C.P. No. 1224

C.P. No. 1224

PROCUREMENT EXECUTIVE, MINISTRY OF DEFENCE

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

Dynamic Calibration of Gas Flowmeters

by

K. R. Maslen

Engineering Physics Dept., R.A.E., Farnborough

LONDON: HER MAJESTY'S STATIONERY OFFICE

1972

PRICE *30 p* NET

UDC 681.121.8 : 533.6.011 : 621.317.39 : 531.7.089.6

CP No. 1224 *
March 1971

DYNAMIC CALIBRATION OF GAS FLOWMETERS

by

K. R. Maslen

SUMMARY

A major difficulty in obtaining the dynamic response of flowmeters is assessing the true dynamic flow, since this depends on the pneumatic impedance of the system of which the flowmeter measuring element is part. In this paper, a method is described of obtaining the impedance from the comparison of pressure measurements in a reference system of known pneumatic impedance to which the flowmeter is attached. Experimental results for the impedance of the measuring elements of some viscous resistance type flowmeters for sinusoidal oscillations up to 90 c/s show good agreement with calculation and with steady flow measurements. The response of the sensing transducer must also be taken into account in assessing the overall response. In particular, anomalous results may be obtained if asymmetric transducers are used. The effects of line impedance are also briefly discussed.

* Replaces RAE Technical Report 71048 - ARC 33462

CONTENTS

1 INTRODUCTION

This Report is basically a paper presented to a Symposium on the Measurement of Pulsating Flow, organised by the Institute of Measurement and Control at the University of Surrey in April 1970.

The principles which will be discussed are of general application, and, in theory at least, could be adapted to calibrate dynamically any type of flowmeter for any range of flow or frequency. However, the method has so far been applied to only one type of flowmeter, so it may be as well to start with a description of this type, and of the kind of flow measurements for which it is generally used.

The chief application is to respiratory flow measurement, human or simulated, of air or oxygen, at normal sea level pressure, or at reduced pressure down to about one fifth of an atmosphere. The breathing cyclic time may be anything between 1 second and 7 or 8 seconds, and the peak breathing rates between 20 litres/minute and 180 litres/minute. Good dynamic response is needed because peak flows and rates of change of flow are among the parameters required, and the flow patterns are known to contain components up to at least 30 c/s [1].

2 DESCRIPTION OF FLOWMETERS

The flowmeters used consist essentially of a small viscous pneumatic resistance between pressure averaging manifolds and a sensitive differential pressure transducer connected to the manifolds. Viscous resistances have several advantages in this work, since the pressure drop is linearly related to the volumetric flow, the sensitivity depending only on the geometry of the flowhead and the gas viscosity. Since the viscosity is independent of absolute pressure, this type of flowmeter may be used at reduced pressure without much change of sensitivity, the only corrections required being for temperature and for the viscosity of the gas in use.

Two types of pneumatic resistance, commonly called flowheads, are in general use. The first, originally developed by Fleisch in 1929 and later refined[2] consists of a set of fine tubes in parallel, enclosed in a suitable pipe (see Fig.1a) with pressure averaging manifolds mounted a little way in from the ends. This type is also provided with a heating coil, to prevent condensation and maintain constant temperature when expiratory gas is to be monitored. The flowheads are made in different sizes, so that the pressure drop for the full flow range is about 1 cm water gauge. In the second type, (Fig.1b) the viscous element consists of layers of wire or nylon gauze, the number of gauzes and the shape of the inlets being adjusted to suit different flow ranges. This type of flowmeter was described in detail by Lilly[3].

3 EXPERIMENTAL METHOD AND ANALYSIS

It is convenient in this work to treat pneumatic systems by analogy with electrical circuits. Pressure and flow correspond to voltage and current, and the impedance of a system is given by the ratio of the pressure drop across it to the flow through it. If the pressure is measured in dynes/cm^2, and the flow in cm^3/sec, the unit of impedance is measured in pneumatic (or sometimes, acoustic) ohm, where 1 pneumatic ohm is the resistance of an element in which a flow of 1 cm^3/sec is produced by a pressure drop of 1 dyne/cm^2. In practice, it is generally more convenient to use cm wg for pressure, and litres/sec for flow, and the unit of impedance is then 1 cm wg/(litre/sec), which is about 2% less than the earlier definition.

So long as the wavelength of sound at the frequencies under consideration is large compared with the component dimensions, a smooth rigid pipe may be treated as an inductance and a rigid container as a capacitance, and their values calculated from the dimensions and known physical constants[4]. For viscous flow, resistive terms appear as constant resistors, but with turbulent flow, the resistance will usually vary with the flow.

Using the pressure drop across a pneumatic element to assess the flow in a system is therefore analogous to measuring the current in an electrical circuit by measuring the voltage across a known impedance, and the problem of calibrating a flowmeter dynamically is basically the problem of determining its effective impedance at various frequencies.

