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A probe for measuring fluctuating flows in axial compressors

J. DUNHAM
Cambridge University Engineering Laboratory

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The design and development of a probe and its associated pressure transducer system is described. The probe was required for estimating instantaneous values of the pressure, velocity, and direction of air flow during stall propagation in an axial compressor. The measurements were to be made anywhere in the flow, not only at the walls, and the maximum expected amplitude and frequency of the stall cell pressure fluctuations were ±15 in. of water, and 85 c/s. An explanation of the principle used to deduce the required information from pressure measurements with a single hole probe is given, followed by an account of the construction and calibration of the pressure transducer.

1. Introduction

As the science of aerodynamics has developed, the need has arisen for accurate observations of rapidly fluctuating flows as well as steady flows. Various types of pressure transducer and hot wire anemometer have been developed to meet this need, and the choice of instrument for any particular investigation must be made in the light of practical experience of the particular requirements and difficulties involved. This paper discusses the choice of instrument for observing periodically fluctuating flows in an axial compressor, and describes the development and calibration of a probe and pressure transducer system for this purpose in the Cambridge University Engineering Laboratory.

2. Requirements of the system

The flow parameters of major importance in a compressor are the pressure and speed and direction of the air flow. Temperature is of secondary importance in a study of the internal aerodynamics. When the flow is unsteady, because of either a forced fluctuation imposed by external conditions or a self-excited oscillation (rotating stall or surge), all these parameters will vary. Ideally, an instrument or instruments are required to give accurate numerical values of these variations, however fast they occur. In practice a limited frequency response can be achieved and the important frequency range must be defined.

During stall propagation in a compressor the pattern of the air flow changes periodically from an unstalled pattern to a stalled pattern and back again; the change takes place quite abruptly and involves the pressure, speed and direction of the air flow simultaneously. In the particular compressor (Horlock 1955) for which the instrument was required, the stagnation pressure varied in the range atmospheric ±15 in. of water and the speed varied in the range 0–250 ft sec^{-1}. A typical sudden pressure change was of the order of 5 in. of water. The yaw angle varied by as much as 180°. Changes occurred at an unknown rate, with a maximum frequency of 85 c/s. Assuming that changes occurred instantaneously, the pressure waveform would be a square wave at 85 c/s, and to enable a satisfactory picture of such a fluctuation to be obtained, a target was set of a flat frequency response from 0 to 1000 c/s. Blade wakes occurred at 1400 c/s, but there was no intention of studying them; in fact they would have to be filtered out as a nuisance.

Accurate values of pressure level were required, calling for a system with minimum drift with time or temperature, and it was important that the inevitable mechanical vibration of the instrument should not give spurious signals.

Only limited information on the flow can be obtained from readings at or near an annulus wall; the instrument was required to observe flows four or five inches inside the air flow.

3. Choice of instrument

It has been customary to use a hot wire anemometer in rotating stall investigations. It gives accurate information on the frequency and width of stall cells, and can be used to measure the speed and direction of a flow, provided the changes in direction are fairly small. It cannot be used to measure pressure.

For the author's rotating stall research a new technique was devised, which offered the chance of obtaining all the required information (pressure, speed and direction of flow) using a single, pressure-measuring, instrument.

4. Theory of instrument

The pressure distribution round a cylinder with its axis normal to the plane of flow is sketched in figure 1. The familiar three-hole probe used in steady flow investigations consists of a tube with holes drilled in the surface at angles

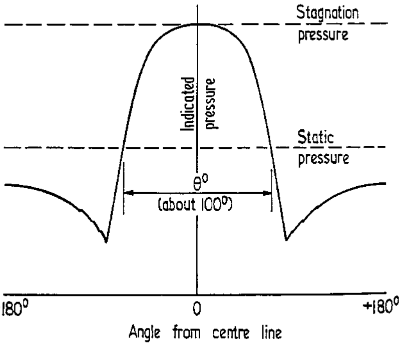


Figure 1. Pressure distribution round a cylinder.

θ apart, which is rotated until the pressures in the outer holes are equal and less than that in the middle hole.

This method cannot be used in a flow fluctuating in direction because the probe cannot be continuously aligned with the flow, but the principle behind it (figure 1) can be used. If a number of readings of pressure are taken at a single hole, with the tube set at a range of yaw angles from 0 to 360°, provided the flow pattern repeats itself in a clearly defined cycle, instantaneous pressure distributions round the tube can be obtained at any point of the cycle, and hence the required flow parameters can be found.

Suppose, for example, that the flow actually alternates between flows A and B:

	A	B
stagnation pressure (in. water gauge)	10	7
static pressure (in. water gauge)	4	3
flow angle	30°	90°

then the pressure distribution will alternate between the patterns of figure 2. The observed fluctuation of pressure with time will then appear as in figure 3 at a variety of yaw angle settings of the tube. It is clearly easy to work back from figure 3 to obtain the figures in the table above. As the pressure readings are plotted against yaw angle in the first place, some check on the accuracy and regularity of the observations is immediately apparent.

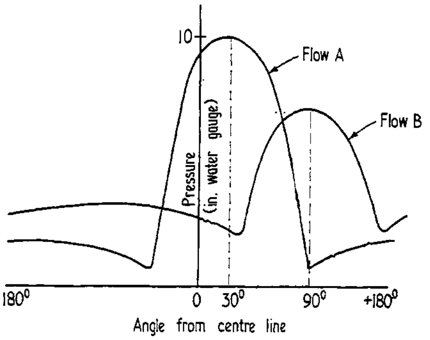


Figure 2. A hypothetical alternating flow.

