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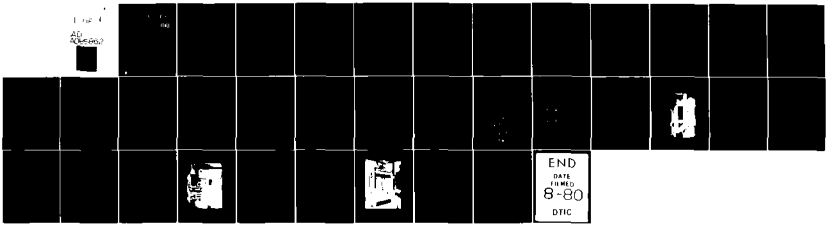

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TESTS ON PNEUMATICALLY POWERED PRECISION FORCE GENERATORS

by

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SUMMARY

An assessment has been made of the performance of two different types of pneumatic force generator, covering forces up to a 100 kN, with a view to their use in balance calibrations in the RAE 5m wind tunnel. This Report describes tests performed on the force generators using a precision pneumatic control system firstly in conjunction with a static weighbeam test rig, followed by a series of tests to check the overall accuracy of performance against the 'dead-weight' Force Standard Machines at NPL Teddington.

It has been shown that force generators using a rolling diaphragm seal can produce forces to an accuracy within 0.01% of maximum output assuming a linear calibration. Individual values of force output could be repeated to 0.003% of maximum output when checked against a simple weighbeam under fixed experimental conditions.

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LIST OF CONTENTS

013

1 INTRODUCTION

Calibration of wind tunnel balances, which has traditionally been carried out using a mass and pulley system, has become a relatively cumbersome part of the operation of modern wind tunnels. The development of the new 5 m tunnel at RAE Farnborough has provided a compelling need for an automatic calibration facility for high-load strain gauge and mechanical balances. This report details the development and assessment of a pneumatic force generator which has formed the basis of a balance calibration machine for use in the 5 m tunnel[1]. By avoiding application of unwieldy deadweights and by controlling the machine through one of the computers of the tunnel data acquisition system, balance calibration time has been greatly reduced, enabling more frequent calibrations and giving a greater confidence in model force measurements.

The feasibility of such an automatic calibration system stems from the advent in the 1960s of commercially available high precision pressure gauges and controllers based on the application of pressure sensing elements made of fused quartz. It was thought that these instruments could be used to drive low stiffness pneumatic actuators, or force generators, to provide accurate control of large forces by precision control of gas pressure input. A scheme to employ pneumatic force generators as elemental parts of an automatic calibration system was planned.

Experimental work associated with testing force generators to 50 kN force was started at RAE Bedford in May 1971. Two main types of force generator were built (A and B), both based on a freely moving piston supported in a pressurised housing. The first type (Fig 1) used a fabric-reinforced-rubber rolling diaphragm seal between the piston and the cylinder and the second type (Fig 2) employed a flexible steel bellows for this purpose. Both unidirectional and bidirectional versions of the first type were made and a larger (100 kN) bidirectional version of the rolling diaphragm force generator was built and tested.

A pneumatic control system for the supply of air to the force generators was designed incorporating a fused quartz precision differential pressure gauge and controller. The pressure range used for test purposes was up to 2 MPa for the smaller generators and 1.5 MPa for the larger generators.

A single channel weighbeam test rig was developed for comparative assessment
013 of force generator performance, and in addition some tests were carried out in
the NPL 50 kN and 500 kN force standard machines.

Specific tests were performed on the generators to examine the effects of temperature changes, to expose and control non linearity and hysteresis and to establish their repeatable performance in their likely working conditions.

The principal objective of the present tests was to develop a force generator which was capable of achieving a level of accuracy of developed force within 0.01% of its full scale output. This standard of accuracy for this primary element was judged to be that necessary to guarantee the loading accuracy of a typical calibration machine set up to within ±0.05%. The accuracy of the force standard machine at NPL is ±0.004% of load[2] and the mechanical repeatability of the precision pressure controllers used with the force generators is better than ±0.001% of full scale. Thus if each force generator were uniquely associated with a given pressure controller during calibration and subsequent use, the 0.01% requirement ought to be met without great difficulty. Under these conditions no recourse would be made to primary calibration of the pressure controller, all force calibrations being performed in terms of pressure controller readings.