The method used was developed in another connection, and has been described in detail in Ref.5. Briefly, a reference system was constructed of pneumatic elements for which the impedance could be calculated. The flowmeter was then attached and the ratio of the pressure at two points in the system was compared when an oscillating pressure was injected into the system. From this, the impedance of the complete flowmeter could be calculated. The next step was to compare the pressure fed into the flowhead with the pressure drop across the pressure averaging manifolds, and hence deduce the effective element impedance.

Fig.2a shows the experimental set-up. The pressure oscillator delivers a sinusoidal pressure wave of frequency up to 90 c/s by the movement of a piston in a 3-litre cylinder. The outlet of the cylinder is connected to a smooth pipe leading to a rigid volume. When the outlet of this volume is closed, we have a Helmholtz resonator with very little internal damping, as can be checked by comparing the pressure at the inlet and in the container by means of the pressure transducers. If the flowmeter is now connected to the container, its impedance at f c/s is given by the formula

$$Z = jf/2\pi f_0^2 C(p_i/p_0 - 1 + f^2/f_0^2) \text{ cm wg/(litre/sec)} \quad (1)$$

where f c/s is the natural frequency of the resonator, and C is the capacitance of the container, calculated from the formula

$$C = (V/\rho c^2)\ (g/1000) \text{ litres/cm wg} \quad (2)$$

where ρ gm/cm^3 is the gas density, c cm/sec is the velocity of sound in the gas, V cm^3 is the volume of the container and p_i/p_0 is the complex ratio involving both amplitude and phase.

The next step, having the impedance of the complete flowmeter, is to compare the pressure drop across it (that is, p_0) with the pressure drop across the measuring element (p_m), and hence obtain the impedance Z_m of the element by the formula

$$Z_m = Zp_m/p_0 \ . \quad (3)$$

It will be noticed that, since only pressure ratios are required, there is theoretically no limit on the transducer response so long as two transducers of similar response are used. The transducers actually used were a pair of SE 70 inductance-type transducers, which gave an output constant in amplitude up to 90 c/s, though a small phase shift was observed. Since the responses were very nearly identical, each test was repeated with transposed transducers to obtain accurate results.

The calculations are only valid so long as they refer to a pure sine-wave, and though the pressure wave produced by the generator is nearly perfect, the addition of the reference system introduces harmonics which distort the wave. This difficulty is overcome by using a Solartron Resolved

Components Indicator which locks onto a signal from the generator shaft, and computes the amplitude of the fundamental (eliminating the harmonics) and its phase to the trigger signal.

4 RESULTS

Fig.3 shows the value of Z_m obtained in this manner for one of the Fleisch flowheads. The separated resistive (x) and reactive (y) components are shown, together with the modulus. The resistive component agrees very well with the steady flow resistance, with a slight apparent increase at the higher frequencies; while the reactance is proportional to the frequency, showing that this is the effect of the gas inertance. The value agrees with the formula for inertance calculated from the dimensions, if it is assumed that 70% of the cross-sectional area is effective. The implication of these results is that with this flowmeter, for a flow F, the indicated flow will be

$$F_i = (F + K\, dF/dt) \qquad (4)$$

where K = 0.0045. If only the amplitude of the flow oscillation is required we need the modulus $|Z_m|$. It will be noted that this has nearly doubled at the top of the range, and, if the frequency were further increased, the reactive component would take over, making the modulus proportional to the frequency.

This particular flowhead with its steady flow resistance of 0.72 ohm has a nominal range of 80 litres/minute. Two other larger sizes are available having steady flow resistances of 0.29 ohm and 0.12 ohm for flows up to 200 litres/minute and 460 litres/minute respectively. It was found that the impedance of these flowheads was of exactly the same form as for the smallest and equation (4) still holds. This was to be expected, since the heads are composed of identical small tubes.

Fig.4 shows similar results for a gauze-type flowhead. Only the resistive component is shown here, since the reactive component was found to be small (less than 5% of the resistive component) throughout the range, and the modulus is scarcely affected by it. The resistive component agrees with the steady flow resistance up to about 40 c/s, but increases by about 30% at higher frequencies. The cause of this increase has not so far been established, but it is thought that it may be due to reduction of the effective area of the gauze interstices.

5 EFFECTS OF TRANSDUCER CHARACTERISTICS

All the measurements described so far were performed with transducers of known high natural frequency, and in each case the connections to the two sides of the flow measuring element were made as short as was reasonably possible, and of equal length. In these circumstances, the flow is given by the pressure drop divided by the impedance. If, however, a transducer of low acoustic frequency is used, or if it is connected to the flowhead by long pipes so that its natural frequency is reduced, errors may occur. Further errors may be introduced if an asymmetric transducer is used, or a transducer made asymmetric by the use of dissimilar connections to the flowhead, and, in this case, the output depends not only on the difference of pressure oscillation on the two sides of the element, but also on the mean level. It is easy to see in general terms why this should be so.

