are used to convert the capacitance change into an identical voltage-time signal, then the smooth form of the curve is ideal for transmission purposes. Of particular advantage is the fact that the curve shape is not a function of the rate at which the vane sweeps past, and assuming a perfect circuit conversion, the peak amplitude will also remain constant. If the distance between the vane and sensing area is increased, this will of course reduce the magnitude of the capacitance change, but the curve shape will remain of the same form, as predicted by the above theory.

If tachometry applications are considered, then a small projection on the rotating mechanism, passing a pickup probe, must produce a curve having the same characteristic shape, since the above theory will apply equally well. Consequently, if a simple method for monitoring such small capacitance changes is available, then the principle can be developed to meet the requirements listed in Section 1.3.

3 Circuit technique for the detection of small capacitance changes

To enable the capacitance change with vane angle to be reproduced as a voltage-time signal, an amplitude-modulation technique provides the most satisfactory solution. This principle has the advantage of not requiring a specific and stable residual-capacitance value for reliable operation, as in the frequency-modulation method.[7]

The technique can be developed by considering the waveform shown in Fig. 4A applied to the RC circuit of Fig. 4B, where C_x

represents the variable capacitance component. The Fourier series for the halfwave-rectified signal shows a strong fundamental term with rapidly decreasing amplitudes for the higher harmonics. To a good approximation the signal can therefore be represented by

$$v(t) = \frac{V}{\pi}\left(1 + \frac{\pi}{2}\sin\omega t - \frac{2}{3}\cos 2\omega t\right) \tag{5}$$

For the circuit of Fig. 4*b* the transfer function $T(s)$ can be written as

$$T(s) = \frac{C_x}{C_x + C_L}\frac{(s + a_1)}{(s + a_2)} \tag{6}$$

$$\text{where } a_1 = \frac{1}{C_x R_x} \text{ and } a_2 = \frac{1}{\frac{R_x R_L}{R_x + R_L}(C_x + C_L)}$$

If the signal expressed by eqn. 5 is now applied to the circuit then

$$v_{in}(s) = \frac{V}{\pi s} + \frac{V}{2}\frac{\omega}{(s^2 + \omega^2)} - \frac{2V}{3\pi}\frac{s}{(s^2 + 4\omega^2)} \tag{7}$$

In conjunction with eqn. 7, the output voltage can be written as

$$\begin{aligned} V_{out}(t) = \frac{C_x}{C_x + C_L}&\left\{\frac{V}{3\pi}\exp(-a_2 t) + \right. \\ &+ \frac{Va_1}{\pi a_2}\{1 - \exp(-a_2 t)\} + \frac{\omega V}{2}\frac{\sin\omega t}{\omega} \\ &+ \frac{\omega V}{2}\frac{(a_1 - a_2)}{(a_2^2 - \omega^2)}\left(\exp(-a_2 t) + \frac{a_2}{\omega}\sin\omega t - \cos\omega t\right) \\ &+ \frac{2V}{3\pi}\frac{(a_1 a_2 + 4\omega^2)}{(a_2^2 + 4\omega^2)} \\ &\left(\exp(-a_2 t) + \frac{a_2}{2\omega}\sin 2\omega t - \cos 2\omega t\right) \\ &\left. - \frac{2V}{3\pi}a_1\frac{\sin 2\omega t}{2\omega}\right\} + \frac{R_L}{R_X + R_L}\frac{V}{\pi} \end{aligned} \tag{8}$$

If the following circuit conditions are now imposed:

$$t > \frac{1}{a_2} > \frac{1}{a_1}; \quad a_1 \gg a_2; \quad \omega^2 \gg a_1 a_2 \tag{9}$$

over the range where $\omega C_x R_x \gg 1$ and where $C_x \ll C_L$ then

$$\begin{aligned} v_{out}(t) \simeq \frac{C_x}{C_x + C_L}&\left[\frac{V}{3\pi} + \frac{V}{\pi}\frac{R_L}{R_x + R_L}\frac{C_x + C_L}{C_x} + \frac{V}{2}\sin\omega t\right. \\ &\left. + V\frac{(1 - \cos\omega t)}{2\omega C_x R_x} + \frac{2V}{3\pi}(1 - \cos 2\omega t)\right] \\ &+ \frac{V}{\pi}\frac{R_L}{(R_x + R_L)} \end{aligned} \tag{10}$$