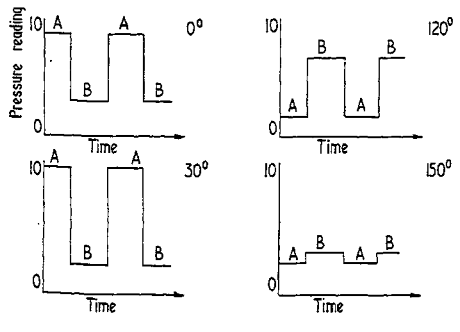


Figure 3. Hypothetical pressure fluctuation patterns at various yaw angles. (Flow of figure 2.)

The method is open to the objection that the pressure distribution round the tube will be different in an unsteady flow; in particular there will be a time lag in which the boundary layer flow round it must be changed. An estimate of this time lag is the time t_1 taken for a particle to flow past the tube:

$$t_1 = \text{diameter of tube/flow velocity.}$$

If the period t_2 of the pressure fluctuation being observed is much larger than this, the time lag will be unimportant. In the case under consideration, the ratio t_1/t_2 is small, being usually only about 0·08. It only rises as high as 0·2 when the dynamic head falls to 0·3 in. water; at such low flows the level of large-scale turbulence makes the reading inaccurate anyway.

5. Design of the probe and transducer

5.1. *Choice of transducer*

The ideal arrangement, inserting a tiny transducer into the tube, close to the hole, was considered impossible. The only type of transducer which could be made as small as ¼ in. diameter, and yet sensitive to the pressure changes expected, is a piezo-electric crystal; this method was rejected for two reasons. It could not be made sensitive to steady pressures, and it would respond to the mechanical vibration of the compressor to such an extent as to mask the pressure fluctuations being studied. It was therefore decided to mount a diaphragm transducer outside the compressor and to bring the pressure to be measured to it along a tube.

A serious difficulty arose immediately in designing a system with an adequate frequency response. The need to make measurements at least 5 in. inside the flow has been mentioned, and with a casing 2 in. thick the tube would have to be at least 7 in. long. The resulting 'organ pipe' frequency (one end closed) of 470 c/s was within the range of interest. In practice, the traversing mechanism used to move the tube to the required location in the compressor needed a much longer tube, 18 in., so the 'organ pipe' resonance became of major importance. Two other types of resonance may also be encountered in a pressure transducer. One is the mechanical natural frequency of the diaphragm assembly. The design should clearly be directed towards removing this from the range of interest if possible. It cannot satisfactorily be filtered out later, as the magnitude of the signal depends not only on the pressure fluctuations but also on the mechanical vibration of the outer case. The second type of resonance is the acoustic resonance known as a Helmholtz resonance, characterized by air vibration in a large bottle with a narrow neck. The frequency depends on the size of the bottle and the neck. To eliminate such a resonance, the transducer must be designed carefully to avoid large internal volumes. The original Langham Thompson transducer had to be modified for this reason.

The best compromise between the conflicting requirements of high sensitivity and high natural frequency was clearly a design with a minimum weight of diaphragm and attached parts, and a highly sensitive method of detecting diaphragm deflection. A reliable and drift-free method was considered to be that of using unbonded strain gauges. A modified Langham Thompson type UP 1 transducer of this kind was made the basis of the instrument.

5.2. *Langham Thompson transducer*

In the transducer as bought (shown at the top of figure 4), the pressure to be measured is brought to one side of a bellows; the other side is open to atmosphere (or a backing pressure). The movement of the bellows is transmitted by a thin rod to a displacement detector in the smaller diameter section of the body. The displacement detector has a low mass and stiffness, and its principle is sketched in figure 5. The strain gauges are connected in the form of a bridge, also shown in figure 5. The movement of the detector is limited to 0·0015 in. by stops.

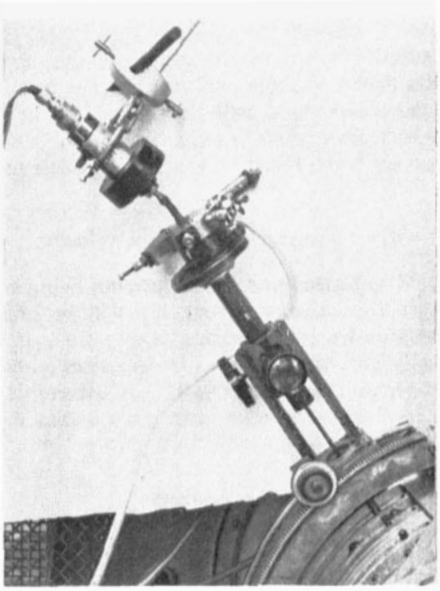


Figure 4. Instrument mounted in traverse gear.

It was found during frequency calibration that the large volume of air (1·1 in^3) inside the bellows resulted in a Helmholtz resonance. The bellows were therefore replaced by a diaphragm, and the unwanted volume reduced to a minimum by the insertion of a brass block (figure 6).