For example, if an abrupt change of pressure occurs simultaneously on the two sides of the pneumatic resistance, there will be no resultant flow. But, if the two sides respond differently, there will be a transient differential pressure across the transducer producing an apparent transient flow.

Analysis of the effect is, however, rather complicated, even in a simplified case.

Suppose the mean amplitude is p, and the amplitudes at the two ends of the flowhead are $(p \pm q)$, and consider the simple case when the two sides of the transducer with their connecting pipes may be considered as undamped Helmholtz resonators of natural frequencies f_1 and f_2. Then the pressure difference across the diaphragm at f c/s is given by

$$\begin{aligned} p_m &= (p + q)/(1 - f^2/f_1^2) - (p - q)/(1 - f^2/f_2^2) \\ &= q[1/(1 - f^2/f_1^2) + 1/(1 - f^2/f_2^2)] \\ &\quad + p[1/(1 - f^2/f_1^2) - 1/(1 - f^2/f_2^2)] \; . \end{aligned} \tag{5}$$

In other words, the sensed pressure difference will not be independent of the mean pressure unless the two sides of the transducer respond identically so that the second term of equation (5) disappears. Fig.5 shows the effect when a very sensitive asymmetric transducer (Statham ±0.05 psi) is used with a Fleisch flowhead. The curves show the amplitude response when the end of the flowhead is open to atmosphere (p a little larger than q), and with an added resistance ($p \approx 10q$), with the input and reference sides of the transducer upstream in each case. It will be seen that the response increases at very low frequencies, and there are large differences between the four cases especially in the region of 60 c/s where there may be a factor of 20 between different conditions. Some improvement could be affected by adjusting the connections to the two sides of the transducer to bring them both to the same natural frequency, but there still remains the problem of matching the damping, which may not be easy if a moderate length of piping is needed to match the frequencies. The conclusion must be that if a high frequency response is required, a basically symmetric transducer must be used even if this results in reduced sensitivity.

6 EFFECTS OF DIFFERENT SYSTEMS

Another point which is not always appreciated is that the flow passing through a flowmeter does not necessarily give the dynamic flow at other parts of the system. Some possible effects are shown in Fig.6. Two flowmeters of similar characteristics were arranged in series, either directly, or with intervening systems, and the amplitude ratio of the downstream to upstream flow was measured. With no intervening or downstream system, the ratio was approximately unity throughout the range. Curves 1 and 2 of Fig.6 show the effect of a rigid 3-litre can and of a yard of corrugated hose fitted between the flowmeters, and curve 3 shows the effect of the same hose fitted downstream of the second flowmeter. With the rigid can, the results show the effect of the combination of the impedances of the can and the downstream flowmeter, and calculations agree fairly well with experiment. The flexible pipe was too long to allow the use of simple lumped theory, and moreover, its impedance depends not only on the pneumatic but also on the mechanical characteristics, and both of these may be changed by arranging the pipe differently. The general form of the results suggests that in both of these cases there is an organ-pipe type of system, with shifting nodes and anti-nodes.

7 CONCLUSION

A method of calibrating gas flowmeters dynamically by measuring their impedance in oscillating flow has been described. The results discussed here have all been obtained with zero mean flow, but they should apply for any mean flow in the flowheads so long as the peak flow does not produce turbulence. It would obviously be desirable to establish the limits of laminar flow by tests with various mean flow rates and various flow oscillation amplitudes, and, if the method were extended to non-linear elements such as orifices, the response would have to be established for a number of mean flow and flow oscillation combinations. But there seems to be no fundamental reason why the method should not be so extended. Alternatively, a viscous type flowmeter might now be carefully calibrated, and then used as a standard to calibrate other flowmeters.

REFERENCES

No.	Author(s)	Title, etc.
1	Donald L. Fry, *et al.*	Evaluation of three types of respiratory flowmeter. J. Appl. Physiol., 10, pp.210-216, March 1957
2	A. Fleisch	Le Pneumotachographe. Helv. Physiol. Acta, 14, pp.363-368 (1956)
3	John C. Lilly	Flowmeter for recording respiratory flow of human subjects. Methods in Medical Research, 2, Year Book Publishers Inc., Chicago (1950)
4	Harry F. Olson	Dynamical Analogies. Van Nostrand Co. (1943)
5	K.R. Maslen G.F. Rowlands	A new method of measuring the impedance of the human respiratory system at moderate frequencies. ARC CP 1031 (1966)