The d.c. component of $v_{out}(t)$ which is a function of C_x can therefore be written as

$$v_{out}(\text{d.c.}) = \frac{C_x V}{C_x + C_L}\left(\frac{1}{3\pi} + \frac{1}{2\omega C_x R_x} + \frac{2}{3\pi}\right) \tag{11}$$

over the range where $\omega C_x R_x \gg 1$ and where $C_x \ll C_1$ then

$$v_{out}(\text{d.c.}) \simeq \frac{C_x}{C_x + C_L}\frac{V}{\pi} \simeq \frac{C_x V}{C_L \pi} \tag{12}$$

Eqn. 13 shows that within the constraints imposed, the d.c. output voltage will track the capacitance change, i.e.

$$\Delta v_{out}(\text{d.c.}) = K\Delta C_x \quad \text{where } K \text{ is a circuit constant} \tag{13}$$

Using this technique it now becomes a straightforward matter to ensure that the output voltage will follow the maximum rate of change of C_x, in that the time taken to sweep past the sensing area at the highest rotational velocity is greater than the product $\frac{R_x R_L}{R_x + R_L}(C_x + C_L)$. This ensures that the exponential terms in eqn. 8 make no significant time varying contribution, i.e. $\exp(-a_2 t)$ always approaches unity.

For a typical set of circuit parameters, the resulting change in the d.c. output voltage can be predicted, e.g. at a frequency of 50kHz, $R_L = 33\,\text{k}\Omega$, $R_x = 100\,\text{k}\Omega$, $C_L = 10\,000\,\text{pF}$ and $V = 20\,\text{V}$.
If it is assumed that C_x varies from 0 to 100pF, eqn. 11 gives

$$v_{out}(\text{d.c.}) = 0{\cdot}0047\,\text{V} = 0{\cdot}094\,\text{V}$$

Therefore, superimposed on the steady d.c. component $\left(\frac{V}{\pi}\frac{R_L}{R_L + R_x}\right)$ of 4·8 V is a 94 mV signal following the time variation of C_x. The sensitivity factor K can be increased by using a fullwave-rectified signal and the technique will apply for any unidirectional waveform.

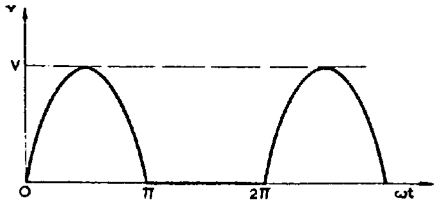

Fig. 4A
Suitable input waveform

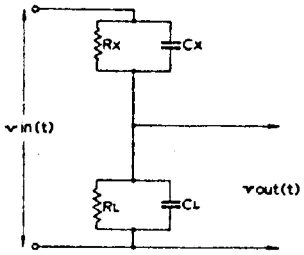

Fig. 4B
General circuit requirement

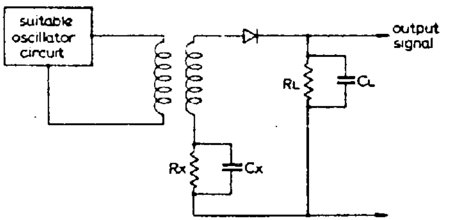

Fig. 4C
Practical realisation of circuit technique

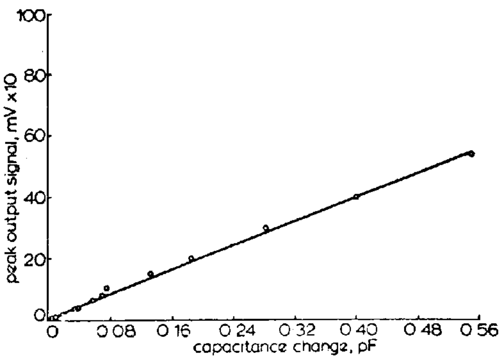

Fig. 5
Transducer output signal for small capacitance-change values

A practical realisation of this method can be achieved by a circuit of the form shown in Fig. 4C where, in order to obtain the required sensitivity, the frequency of operation can be increased to an arbitrary 2 MHz. It is difficult in such an arrangement to predict accurately parameters such as K, especially at such frequencies, owing to the fact that the diode conduction angle will vary as the result of changes in the value of C_x, since the impedance of the rectifying circuit is finite. This effect limits the range over which the output voltage is linearly related to the value of C_x but in the majority of applications this is not a circuit requirement and can therefore be neglected.