However in order to check the general behaviour of the pressure controllers some time was spent examining their repeatability against primary pressure standards which at best can give a practical accuracy of 0.01% of reading.

2 DESCRIPTION OF THE TEST FACILITY

2.1 Types of force generator

2.1.1 The rolling diaphragm type (Types A1, A2, A3)

Initially a single acting force generator (Type A1) was developed consisting of a steel cylinder having a piston supported by a shaft passing between sets of recirculating linear ball bearings. The piston of diameter 152.4 mm was arranged to move within the steel cylinder of diameter 165.1 mm, the gap between the two being sealed with a commercial fabric-reinforced rubber rolling diaphragm. The diaphragm was installed to form a U shaped loop in the annular space between the piston and cylinder walls. The effective piston diameter should be approximately the diameter described by the mid-point of the space between the piston and cylinder and represented by the centre of the convolution of the rolling diaphragm. This diameter should remain constant except for the normal elastic deformation of the cylinder under pressure, thus giving a nearly linear output of force from the piston with respect to pressure. In the case of the single-acting generator, the cylinder was the fixed part with the piston moving relative to it and having 013
internal stops. Gas admitted at a controlled pressure to the space behind the diaphragm seal thus produces a force proportional to the pressure level and the

effective area of the piston; in the present case the maximum force output was 50 kN at a gas input pressure of approximately 2 MPa.

A double-acting force generator (Type A2) shown in (Fig 1) was developed as a result of experience gained from initial tests and modified to be more representative of the requirements of a calibration machine in that it was capable of generating bidirectional forces. The internal dimensions were the same as those for the single-acting version but differed in that it incorporated a double-ended piston with two diaphragm seals acting in opposition. In this design the piston was the fixed part through which pressurised air could be admitted via drilled passages to the cylinder appropriate to the required direction of the output force. As before the piston was guided by linear recirculating ball bearings mounted within the body casing of each cylinder. A 100 kN double-acting force generator (Type A3) of similar design was subsequently built and this incorporated a 292.1 mm diameter piston having the same radial clearance as the 50 kN unit to accommodate the piston seal diaphragm.

2.1.2 The sealed bellows type (Type B)

This force generator (Fig 2) was of a design and force range similar to the single acting rolling diaphragm type except that the piston (of 152.4 mm nominal diameter) was welded around its circumference to a convoluted steel bellows seal. The free end of the bellows seal, which was about 150 mm long and incorporated 20 convolutions, was welded to a flange attached to the cylinder. In order to sustain the pressure loads the bellows had to be of fairly substantial construction, and hence it was fabricated from a stainless steel tube with a wall thickness of 0.46 mm, with the result that it had a fairly high spring rate of 170 kN/m extension. If such a force generator were used in an application which allowed some piston movement the output force would be diminished compared to that calculated on a simple piston area basis. Compression and extension of the convolutions will also effect small changes in their major and minor diameters and hence in the effective area of the piston. This latter parameter, usually taken as the mean area is defined empirically by the relation:

$$\text{Effective area} = \frac{\pi}{4}(R_{in} + R_{ex})^2$$

However a more rigorous analysis[3] taking into account end effects, gives the effective area of such a bellows as :

013

$$\text{Effective area} = \frac{\pi}{3}(R_{in}^2 + R_{in}R_{ex} + R_{ex}^2)$$

R_{in} = internal diameter $\qquad$ R_{ex} = external diameter

2.2 The pneumatic pressure system (Fig 3)

The control of pressurised gas to the force generators was achieved by a commercial servo-driven precision pressure regulator used in conjunction with a precision pressure gauge. The pressure gauge consists of a fused-quartz Bourdon tube which when pressurised rotates and deflects light on to an optically-sensitive transducer which generates an electrical error signal. The servo control system of the pressure regulator then drives the regulator valve until the output pressure is such that a null signal results from the error sensor in the pressure gauge. For optimum performance the pressure gauge and controller characteristics need to be carefully matched and the output volume has to be controlled to about 1 litre to match the design conditions of the pneumatic controller. The desired differential pressure output from the controller is obtained by setting a mechanical counter on the pressure gauge. When the gauge alone is used it is disconnected from the servo controller but the same counter provides the readout.