5.3. *Diaphragm design*

The natural frequency of a clamped uniform circular diaphragm is (Timoshenko 1955)

$$f = \frac{\alpha h}{2\pi r^2}\left(\frac{gE}{12\rho(1-\nu^2)}\right)^{1/2} \text{ c/s}$$

where r = radius and h = thickness of diaphragm, E = Young's modulus, ν = Poisson's ratio and ρ = density of diaphragm material and α is a constant which for the lowest natural frequency mode is 10·21. Hence for a phosphor bronze diaphragm $f = 67\,600h/r^2$ c/s. The deflection of the centre of a uniform circular diaphragm is (Timoshenko 1948)

$$\delta = \frac{3pr^4(1-\nu^2)}{16Eh^3}$$

where p = air pressure on the diaphragm, which for phosphor bronze gives

$$\delta = \frac{4\cdot 12r^4}{h^3} \times 10^{-9} \text{ in.}$$

for 10 in. water pressure. Hence with a diaphragm 0·7 in. radius and 0·007 in. thick f = 970 c/s. This corresponds to the observed natural frequency of about 900 c/s.

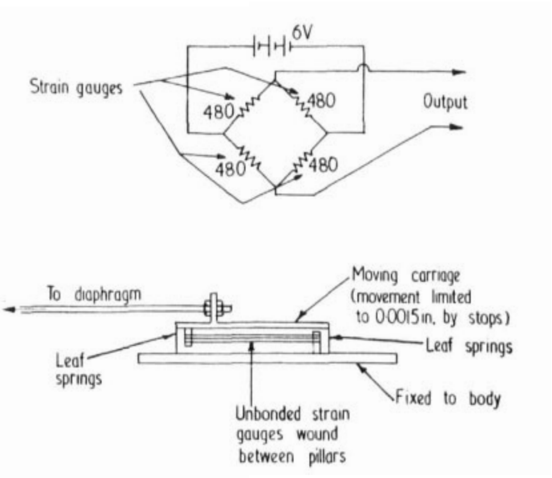


Figure 5. Langham Thompson transducer: principle of movement detector.

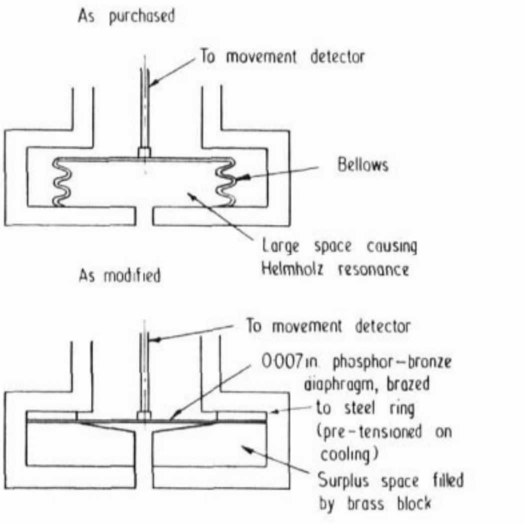


Figure 6. Langham Thompson transducer: modifications. Figures 5 and 6 are purely diagrammatic: details of sealing arrangements and mechanical construction are not shown.

The calculated deflection δ is 0·0029 in. for 10 in. of water. In fact there is considerable extra stiffness in the movement detector (strain-gauge unit), and the deflection does not exceed 0·0015 in. (where the stops operate) over the full range of calibration.

5.4. *Traverse gear*

The compressor used in the unsteady flow investigation had sufficient clearance between blade rows to enable a tube to be traversed in the gap. The traverse gear to enable the tube to be accurately located at any radial position, any circumferential position over a 36° range, and at any yaw angle, is shown in figure 4, with the probe and transducer mounted in it. It was made for experiments described by Horlock (1955) and needs a tube of minimum length 18 in.

5.5. *Tube*

The details of the hole at the end of the tube are shown in figure 7. The hole is very large, and as a result fails to record true stagnation pressure. The zero point on the yaw angle scale was aligned with the hole by eye. The tube was

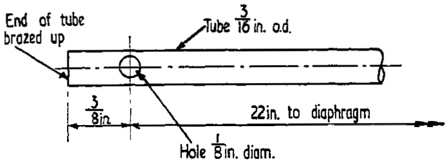


Figure 7. Hole in Pitot tube.

therefore calibrated in a small wind tunnel to establish the correct yaw-zero, stagnation pressure correction, and the angle for static pressure readings. This calibration is shown in figure 8. It was important to have a large hole in the end of the tube, rather than a small one. As the mass flow through an orifice is proportional, not to the pressure difference across it, but to the square root of the pressure difference, any serious restriction, like a small hole, makes the response non-linear, in that the output is no longer proportional to the input at frequencies above zero.

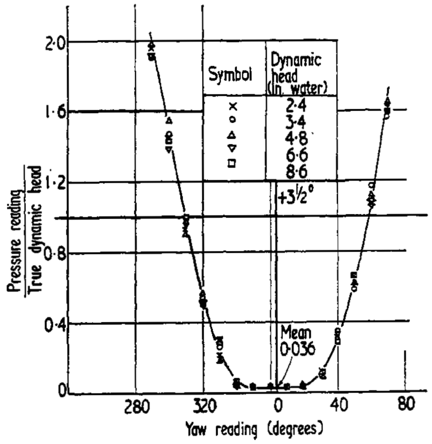


Figure 8. Calibration of Pitot tube. True yaw = yaw reading − 3½°; true static readings are 109° apart; true dynamic head = 1·036 × observed value.