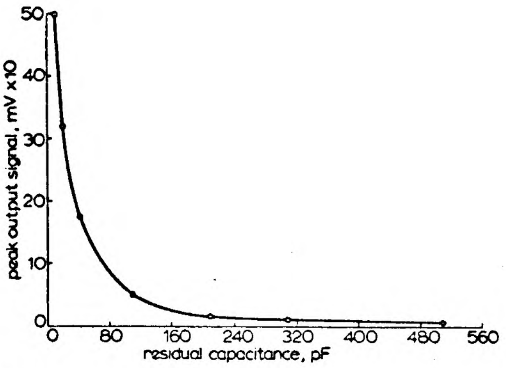

Fig. 6
Transducer output signal with residual capacitance added

The simplicity of the circuit arrangement is such that it can be presented as a small encapsulated block at the sensing area position. A single transistor oscillator has adequate stability with respect to temperature and supply variations, and an LC filter can be used in the output circuit to remove unwanted a.c. components.

With a view to applications in tachometry and anemometry the circuit can be evaluated for sensitivity under specific operating conditions. The results obtained from a tachometer test ring are shown in Fig. 5, where the measured capacitance change between the pickup area and rotating component has been plotted against the peak output signal obtained from a full wave version of the circuit shown in Fig. 4C.

It will be observed that over this range of ΔC_x, with low residual values, the linearity predicted by the theory is achieved. In addition, it is possible with this arrangement to resolve the signal caused by a change in capacitance of less than 0·01 pF (C_{max} = 1·95 pF).

The resolution performance for a given change of C_x in the presence of a residual capacitance C_{res} has also been investigated. A rotating-vane anemometer which produced a change of 0·5 pF with C_{res} = 10 pF as each vane swept past a fixed sensing area, was loaded with fixed capacitance values to simulate residual effects, and then driven at a constant velocity. The results, Fig. 6, exhibit the unexpected nonlinearity as C_x is increased over the range where resolution of the signal still occurs. The results also show that it is possible to continue to detect the ΔC_x of 0·5 pF with a residual capacitance of up to 300 pF added and with the addition of a single section LC filter to the output circuit, a well defined 5 mV change occurs with C_{res} of 450 pF.

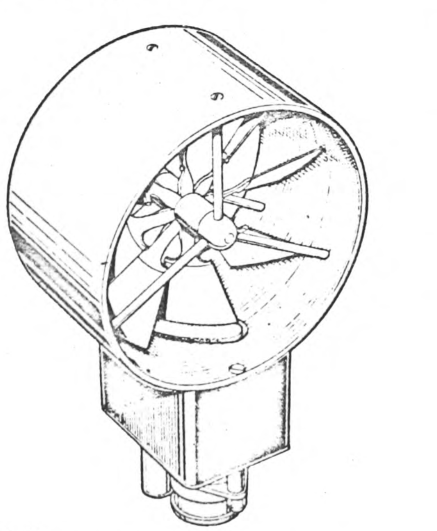

Fig. 7
Electronic rotating-vane anemometer

4 Application of the capacitance-change effect to rotating-vane anemometry

The circuit technique outlined in the previous Section has been applied to a range of rotating vane instruments. The flexibility and simplicity of the method allow the aerodynamic design of such flowmeters to be optimised, and to approach very closely the theoretically predicted linearity and speed of response, qualities which are difficult to achieve when mechanical coupling is employed.[8]

If a conventional rotating-vane anemometer is constructed with a sensing area located on the periphery, Fig. 7, then a change of approximately 0·5 pF, with a C_{res} of 10 pF, is obtained as each vane blade sweeps past. These capacitance values allow the circuit of Fig. 4C to operate in the linear region, so that eqn. 13 is applicable, and the capacitance variation as the vane passes the pickup area will be transformed into a voltage-time replica of itself. A spectrum analysis on the signal, which is of the form predicted by the theory, confirms the low harmonic content (2nd-harmonic 13dB down and all remaining harmonics greater than 20dB down), so that transmission on long cable lengths and on telemetry systems is readily achieved. At the receiving end the flow information is then resolved via a pulse shaper and frequency-to-d.c. conversion to provide both digital and analogue signals.[9]