Air was supplied from standard high pressure cylinders and its pressure was reduced by a manual regulator to the appropriate level for input to the precision control system. For the force generators tested the maximum output pressure required was 2 MPa. The pressure control equipment had a resolution of 160000 counts for full scale output (2 MPa) and a full scale repeatability of better than 0.001% when used under the conditions for optimum performance. The gauge was calibrated against a piston-type primary pressure standard of absolute accuracy 0.015% of reading. A linear interpolation method was used to provide pressure settings as required between the 30 calibrated points. It was assumed that the slight volumetric changes occurring in the force generator due to the movement of its piston would not adversely affect the performance of the pressure controller. Valves were provided for opening the generator diaphragms to atmosphere when necessary and inputs were provided for an additional quartz gauge to monitor the actual achieved pressure at the piston face.

A manual precision control valve was provided for the supply of a backing pressure to the second diaphragm in force generator Types A2 and A3 for certain tests, and the system included on/off valves to allow the backing pressure to be applied to the gauge reference if required.

2.3 The weighbeam test rig (Fig 4)

A specially designed weighbeam rig was used for assessing comparative 013
performance of the force generators. The test rig consisted of a substantial steel frame supporting a system of levers acting about flexured pivots and connected to a weighbeam. Each force generator under test was mounted in its

own support cradle at one end of the frame and the force developed was applied to the main lever arm through a flexured steel link. The point at which the force generator acts on the main lever arm was close to the pivot attached to the main frame, to reduce the load in the weighbeam to manageable proportions. The connections between the lever arm and the weighbeam were also of the flexure type.

The weighbeam leadscrew of 2.54 mm pitch and 5.08 mm lead was driven directly by a 200 steps/rev stepper motor giving an overall resolution of one part in 50000. A position transducer on the weighbeam indicated its 'null' position. A rider weight of mass 3.63 kg with three additional 3.63 kg weights was driven by the weighbeam leadscrew. The sensitivity and load range could be changed by adding to the mass of the rider weight, and counterbalancing weights were fitted to retain full travel of the weighbeam.

For dead load calibration of the weighbeam itself knife edges were fitted at two positions on the main lever arm, giving alternative mechanical advantages for the weighbeam relative to load. The main lever arm was equipped with sliding adjusting weights to counterbalance the weight of the scale pan and the unbalanced loads in the lever system.

2.4 The force standard machines at NPL

The 50 kN force standard machine at NPL Teddington was used for tests and primary calibrations on both A2 and B types of force generator. This machine is a dead-weight loading device consisting of a fixed platen, on which the force generator stands in its cradle, and a moveable upper platen fixed to a yoke. Rods attached to the yoke go through the machine base to a scale pan and weight stack system, enabling the chosen increments in load to be applied between the lowest consisting of the mass of the yoke and scale pan assembly, and the full machine rating to be applied. A steel balljoint or multiple flexure assembly was placed between the moveable part of the force generator and the upper platen to transmit the load without introducing an interactive couple.

The 500 kN force standard machine used to calibrate the Type A3 force generator, is similar in design to the 50 kN force standard machine except that incremental loading is not possible in the larger machine. After each loading action the masses have to be removed from the scale pan and replaced in their carriers in the load stack before the control system can select the masses required for the next loading.

3 INITIAL TESTS ON THE WEIGHBEAM TEST RIG

3.1 Introduction

Before embarking on tests on the Type A1 force generator, the weighbeam test rig was calibrated with dead loads to check linearity and response over the load range. An absolute calibration of the rig was not required as it was only intended to give a comparative assessment of results. Some appreciation was necessary of the resolution and the ability of the rig to produce consistent results. Dead load tests showed repeatability within the limits of the knife edge loading arrangement and revealed reproducible non-linearity of approximately 0.02% of full scale.

For the initial tests on the Type A1 force generator, the cylinder was bolted to the frame of the rig, and the piston connected via the flexured link to the main lever arm (Fig 4). The weighbeam was set up so that the maximum force generator output commanded a full range travel on the weighbeam. Before commencing the test, the diaphragm was pre-loaded pneumatically to a point beyond the maximum envisaged for that test to ensure that it was correctly aligned and positioned in its proper working condition. The force generator was then vented to atmosphere to establish the true zero pressure conditon.