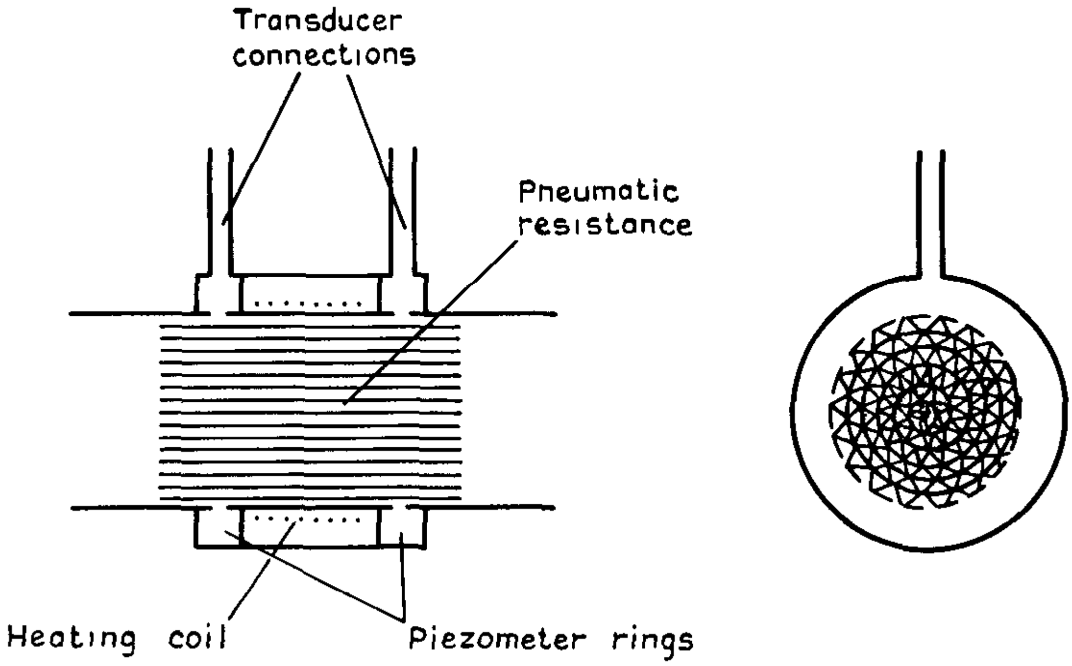

Fig.1a Fleisch flowhead

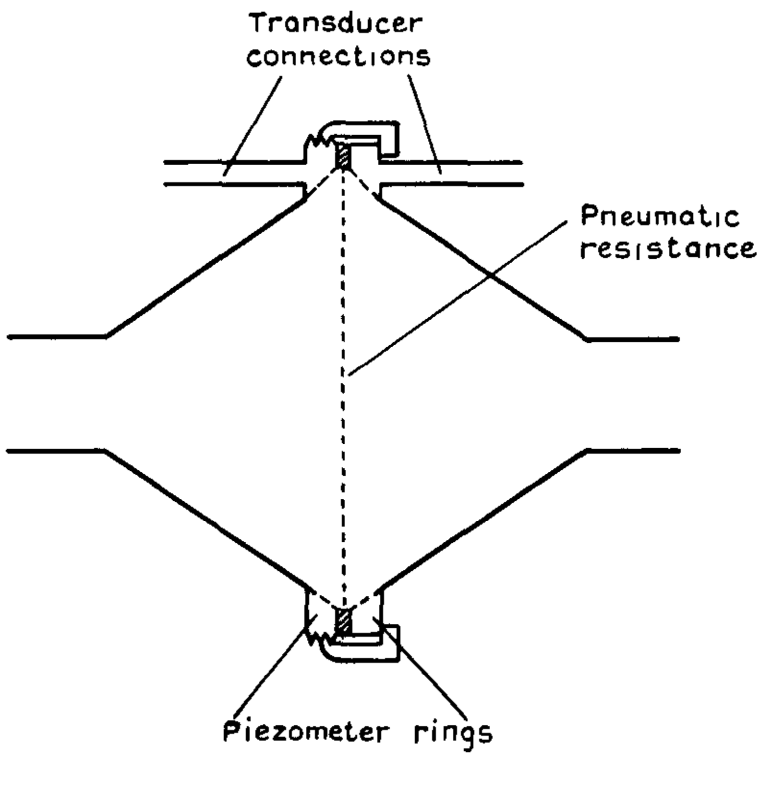

Fig.1b Gauze flowhead

$$f_o^2 = 1/LC$$

$$z = jf/2\pi f_o^2 C(p_i/p_o - 1 + f^2/f_o^2)$$

$$z_m = z p_m / p_o$$

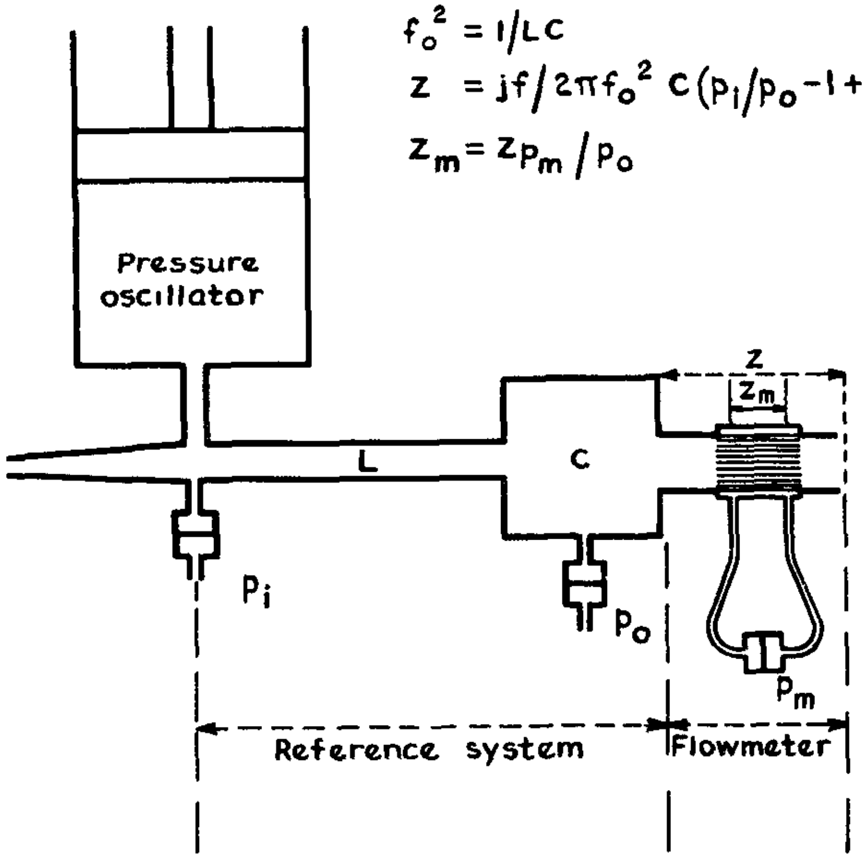

Fig.2a Experimental method

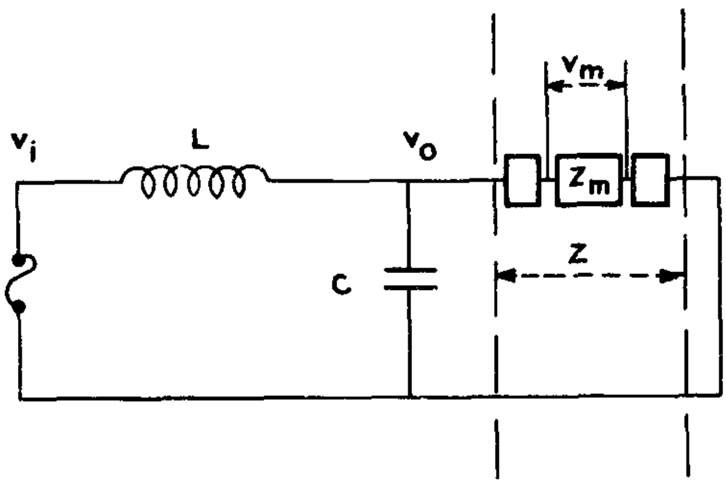

Fig.2b Electrical analogue

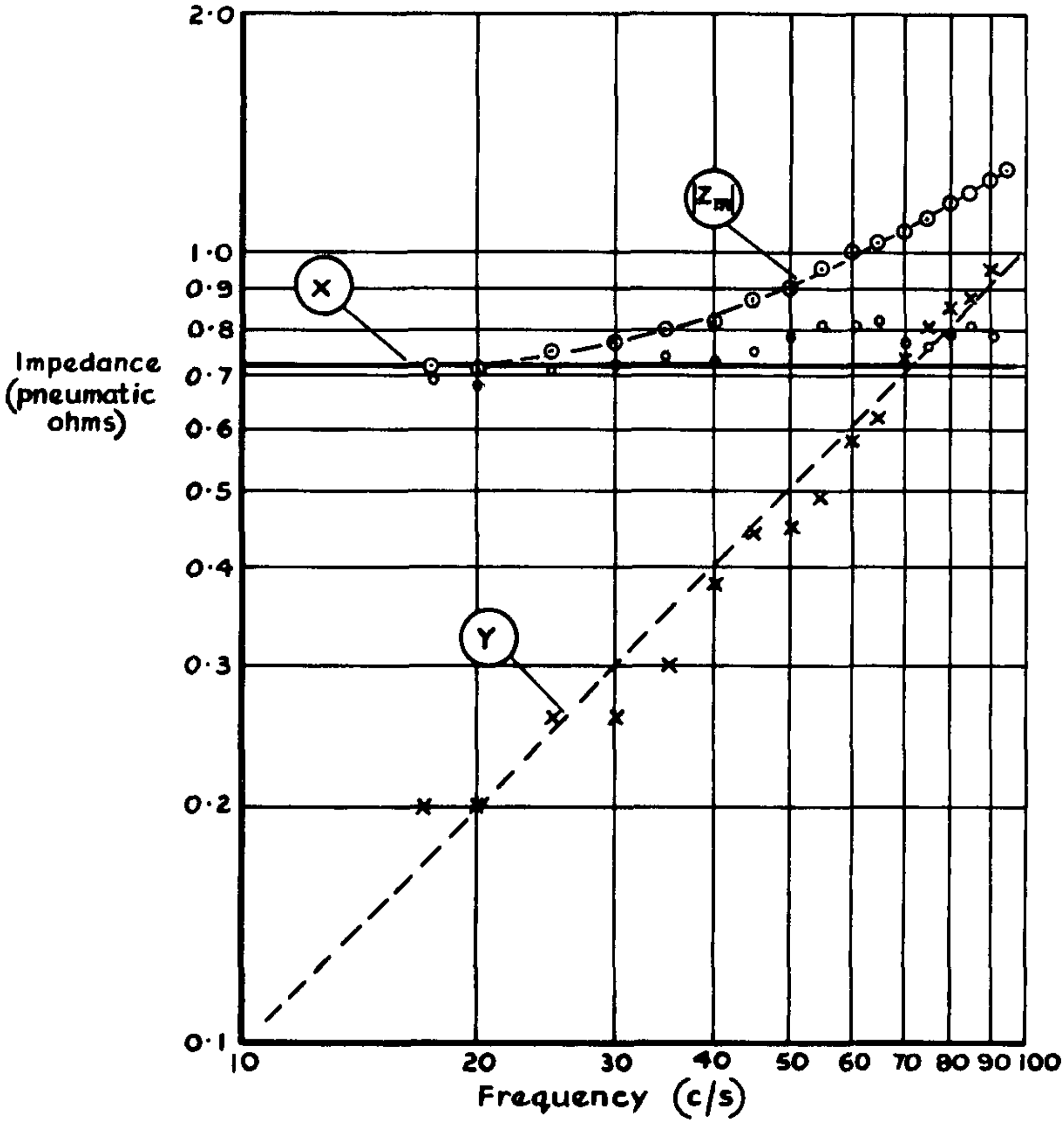

Fig.3 Impedance of Fleisch flowhead

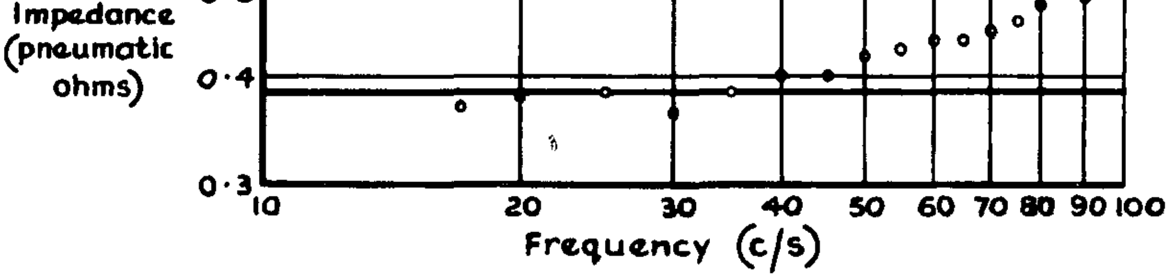

Fig.4 Impedance of gauze flowhead

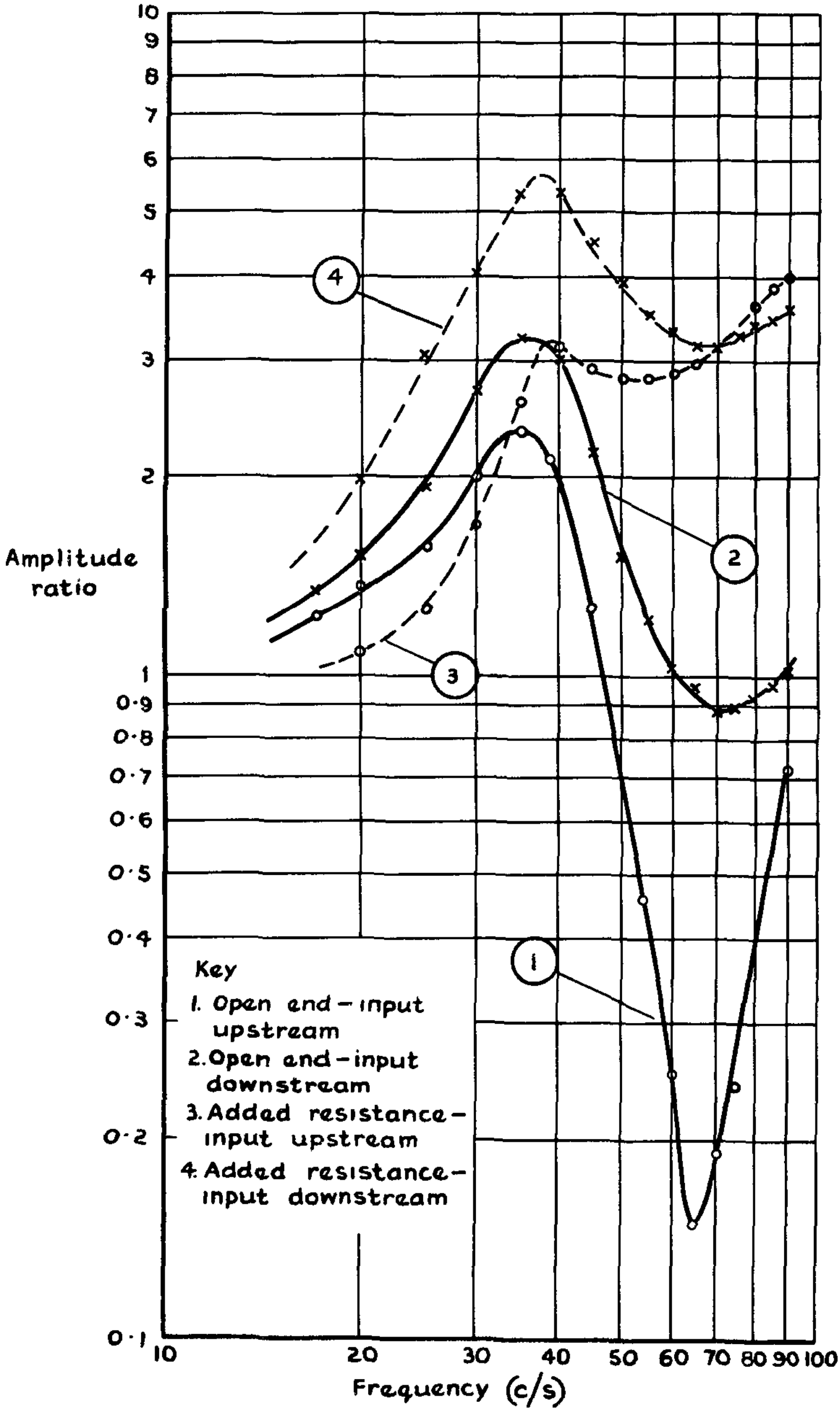

Fig.5 Sensitivity with asymmetric transducer

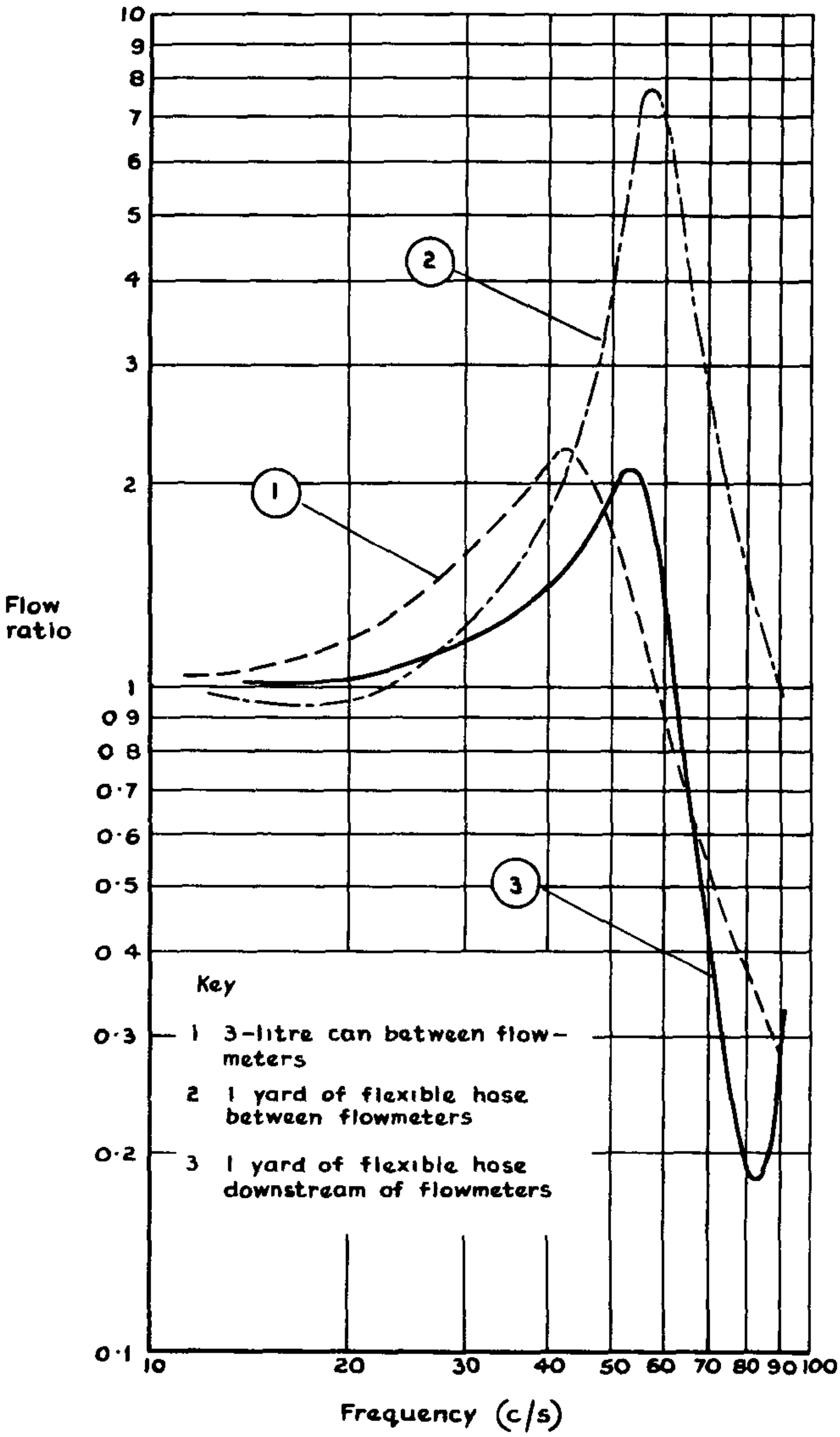

Fig.6 Effect of added system on flow

Printed in England for Her Majesty's Stationery Office by the Royal Aircraft Establishment Farnborough Dd 503427 K4

ARC CP No 1224 | 681 121 8
March 1971 | 533.6 011
 | 621 317 39
Maslen, K R. | 531.7 089.6

DYNAMIC CALIBRATION OF GAS FLOWMETERS