Experience has shown that the rotating-vane anemometer with capacitive change sensing is capable of operation in areas having severe environmental conditions. For example, in monitoring air flow in mines where problems of intrinsic safety, dust and moisture eliminate a number of alternative methods. Experiments have shown[10] that as expected, exposure to dust and water droplets will not affect the transducing principle, and consequently with careful mechanical design long-term operation under such conditions is practicable.[11]

If the sensing area is encapsulated in an eposy resin to eliminate the conductive component then the technique can be applied to measure liquid flow. In this respect, the drag-free advantage over its magnetic counterpart allows measurement at low flow rates and, owing to the high transducer sensitivity that can be achieved, the method can also be applied to small-bore pipes, where miniature vane assemblies are required.

The residual capacitance results of Fig. 6 show that it is possible to sense a change of 0·5 pF with C_{res} of (say) 100 pF, without any further circuit requirements. This allows an insertion-type flowmeter to be constructed where the ΔC_x of 0·5 pF is transferred to the measurement circuit via a length of cable, whose distributed capacitance is equivalent to C_{res}. Such a flowmeter is ideally suited to the measurement of gas flow where the rotating-vane head is inserted through a valve into the flow line, and where the intrinsic safety requirements are readily achieved.

The capacitance-change transducer has been applied to the problem of monitoring respiratory and anaesthetic parameters, where the spinning-vane technique has proved to be of considerable value. From the results of Fig. 5, the low values of ΔC_x that can be resolved enable a subminiature (1·8 cm^2 surface area), low mass (less than 0·05 g) flat vane to be employed in an unidirectional flow meter.[12] This sensor has a designed capacitance change of only 0·2 pF with a residual value of 2·6 pF, but nevertheless only requires a single transistor amplifier stage following the circuit of Fig. 4C to provide a 1 V signal having the characteristic waveform predicted by the theory for a flat vane passing a sensing area, where the transducing circuit operates in the linear region. It is found that, as a consequence of the application of this sensing technique, the flowmeter possesses the following required characteristics which are generally difficult to achieve in total, using alternative methods: (*a*) fast speed of response – having a typical time constant of 30 mS to a step change in air velocity; (*b*) linearity of frequency of output signal to flow rate – better than 1% linearity over the range 1 – 40 L/m; (*c*) insensitivity to considerable moisture deposits; (*d*) capability of autoclaving of the flow chamber at elevated temperatures; and (*e*) Robust construction – capable of withstanding severe mechanical shock.

4.1 Tachometry and batch counting applications using the capacitance-change transducer

The tachometry test rig results of Fig. 3 and 4 are indicative of the wide range of applications to which the principle can be applied. Of particular value is the transfer of the capacitance change along a short cable length, so that the method is applicable even to extremely inaccessible components in high temperature and pressure areas. It is found that the capacitance-change profile remains consistent, whatever ΔC_x values occur, and if sufficient circuit gain is available to operate the pulse-shaper integrated circuit, no measurement error will occur, when mechanical adjustment modifies C_{re}, and/or ΔC_x. Such attributes thereby represent a considerable improvement in the accuracy, sensitivity and the range of application when compared to alternative transduction methods, such as magnetic pickoff.

The direction of rotation can be resolved by using two pick up points, feeding separate transducers.[9] This also enables additional parameters such as shaft torque to be computed.

The sensitivity exhibited by the transducer in detecting very small capacitance changes can also be utilised in batch-counting applications. The capacitance between the pickup area and the ground plane will vary when any object passes between, owing to the change in permittivity.

In practice, the sensor is capable of detecting the passage of most objects ranging from glass containers to pharmaceutical capsules, and has the advantage of being capable of long-term operation in hostile environments.

5 Acknowledgments

The author wishes to acknowledge the assistance given by David Tonge of the Department of Mathematics & Computer Science who derived the transformation equations quoted in the text, and to G. Draper for programming of the graphical data. He is also indebted to D.M. Dummer, head of the Department of Electrical Engineering at the Glamorgan Polytechnic, for his assistance in preparing the final draft of the paper. The rotating-vane anemometer drawing, Fig. 7, is reproduced by kind permission of Envit Limited, South Wales.