The test procedure consisted of setting up a known pressure and measuring the force output on the weighbeam. A series of readings in terms of weighbeam counts for different pressures was taken typically at increments of 69 kPa starting at zero pressure and going up to a full scale value of 2 MPa, then returning decrementally by the same pressure points to zero thus completing a cycle. A second quartz gauge which had been calibrated against the same primary pressure standard and at the same time as the control instrument, was used to check that the pressure levels actually achieved in the force generator were the same as those demanded. Tests in this manner were performed on all the force generators, although the force generator (Type A3) could not be loaded to its full output, because of the range limitation on the weighbeam rig.

3.2 Results of initial tests on the weighbeam rig

The initial tests on the Type A1 force generator produced results which, when plotted as a distribution of weighbeam counts against true applied pressure (to expose non-linearity and hysteresis) produced an unexpected cyclic waveform recurring at pressure increments of approximately 100 kPa (Fig 5). The non- 013
linearity was generally within 0.02% of full scale and there was also some hysteresis present which gave errors of the order of 0.01% of full scale. It was also observed that the force output at constant pressure was varying by up to 0.02%

in the course of these tests, an effect which was later shown to be entirely due to variations in the mean working temperature of the rig (section 4.4).

Tests using the Type B force generator following the procedure outlined above also produced similar results as before but gave an error distribution characteristic with higher non-linearity of 0.04% of full scale and lower hysteresis of 0.005% of full scale. The same high standard of repeatability of the results which characterised the tests on the Type A1 force generator (Fig 6) was also observed in these tests.

Tests on the Type A2 force generator using both diaphragms in turn gave results which were almost identical with those of the single acting type (Fig 8) except for small differences in force output attributable to slight variations in piston diameters. The second (unused) diaphragm did not seem to adversely affect results while the other diaphragm was operative, as was demonstrated by applying a constant pressure (100 kPa) to the second diaphragm whilst the working piston was being operated at the same pressure differences between the pistons as for the earlier tests. The results from this exercise are almost identical to those achieved when the unused piston and diaphragm were vented to atmospheric pressure.

The Type A3 force generator was later tested over a reduced range on the weighbeam. A cyclic test revealed hystersis of 0.01% of full scale, and non-linearity consistent with that achieved over the same range for the Type A2 force generator (Fig 12).

4 SOME FEATURES REVEALED BY TESTS USING THE WEIGHBEAM RIG

4.1 The cyclic waveform

The cyclical nature of the error pattern observed and noted in 3.2 might be expected to arise from any one of four main causes.

(a) The interpolation method used for determining the correct gauge setting for pressures other than those corresponding to the primary pressure calibration instrument.

(b) Pitch errors in the pressure gauge drive gearing.

(c) Striations in the optical window of the Bourdon capsule in the pressure gauge.

013

(d) A pattern induced by the weighbeam rig itself perhaps by pitch errors in the leadscrew.

A number of tests were carried out in an effort to pinpoint the source of the observed peculiarities.

The interpolation method was examined and thought not to be responsible for the cyclical error pattern. Nevertheless, the pressure gauge was recalibrated at 17.25 kPa intervals and a further test performed on the Type A1 force generator using the weighbeam. A plot of the results identified even more clearly the waveform superimposed on the results, since the pressure increments were small compared to the pitch of the error waveform. The pressure controller was then re-calibrated against a different primary pressure standard, as it was thought possible that the origin of the observed pattern could lie in the standard weights which are used with this instrument and applied sequentially in a closely-defined system of combinations. Subsequent tests showed that the error pattern was completely undisturbed. The monitor gauge also recorded the waveform exactly, as plots of its output against weighbeam counts revealed.

The mechanical gearing in the pneumatic controller counter was then investigated to check for eccentricity in one of the gears but none of the possible resulting angular errors affecting counter rotations were found to coincide with the observed cyclic frequency of errors.

A new optical cover glass for the Bourdon tube in the precision pressure controller was fitted, this cover having been ground internally and externally to minimise 'lensing' due to surface irregularities. Again no corresponding improvement was observed.

It was concluded that the origin of the waveform could not lie in the force generator itself since the steel bellows generator gave the same result. Furthermore, attempts at interrupting the waveform by beginning tests at a false zero, that is starting with a pre-determined pressure on the diaphragm for the initial weighbeam reading and returning to the same point, did not affect the waveform at all.