A major difficulty in obtaining the dynamic response of flowmeters is assessing the true dynamic flow, since this depends on the pneumatic impedance of the system of which the flowmeter measuring element is part In this paper, a method is described of obtaining the impedance from the comparison of pressure measurements in a reference system of known pneumatic impedance to which the flowmeter is attached Experimental results for the impedance of the measuring elements of some viscous resistance type flowmeters for sinusoidal oscillations up to 90 c/s show good agreement with calculation and with steady flow measurements. The response of the sensing transducer must also be taken into account in assessing the overall response In particular, anomalous results may be obtained if asymmetric transducers are used The effects of line impedance are also briefly discussed

These abstract cards are inserted in Technical Reports for the convenience of Librarians and others who need to maintain an Information Index.

Detached cards are subject to the same Security Regulations as the parent document, and a record of their location should be made on the inside of the back cover of the parent document.

Cut here

ARC CP No.1224 | 681 121.8
March 1971 | 533 6.011
 | 621 317 39
Maslen, K R. | 531 7.089 6

DYNAMIC CALIBRATION OF GAS FLOWMETERS

A major difficulty in obtaining the dynamic response of flowmeters is assessing the true dynamic flow, since this depends on the pneumatic impedance of the system of which the flowmeter measuring element is part. In this paper, a method is described of obtaining the impedance from the comparison of pressure measurements in a reference system of known pneumatic impedance to which the flowmeter is attached Experimental results for the impedance of the measuring elements of some viscous resistance type