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APPENDIX 2

Paper presented at the IEE Colloquium on 'Novel Types of Transducer', London, Nov. 1972
IEE Colloquium Digest 1972/18, Paper No. 5.

RESPIRATORY FLOW TRANSDUCER

C. L. Smith

To be suitable for monitoring respiratory parameters, a transducer must ideally possess the following properties:

1. Have a fast response to achieve accurate measurements under peak flow rates, particularly those obtained from lung ventilators.
2. Be electrically and mechanically drag free.
3. Have an unidirectional response so as to provide expiration data.
4. Be robust and capable of being autoclaved.
5. Be insensitive to considerable deposits of moisture whilst in operation, ideally over long periods without attention.
6. Be capable of being either relatively insensitive to gas density or readily differentiating electrically between various densities.
7. Have a low pressure drop and minimum dead space. Ideally, an electrical respiratory transducer should consume minimal current and be of small physical proportions so as to improve on the portability of existing types.

The ideal sensor would be one in which there were no moving parts and in which the transfer mechanism between the flow and the resulting electrical signal involved no time lag. Consequently, the choice of a suitable electrical sensing arrangement is somewhat limited and up to the present time mechanical solutions have tended to be universally employed. However, it is possible to monitor average flow rates (minute volume) with heated wire or thermistor techniques, although the thermal time delay of such techniques does limit their performance on transient flow parameters, such as the Forced Expiratory Volume, and

Peak Flow Rate. Furthermore, lung ventilators tend to produce a peaky sinewave flow/time pattern which may not be faithfully tracked by such devices.

One of the most successful transducer techniques in respiratory monitoring has been to measure the pressure gradient using a sensitive differential pressure sensor (pneumotachograph). Such instruments have excellent response characteristics but they are usually bulky and restricted to mains operation in order that an electric heating element can be incorporated to minimise the effect of condensation of water vapour.

In an attempt to meet the specifications listed above, the transducer which has been developed* employs an electro-mechanical technique which is believed to be unique in this application. The sensor consists of a cylindrical tube having British standard medical equipment taper, Fig. 1a, through which the flow to be measured is continually passed. Within this tube is a flat kapton vane, Fig. 1b, of approximately 1.8 cm^2 surface area, mounted in jewelled bearings journalled in the wall of the tube, to allow substantially inertia-free movement of the vane. The vane, which is coated with a conductive substance, then provides a rotating system having a total mass of less than 0.03 gm. and yet possessing adequate rigidity. Due to its low mass the vane displays an excellent flow transient response with minimal lag and run on characteristics. Since only expiration data is normally required the unidirectional flow response is achieved by means of a swirl plate, Fig. 1c, which is inserted within the cylinder

*In conjunction with T.D. Webster, Esq., Envit Ltd.

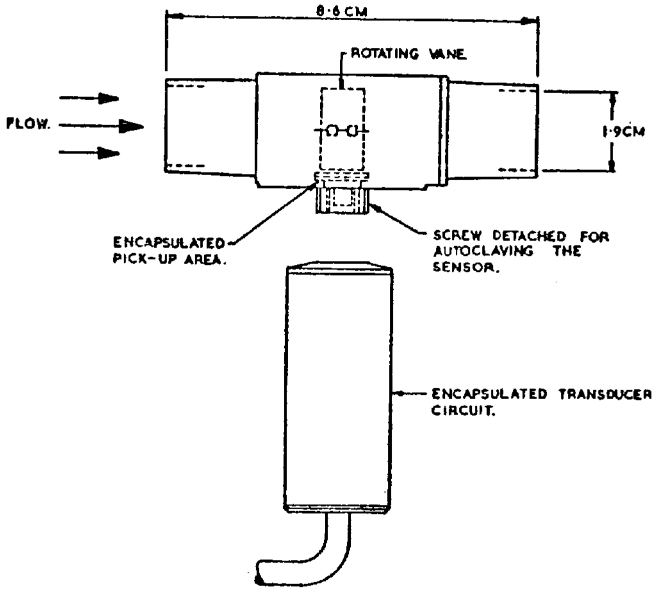


FIG 1 (A)

SENSOR AND TRANSDUCER.