Further tests using different rider weight masses to vary the weighbeam sensitivity were carried out to try and establish a relation between the errors and the positional changes of the rider, but no such relation could be found. It was concluded that the leadscrew was not at fault in terms of cyclical variations in its screw pitch.

In view of all this the origin of the waveform remains unresolved especially as the tests on the NPL force standard machines did not reveal a waveform as 013
repeatable, or of the same frequency as for the weighbeam tests (section 5.3).

4.2 Hysteresis and friction

The hysteresis demonstrated by the rolling diaphragm generators was investigated and it was thought that there were two factors involved, one of which was mainly related to movement and the other which was attributable to the non-homogeneous nature of the diaphragm material. It was accepted that there might be difficulties in separating the two factors quantitatively, but it was hoped that a method of reducing the hysteresis would be found. It was a certainty that the diaphragm material would stretch when loaded and would slide in an irregular manner over the surfaces of the piston and cylinder. These two items were therefore coated with a thin layer of PTFE, but subsequent tests on the generator with this treatment showed no significant changes from previous results.

Static compression tests on the rubber-fabric material used in the diaphragm indicated that although a smooth non-linear deformation pattern resulted from imposed loading cycles, the recovery on removing the load took place at a much lower rate than when the load was increased. Although this revealed a possible source of hysteresis it was not evident how this could be transformed to affect the results of the present tests.

Reduced load range tests also showed no significant reduction in hysteresis except for a small reduction near the full scale value. Similarly the application of a backing pressure to the second unused diaphragm did not vary the pattern.

The small axial movement of the force generator piston caused by the action of the weighbeam was shown not to be instrumental in producing any effects which might be due to the diaphragm adhering and separating from the piston and cylinder walls during the loading action. This was demonstrated firstly by introducing a lower spring rate into the linkage connecting the force generator to the weighbeam to induce exaggerated piston movements, and secondly by deliberately reducing such such movements by limiting the weighbeam movement between its stops. Careful analysis of results showed no change in the observed hysteresis.

However, hysteresis was reduced when tests were performed with a deliberate overshoot of pressure in the same sense as the pressure change. Thus each calibrated point was reached, with respect to load and pressure, in the opposite direction from that normally approached. Force measured at these overshoot points
013 showed exactly the same amount of hysteresis as in the earlier tests (Fig 7).

4.3 Non-linearity

The weighbeam test rig in the form used to test these force generators was by no means an absolute device and much of the non-linearity observed in calibrations could have been attributable to defects in this apparatus, as had been indicated by the original dead weight calibration. Some mention of the non-linearity observed during tests is necessary, making comparative tests more meaningful, particularly as the linearity error is close to the accuracy required.

Non-linearity observed when testing the rolling diaphragm force generators was of the order of 0.02% of full scale value (Fig 8) and was repeatable, whereas the tests on the sealed bellows force generator gave repeatable non-linearity of 0.035% of full scale value (Fig 6). This higher non-linearity was attributed to a change in shape of the bellows resulting in minor changes in piston area.

The repeatability of all these test results was of a very high order in that it was always possible to repeat the force demands to within a maximum tolerance of 1 part in 20000 of the full scale over a prolonged period of testing. This was undoubtedly helped by operating the force generators under closely controlled restraints giving near-zero piston travel.

4.4 Temperature effects

Force generators using a simple piston and cylinder arrangement as described in this Report will be susceptible to variations in piston area due to temperature changes. These may arise from two causes, a long term effect related to ambient temperature changes, and a short term change arising from adiabatic heating and cooling of air in the cylinder during pressure changes. Assuming the coefficient of expansion for steel to be $11.00 \times 10^{-6}/^{\circ}C$ the former would be expected to result in a piston area change of 0.0022% per $^{\circ}C$ whilst calculations showed that the latter effect would be smaller by about two orders of magnitude and therefore negligible.

The effects of changes in ambient temperature were checked by enclosing the force generator in a temperature controlled chamber while calibrations were performed on the weighbeam rig over a limited force range of 0 to 36 kN. Tests were carried out at fixed temperatures between $17^{\circ}C$ and $38^{\circ}C$, the force generator temperatures being measured by thermocouples embedded in the piston and cylinder.