5.6. *Acoustic filters*

It was hoped to use solely acoustic filters to flatten the frequency response curve. These consisted in principle of a number of Helmholtz resonators, that is, air bottles connected by a narrow neck to the tube. The acoustic filter assembly, made from a 4 in. diameter × ¾ in. thick brass block, contained two ⅝ in. diameter cavities and three ½ in. diameter cavities, arranged radially, and a small connection for a manometer, normally kept closed. The Pitot tube was screwed in at the bottom, and a union for connection to the transducer by a rubber tube at the top. The five cavities, the filters (figure 9), were arranged in such a way as to make the frequency and damping variable, by screwing in and out the large screwed plugs and small screwed and tapered pins. Simple theory (Binder 1951) leads to the result that the natural frequency of a Helmholtz resonator is

$$\frac{\text{velocity of sound}}{2\pi}\left(\frac{\text{cross-sectional area of neck}}{\text{volume of resonator} \times \text{length of neck}}\right)^{1/2}.$$

It was found in practice, unfortunately, that these filters distorted the frequency response at other frequencies. Trial and error led to a final arrangement in which only two of the cavities were used, one including a 3 in. × ⅝in. diameter extension piece visible in figure 4. The resulting response was not good enough, so electrical filters were necessary.

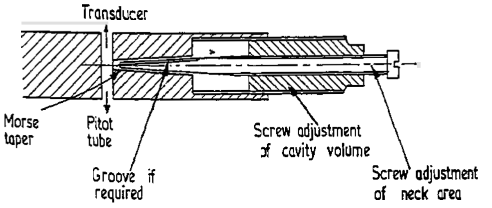


Figure 9. Acoustic filters: cavity arrangement. Sectional elevation, approximately half size.

Additional high frequency damping was provided by a cotton wool plug in the rubber tube connecting the main tube to the transducer. The joints of the acoustic filter assembly were varnished, after the adjustments had been made, to seal it against leaks.

5.7. *Electrical filters and amplifiers*

The electrical requirement was for a d.c. gain of about 250 (for display on a Cossor Model 1049 oscilloscope) combined with certain filter characteristics. Owing to the very low input signal (order of millivolts), both hum and d.c. drift caused difficulty. The final design is shown in figure 10.

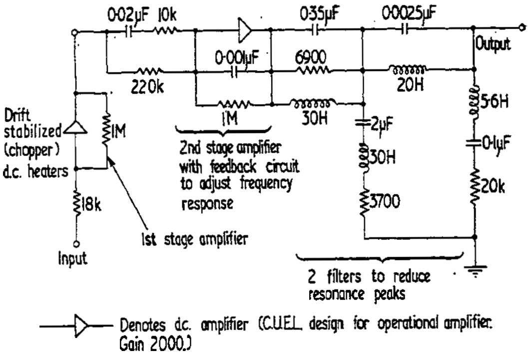


Figure 10. Pressure transducer amplifier circuit.

The first stage amplifier had d.c. heaters, with a 'chopper' drift corrector. The drift corrector introduced a negligible 50 c/s ripple. Even with the drift corrector, it was found necessary to check the zero setting every few minutes by disconnecting the rubber tube between the transducer and the acoustic filter assembly.

5.8. *Vibration isolation*

A transducer sensitive to low pressure is inevitably somewhat sensitive to mechanical vibration. It would have been convenient to screw the transducer directly on to the acoustic filter, but it was found necessary to reduce transmitted vibration to a minimum by using a 1½ in. rubber tube to make the join. The transducer body was attached, not to the (vibrating) traverse gear, but quite separately to a mounting point isolated from the compressor. The rubber tube was flexible enough to permit sufficient rotation of the tube to enable a set of readings to be taken without touching the transducer body. When the radial or circumferential setting was altered, the transducer mounting had, of course, to be adjusted.

Similar care was taken during calibration.

6. Calibration

The static calibration of a pressure transducer sensitive to very slow pressure changes is straightforward. Figure 11 shows the calibration of the complete probe system in its final form; it is very nearly a straight line. The frequency response calibration, however, needs special equipment. As the system was intended primarily for the observation of waveforms up to 85 c/s, a direct check on its suitability for this purpose can best be obtained by applying a square wave input. A simple rig (following Carmichael 1958) was built for this purpose (figure 12). It comprised a slotted disk spun by a variable speed motor between an air jet and the hole at the end of the probe. Provision was also made for mounting a transducer directly without the intervening long tube. Despite its simplicity this system gave satisfactory square waves from its minimum speed of a few revolutions per second up to the maximum available speed of 110 revolutions per second. The square wave input was very useful for adjusting filters for optimum frequency response compensation. This was done by adjusting the screws in the acoustic filters, or by adjusting variable resistors in the electrical filters, while watching the square wave output.