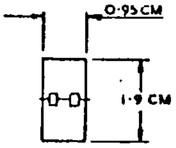


FIG 1 (b)

VANE

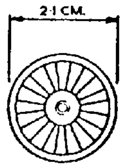
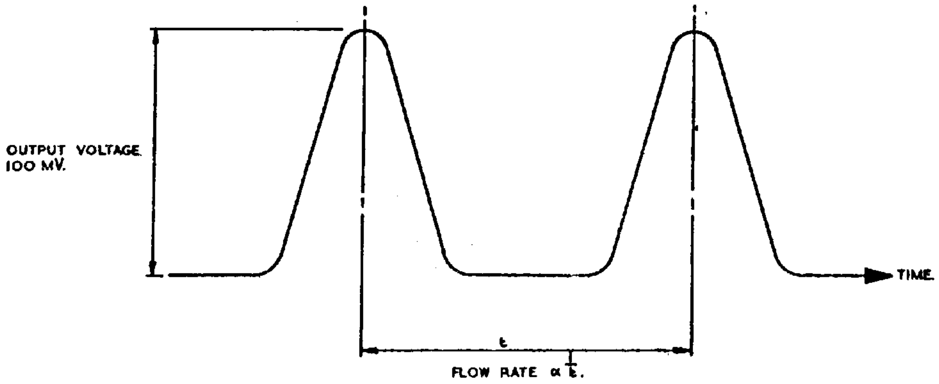


FIG 1 (C)

SWIRL PLATE.

FIGURE 1



TRANSDUCER OUTPUT WAVEFORM.

FIGURE 2.

thereby spinning the flow and allowing the vane to rotate only in the predetermined direction.

Should it also be required to monitor the inspiratory flow the sensor is merely reversed. Consequently, a pair of sensors can be placed in series to measure both directions of flow independently.

A sensing area in the form of a pick-up probe of conductive material is mounted in the tube, Fig. 1a, with a sealed output lead protruding through an aperture in the wall of the tube. The probe has an arbitrary circular surface area of 1.2 cm^2 and is positioned at a convenient point on the periphery of the area swept out by the vane, so that as the vane rotates the capacitance between the vane and probe varies. When the vane passes the sensing area, without coming into physical contact, there is a considerable increase in capacitance, even though at this instant the capacitance value is still of very small value. The pick up probe is connected into an encapsulated block to form the capacitive component of a series LC circuit which is mutually coupled into a transistor sinusoidal oscillator operating at a non-critical frequency in the region of 2MHz. The coupling is so arranged that when the vane passes the sensing area the increased circuit capacitance amplitude modulates the coupled oscillator signal. A diode demodulator circuit is then employed to provide a single pulse output, Fig. 2, whenever the rotating vane passes the sensing area. The frequency of these pulses is directly proportional to the rotational velocity of the vane and hence to the flow rate.

Specific capacitance values are in general immaterial in that the transducer responds to a change in capacitance. If the change in capacitance is increased, by suitable mechanical means, this will merely increase the output signal amplitude but not affect the signal frequency. Since the oscillator is acting as a carrier signal, both its amplitude and frequency stability are in no way critical and the temperature/frequency drift can be ignored, so that a low-cost bi-polar transistor is adequate for this circuit. With the mechanical arrangements of Fig. 1 the amplitude of the output signal is in the region of 100mV, which can then be amplified to several volts with the addition of a further transistor following the demodulator. It has been found in practice that the sensitivity of the transducer is such that the oscillator and vane assembly can be separated by screened cable of typically 1m length and so provides for the possibility of achieving a significant improvement in the techniques of infant respiratory monitoring.

Due to the simplicity of electrical coupling between the pick up area and the oscillator circuit, the cylindrical tube can be easily detached from the system and autoclaved when required. Since the sensing area can be insulated with a non-conductive coating, the sensor is insensitive to moisture deposits and the system can in fact be used as a liquid flowmeter.