Fig 9 gives the results of these tests in the form of a graph showing the change in force generator output with temperature at constant input pressure, and as can be seen the mean slope of this graph confirms the theoretical value for the expansion of the materials of construction of the force generators. The scatter of actual end points of results about the mean line on the temperature against force graph gives a direct indication of the accuracy of the whole experiment. The results were all within 0.007% of full scale as measured from the mean giving a standard deviation of approximately 0.002%.

5 TESTS ON THE NPL FORCE STANDARD MACHINES

5.1 General description

The object of these tests was twofold, firstly to establish an absolute calibration for each force generator and secondly to examine any stiffness and hysteresis effects related to positional changes in the force generator at balance. The Type A2 rolling-diaphragm force generator and the sealed bellows force generator (Type B) were both tested on the 50 kN force standard machine and the Type A3 rolling-diaphragm force generator was tested to its full load in the 500 kN force standard machine. A foreseeable problem with this type of test concerned the nature of the NPL force standard machines in which the force generators are required to lift and support freely suspended masses in a deadload system with no spring rate or damping. It was feared that the precision pressure controller servo, which is designed to control into a fixed volume, might respond adversely to these conditions and cause the force generators to oscillate between the stops at the ends of their travel.

This problem was investigated at RAE Bedford before using the force generators at NPL. The Type A2 force generator was mounted as before, but without the weighbeam connecting link, in a cradle using the weighbeam rig merely as a mounting platform (Fig 10). A yoke frame carrying scale pans suitable for mounting on the force generator was constructed and placed on top of the force generator body so that the generator could be used to lift the whole assembly together with the required dead loads. A transducer was mounted on the generator to indicate vertical positional changes between the piston and cylinder. The total allowable movement of the force generator piston was approximately 5.5 mm and shims were manufactured to restrict its movement as required within this amount. It was found that by varying the input pressure, the spring rate of the force generator produced the very small but necessary increments in force to enable it to be controlled within 0.05 mm of a chosen vertical position.

The initial tests at NPL were performed using the 50 kN force standard machine which employed an incremental loading system, whereby accurately known masses could be attached to a carrier frame suspended on the device being calibrated. The mass of the carrier is also accurately known and could be disengaged by means of an inbuilt hydraulic actuator to set up zero load conditions.
013 The force generators were mounted in a cradle and placed on the support platen within the machine frame and a ball joint or multiple flexure unit was interposed between the force generator and the carrier assembly to ensure that the loading action would not transfer any unwanted couples to the force generator by

misalignment between its axis and the undefined axis of the loading system (Fig 13). Air from the same pneumatic control system as had been used for the weighbeam tests was applied to pressurise the force generator diaphragm and so lift the applied load. A dial test gauge and a position transducer were used to monitor the vertical displacement of the generator.

Although the 500 kN force standard machine has a similar system of operation to the smaller machine it does not incorporate an incremental loading facility, and at each new load the weight carrier plus the existing load therefore has to be lifted clear of the test specimen before activating the load changing mechanism.

5.2 Experiments on the rolling-diaphragm force generators (Types A2, A3)

In tests on the NPL force standard machines it was first necessary to determine the pressure required to balance the weight of the free moving part of the force generator itself and this point was then regarded as the zero load condition. In the 50 kN machine the first true load was 1.779 kN (400 lb) with increments of 1.779 kN up to a full load of 39.144 kN (8800 lb). The corresponding values for the 500 kN machine were 14.946 kN (3360 lb) with 8.896 kN (2000 lb) increments to 93.013 kN (21360 lb).

At each load condition the precision pressure controller was operated to supply air and lift the moving part of the force generator with scale pan and appropriate weights to the mid-position of its travel. The air pressure was then varied marginally about the mid-point of vertical travel to exercise the diaphragm and ascertain precise pneumatic control. The controller counter setting was then carefully increased from a value insufficient to lift the load to allow the generator to reach its mid-position without overshooting. Subsequent readings were taken at a number of points over the full loading range of the force generator in exactly the same manner in an attempt to reduce hysteresis effects by the unidirectional approach.