flowmeters for sinusoidal oscillations up to 90 c/s show good agreement with calculation and with steady flow measurements The response of the sensing transducer must also be taken into account in assessing the overall response In particular, anomalous results may be obtained if asymmetric transducers are used. The effects of line impedance are also briefly discussed

ARC CP No 1224 | 681.121.8
March 1971 | 533.6.011 .
 | 621.317.39
Maslen, K R. | 531.7.089.6

DYNAMIC CALIBRATION OF GAS FLOWMETERS

A major difficulty in obtaining the dynamic response of flowmeters is assessing the true dynamic flow, since this depends on the pneumatic impedance of the system of which the flowmeter measuring element is part. In this paper, a method is described of obtaining the impedance from the comparison of pressure measurements in a reference system of known pneumatic impedance to which the flowmeter is attached. Experimental results for the impedance of the measuring elements of some viscous resistance type flowmeters for sinusoidal oscillations up to 90 c/s show good agreement with calculation and with steady flow measurements. The response of the sensing transducer must also be taken into account in assessing the overall response. In particular, anomalous results may be obtained if asymmetric transducers are used. The effects of line impedance are also briefly discussed.

Cut here

DETACHABLE ABSTRACT CARDS

DETACHABLE ABSTRACT CARDS

C.P. No. 1224

HER MAJESTY'S STATIONERY OFFICE

Government Bookshops

49 High Holborn, London WC1V 6HB
13a Castle Street, Edinburgh EH2 3AR
109 St Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester M60 8AS
50 Fairfax Street, Bristol BS1 3DE
258 Broad Street, Birmingham B1 2HE
80 Chichester Street, Belfast BT1 4JY

Government publications are also available through booksellers

C.P. No. 1224

SBN 11 470782 0