The general application of these techniques has in practice provided distinct advantages over optoelectronic and magnetic pick-off methods. The former method consumes a high current whilst the transducer described above operates from 5V at approximately 4mA. A magnetic pick-off would,in this application, produce considerable drag, and the errors which would then occur would prohibit its use. The capacitance change transducer has also been adapted* to cover a number of important industrial applications in general flow measurement and tachometry. In the latter instance it provides a method for achieving accurate rotational information in inaccessible and/or hostile environments and unlike most magnetic pick-offs it does not produce a variable speed indication when the distance between the pick off point and the transducer is varied.

Electronic circuit designs have been developed for use with the above transducer, to facilitate measuring the following respiratory parameters:

Tidal Volume, Minute Volume,

Forced Expiratory Volume (at times in the range 0.75 to 3 secs.)

Vital Capacity and Peak Flow Rate

The fast response of the transducer has made possible the design of an instrument which will scan each expiration, and provide automatic cancellation and reset between each expiration at rates which exceed 60 respirations per minute**.

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APPENDIX 3

Rotating Vane Anemometer Calibration

The rotating vane calibration information presented in Fig.3.2.b has been obtained in a 0.46 m octagonal wind tunnel with the anemometer positioned centrally in the duct.

The tunnel air speed was derived from pressure measurements using an N.P.L. standard pitot-static tube with a hemispherical nose as shown in Fig.1 below.

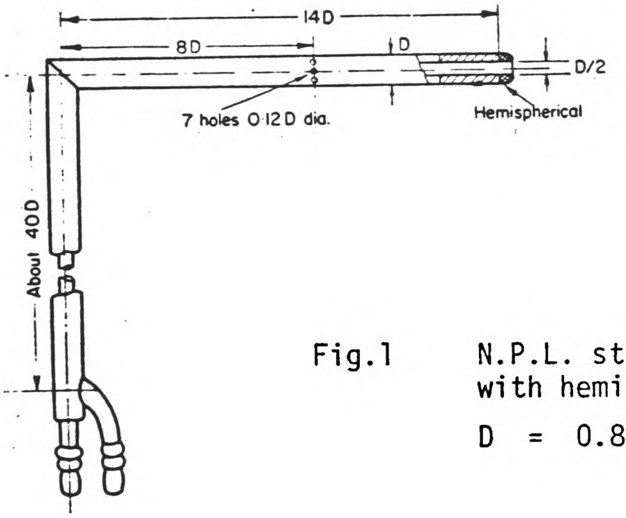

Fig.1 N.P.L. standard pitot-static tube with hemispherical nose

D = 0.8 cm.

The air velocity V is calculated from the unique relationship [1] which exists between pressure and velocity in steady incompressible flow:

$$\tfrac{1}{2} \rho V^2 = K (P_1 - P_2) \qquad \text{......A3.1}$$

where ρ is the fluid density, K is a calibration constant and $P_1 - P_2$ is the pressure difference sensed by the pitot tube.

For the range of air velocity between 1 and 20 m/s the factor K for the pitot tube used can be assumed to be unity with a measurement accuracy within 0.5% of the true air speed then being attained (Reference 3, Page 35). This accuracy can only be achieved in conjunction with a high quality micromanometer (Reference 1, Chapter 9). For the measurements undertaken in this investigation a Betz Projection Micromanometer was used.

During the calibration tests discussed in 3.2 the ambient temperature varied between 22^{o}C and 28^{o}C and the atmospheric pressure between 757 mmHg and 768 mmHg. The tunnel air speed values were derived from the pressure measurements using equation A3.1 by using the standard air density value, i.e., that for dry air at 15^{o}C and 760 mmHg. The anemometer readings in Fig.3.2b have therefore been multiplied by the factor $(\rho/\rho_0)^{\frac{1}{2}}$ as recommended by Ower[3], where ρ is the air density at the time of reading and ρ_0 is the standard value. The calibration provided by the graph Fig.3.2b is therefore valid for the standard value of air density.

The calibration results have also shown that changes in temperature and pressure separately required to give a 1% change in the anemometer reading amounts to 3^{o}C and 8.5 mmHg respectively.

Since these measurements were undertaken a revised British Standard Specification for fluid flow measurement has been issued. Calibration of vane anemometer instruments are now made in conjunction with BS1042 Part 2A - Measurement of Fluid Flow in Pipes, August 1973. This publication advises that an ellipsoidal nose pitot tube should replace the hemispherical type as the N.P.L. standard.