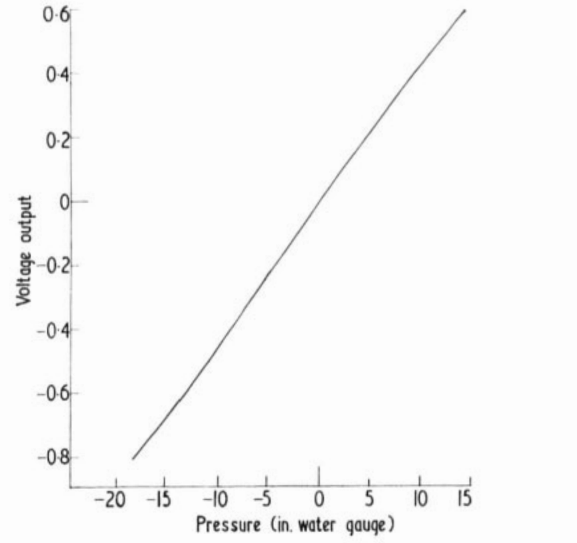


Figure 11. Static calibration of transducer system.

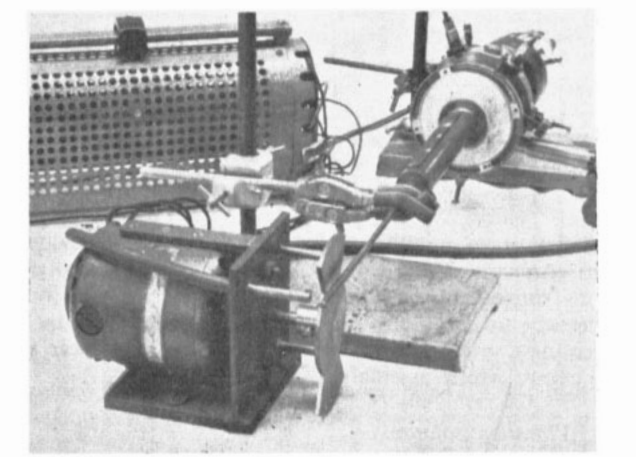


Figure 12. Square wave calibrator.

A square wave input, however, does not give a satisfactory indication of the type of filter to be designed, as it is difficult to discover the frequency ranges needing attenuation or boost. For this purpose, a sine wave calibration was provided of the type described by Westley (1958). A Goodman vibrator, model 390A, driven by a 120 w amplifier, was arranged to vibrate a rubber diaphragm mounted at one end of a small cylindrical cavity resonator (figure 13). The diaphragm of a Southern Instruments capacity transducer formed the other end of the cylinder. The probe to be calibrated was inserted through a hole in the side of the cylinder through a rubber bung.

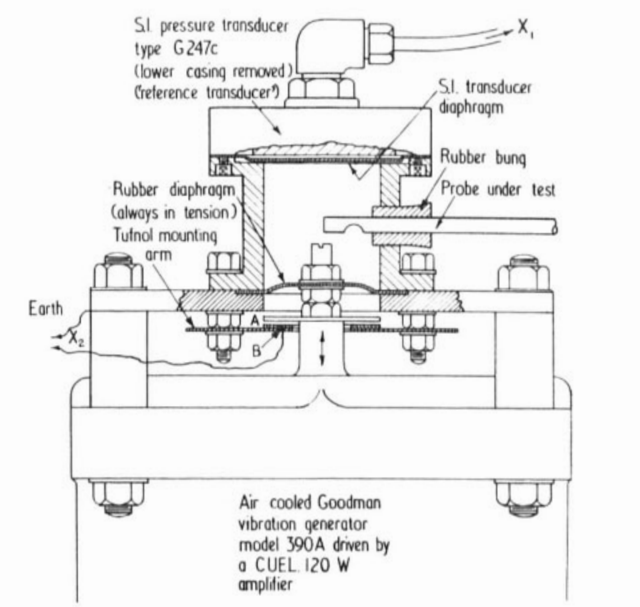


Figure 13. Sine wave calibrator (cavity resonator), partially sectioned. Test probe, Tufnol arm, various bolts and screened electrical leads X_1 and X_2 are shown in the plane of the paper for convenience. Scale 5 : 2.

The signal from the Southern Instruments transducer, which is referred to as the reference transducer, was displayed through a standard frequency modulation system: gauge oscillator 700L, FM gauge amplifier MR220F, and power panel MR 202D.

The movement of the diaphragm was measured by a capacitance method. A small brass disk A was attached to the moving arm of the vibrator, so that it moved relative to a fixed annular disk B. The capacitance changes between these disks was measured by using a second channel of the standard Southern Instruments frequency modulation system.

The method of calibration was this. The probe was initially omitted from the cavity resonator and the hole in the side of the resonator sealed up. For the frequency range 10–1000 c/s, the relationship between the output from the reference transducer and the diaphragm movement was found. It was assumed that the pressure fluctuation inside the plain cylinder was directly proportional to the diaphragm movement. (A slight leak enabled the mean pressure in the cylinder to remain atmospheric.)

The probe was then inserted and, for the same frequency range, the outputs of the probe transducer and the reference transducer were compared. Hence the frequency response of the probe transducer was found.

The dimensions of the cylinder were small enough to avoid any internal resonance up to 1000 c/s, but the introduction of the probe, with its 'organ pipe' effect, made it invalid to assume that the pressure fluctuation remained proportional to the diaphragm movement. Hence the indirect calibration was essential.

The numerical accuracy of this frequency response calibration was probably poor. It was carried out at an amplitude rather smaller than the 5 in. water average working range in the compressor; ±1 in. water was used at low frequencies, but at full power the maximum amplitude available in the square wave calibrator decreased to 0·75 in. at 200 c/s, then more sharply to 0·2 in. at 500 c/s. Nevertheless, it was adequate for designing filters, which was its sole purpose. The frequency response curves are only quoted to illustrate the development process.

Above 500 c/s, the output from the reference transducer was too small to be useful.

In designing the filters, suitable variables were provided for trial-and-error adjustment with the help of the square wave calibrator, as described.

7. Frequency response results

In the course of development, the frequency response of various systems was measured and oscillograph photographs of the response to a square wave were taken. The results are shown in figures 14–21.

Figure 14 shows the frequency response of the reference transducer in position in the cavity resonator, with and without a probe inserted into the resonator. It will be seen that the organ pipe resonance in the probe considerably changes the pressure fluctuation in the cavity resonator. This is why the indirect calibration described in the previous section had to be used. Figure 14 also shows why the Southern Instruments transducer, already available in the Laboratory, was not used as the probe's transducer; its frequency response is poor above 200 c/s, and difficult to correct by simple filters.

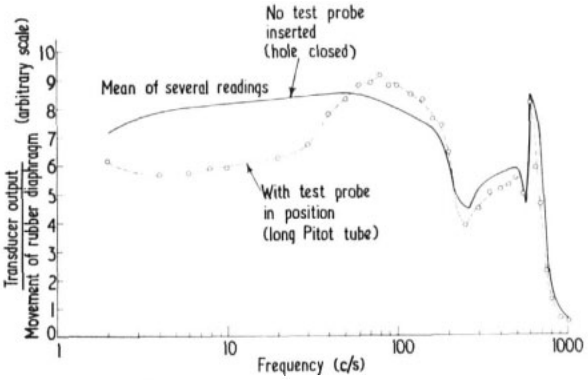
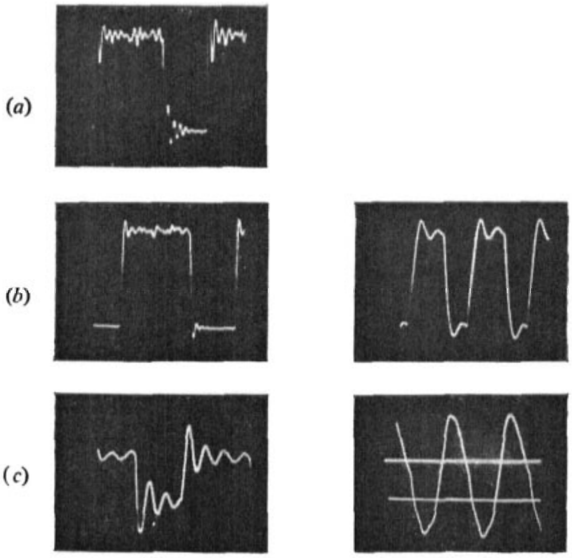


Figure 14. Frequency response of reference transducer.



10 c/s 60 c/s

Figure 15. Square wave response of Southern Instruments transducer. (*a*) Mounted directly; (*b*) as (*a*) damped by cotton wool; (*c*) mounted at end of long Pitot tube.

This would not be evident from figure 15, the square wave response of the same transducer. Although it is good at 10 c/s, without the long Pitot tube, it deteriorates badly at 60 c/s, and is, naturally, even worse with the organ pipe effect of the long tube added. The parallel horizontal traces on the last photograph, and in subsequent figures, show the actual magnitude of the step change in pressure, about 5 in. water.

Figure 16 shows the frequency response of the Langham Thompson transducer as purchased. The serious Helmholtz resonance at about 100 c/s stands out. For this calibration, the transducer was connected to the cavity resonator by a 0·083 in. diameter tube 1 in. long, in addition to its own

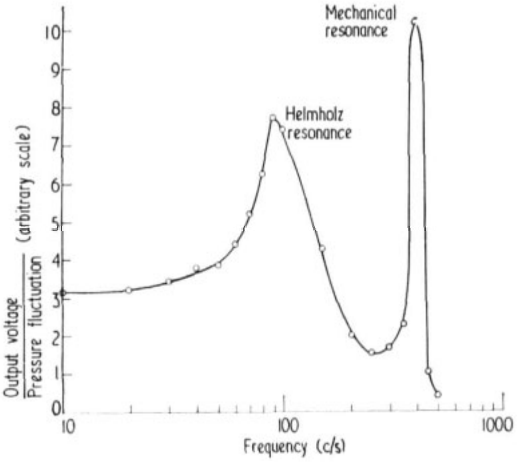


Figure 16. Frequency response of Langham Thompson transducer as purchased; without long Pitot tube.

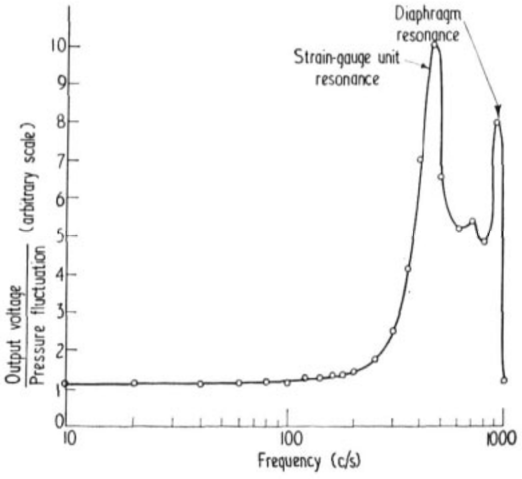


Figure 17. Frequency response of Langham Thompson transducer as modified (figure 6); without long Pitot tube.

0·125 in. diameter union. The calculated Helmholtz frequency is 77 or 146 c/s depending on which part of the connection is regarded as the 'neck'. The 400 c/s resonance may have been the bellows' frequency or a transverse natural frequency of the strain-gauge unit which, according to the manufacturers, occurs in this range. The change to a diaphragm, and the elimination of the large internal volume, eliminated the Helmholtz resonance, as shown in figure 17.

Both figures 16 and 17 refer to the transducer joined to the cavity resonator by only the very short tube. The long Pitot tube, the probe, introduced the organ pipe resonance shown in figure 18 (full line). The acoustic filters alone (chain-dotted line) could not be made to correct the frequency response satisfactorily, so the electrical filters were added to make a further improvement (broken line). Figure 19 shows the frequency response of the final system to a larger scale.

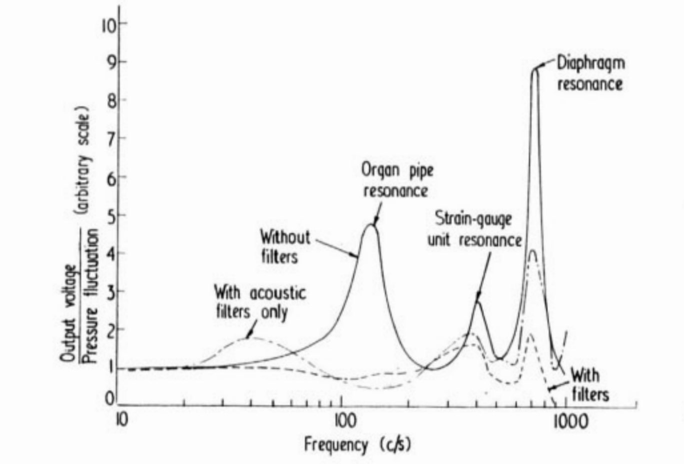
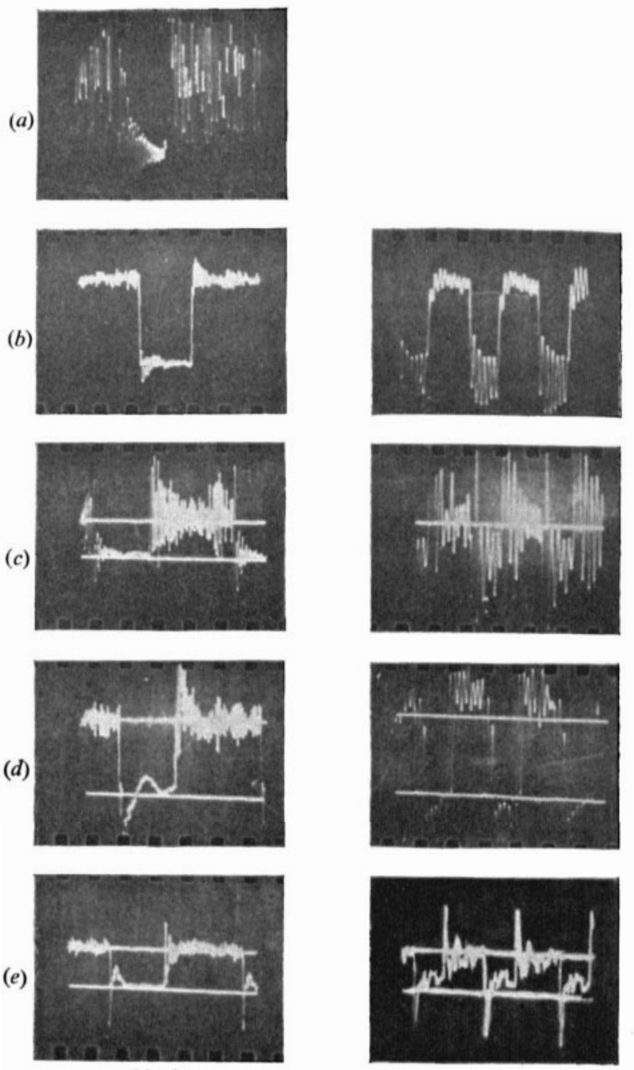


Figure 18. Effect of filters on frequency response. Final version of transducer mounted at end of long Pitot tube.

Figure 20 illustrates the same development from the point of view of square wave response. The top three photographs show how the 400 and 900 c/s resonances affected the response of the transducer before the long Pitot tube was added. The lower six photographs show the contributions made by the various filters. The development is concluded with figure 21. The magnitude of the step change could be



10 c/s 60 c/s

Figure 20. Square wave response of modified Langham Thompson transducer. (*a*) Mounted directly; (*b*) as (*a*) damped by cotton wool; (*c*) mounted at end of long Pitot tube, without filters; (*d*) as (*c*), with acoustic filters only; (*d*) as (*c*) with electrical filters only.

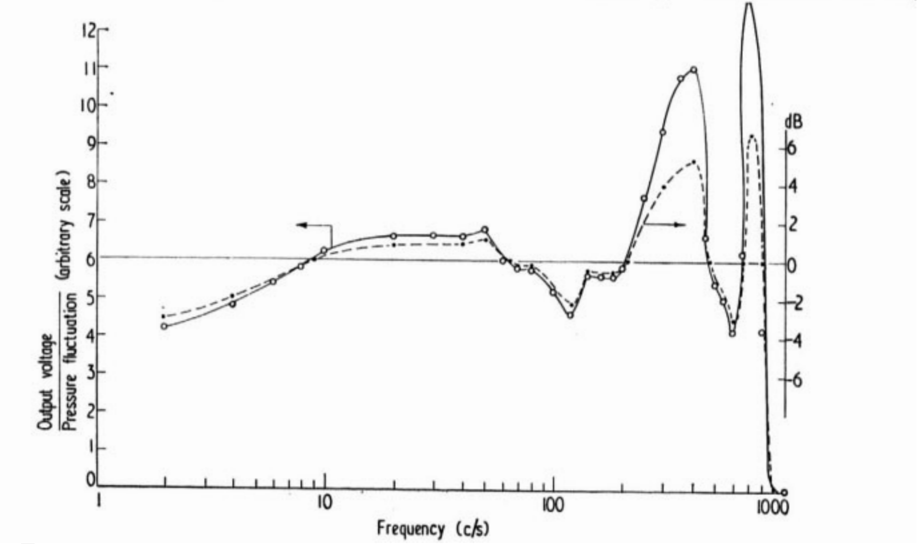


Figure 19. Frequency response calibration. Final version of transducer mounted at end of long Pitot tube.

measured with good accuracy at 60 c/s, and with fair accuracy at 100 c/s. Figure 21(*d*) shows that the noise level introduced by the square wave calibrator was unimportant. This turbulence appears on the upper (higher pressure) step of the square wave response in every photograph. Figure 21(*e*) illustrates the point previously made that the 50 c/s ripple introduced by the 'chopper' drift corrector in the amplifier was negligible. (The 'chopper' was not in circuit in any of the other photographs except (*a*).)

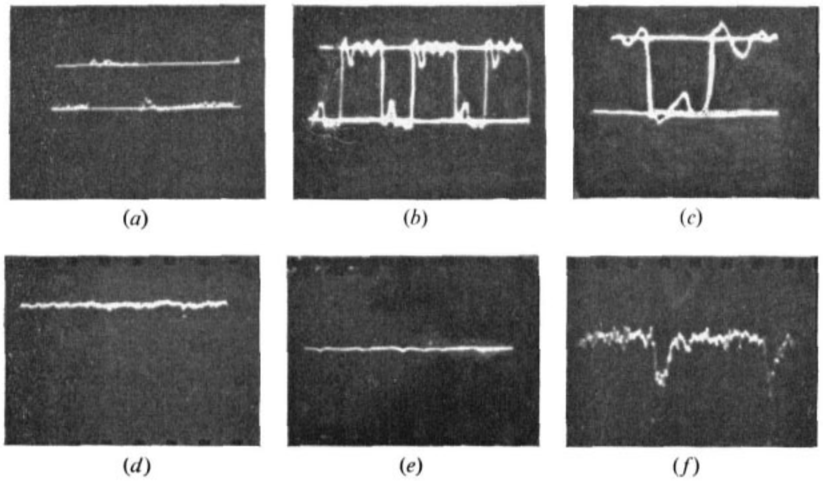


Figure 21. Square wave response of final arrangement of Pitot tube and transducer system. (*a*) 10 c/s; (*b*) 60 c/s; (*c*) 100 c/s; (*d*) turbulence of jet wave calibrator; (*e*) 50 c/s ripple from chopper of d.c. amplifier; (*f*) typical signal, intended application (stall cells in axial compressor).

Figure 21(*f*) shows a typical signal given by a stall cell in an axial compressor; the frequency of these particular stall cells is 38 c/s. It will be seen that the flow is very irregular or turbulent, especially within the stall cell, as would be expected, and this irregularity is more than enough to swamp any remaining defects in frequency response. So although greater attention to detail and a more complex electrical filter could have improved the frequency response, the time and effort involved would not have been justified for this application.

8. Application

The probe has been used to observe stall cells as intended (Dunham 1962) and these are the first reported attempts to make such measurements. They appeared to be consistent and satisfactory, but no direct check on their accuracy is, of course, available.

9. Conclusion

The development of a probe for measuring rapidly fluctuating periodic pressures inside a compressor has been described, and a method of deducing the velocity field from the pressure measurements explained. The probe has subsequently been most useful in pursuing rotating stall research. The general method of design and development has been described, in the hope that it might prove of value to engineers faced with one of the many situations calling for measurements of fluctuating pressure, in an inaccessible place.

Acknowledgments

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References

Binder, R. C., 1951, *Advanced Fluid Dynamics and Fluid Machinery* (London: Prentice-Hall).

Carmichael, A. D., 1958, *Thesis*, Cambridge University.

Dunham, J., 1962, *Aeronautical Research Council Current Paper* 589 (H.M. Stationery Office).

Horlock, J. H., 1955, *Aeronautical Research Council Reports and Memoranda No.* 3031 (H.M. Stationery Office).

Timoshenko, S. P., 1948, *Strength of Materials*, Vol. II, 2nd edn (London: Van Nostrand).

—— 1955, *Vibration Problems in Engineering*, 3rd edn (London: Van Nostrand).

Westley, R., 1958, *Advisory Group for Aeronautical Research and Development Report* 163 (North Atlantic Treaty Organisation).