Latterly a more consistent method of arriving at the force generator mid-position was devised. The precision pressure controller was set to a value roughly predicted to be appropriate to the new load. The servo-drive in the controller was then disengaged and the pressure slightly reduced using the manual override switch. The servo was then re-engaged, the pressure controller bringing the pressure to the level as previously set. If the pressure failed to balance the force generator at its mid-point, as indicated by the position transducers, an adjustment was made to the setting before repeating the above procedure. In practice, relatively few such attempts at setting mid-point balance were required for a consistent and repeatable reading of the pressure controller to be achieved. The repeatable sensitivity was found to be consistent with the resolution of the controlling pressure gauge counter scale, ie 1 in 160000.

5.3 Results and analysis of data on the rolling-diaphragm force generators (Types A2, A3)

The calibration points were plotted as error distributions from a linear calibration for the two types of force generator tested at NPL (Figs 11 and 14). The pressure controller readings were taken as the basis of the distributions forming the 'Y' ordinate since the load increments were fixed*.

For calibration assessment the first data point was taken as the pressure required to support the force generator body including its flexure or ball assembly in the buoyant position, except for tests on the larger generator where the first data point includes the scale pan yoke. All subsequent loads were regarded as additive to this value and a simple extrapolation of pressure against load yielded a value corresponding to the floating weight of the force generator. This was found to be 473.2N in the case of the double acting 50 kN generator and 1.279 kN for the 100 kN generator.

As can be seen from Fig 11 the magnitude of non-linearity is mostly within 0.01% of full scale for the overall calibration of the 50 kN generator. The superimposed waveform observed on all the weighbeam calibrations was not evident at the same frequency nor was it as repeatable as for the weighbeam test. The calibration of the 100 kN force generator on the 500 kN force standard machine (Fig 14) shows a similar level of accuracy relative to its respective full scale output.

5.4 The effective spring rate of the rolling-diaphragm force generators (Types A2, A3)

A deadweight loading system when applied to the force generators gave a convenient way of evaluating their stiffness under load by measuring the pressure changes required to move the generator within its mechanical limits. The pressure controller reading combined with the measured piston area of the force generators enabled the load required to move the generator over small increments in vertical position to be evaluated. This could be carried out for a number of individual increments and hence for the whole allowable movement at any given load condition.

*In the weighbeam tests the distribution was based on the load-related weighbeam counter reading. Hence the respective distributions derived from the NPL and weighbeam tests should not be compared directly on the same axis, particularly as no attempt was made to quantify accurately the non-linearity of the weighbeam.

The operational stiffness was found to increase with load but not proportionally. In the case of the type A2 force generator the stiffness was found to be between 7.7 kN/m and 14.5 kN/m, being least at the centre of allowable movement. Thus for 0.25 mm deflection, which is the estimated force generator travel allowed by the elastic deformation of the mechanical elements of a typical loading system, the error in the force generator output at constant pressure is of the order of 3.6 N or less than 0.01% of its full scale value.

The 100 kN force generator demonstrated a similar but lower stiffness pattern with respect to load, typically a stiffness of 13.7 kN/m for applied force at 32 kN and 17.6 kN/m for applied force of 96 kN. The stiffness for an allowable movement of 0.25 mm on a practical balance under full load of 100 kN force would constitute an error of less than 0.005% in the force generated. These errors are extremely small and can probably be accounted for by imperfections in the piston and cylinder walls and thickness variations in the walls of the rolling diaphragm.

5.5 Experiments with the sealed-bellows force generator (Type B)

A very short series of tests was performed following a similar pattern to that applied to the rolling-diaphragm force generators. The generator (Fig 2) was mounted with internal stops fitted to limit the movement of the piston relative to the cylinder to 6.5 mm. The outer case of the generator sat directly on the lower platen, and the steel piston rod attached to the piston head was connected through a ball joint to the upper platen and weight carrier. A quick calibration was performed as before by selecting a chosen mid-point in the allowable piston travel and by consistently approaching this point from a lower pressure setting. The results were extremely disappointing in that they showed fairly random non-linearity errors approaching 0.1% of full scale load.

These tests were soon abandoned leaving such problems as temperature effects on spring rate and piston area, and piston area changes effected by pressure and vertical movement not investigated. However, a stiffness test was carried out and over chosen vertical increments of 0.25 mm and 1.5 mm total range stiffness was found to average 170 kN/m with variation within 0.3%. This appeared to be independent of applied load and pressure.

5.6 Summary of results

Once a suitable technique had been developed the rolling diaphragm force generators responded well to tests on the NPL machines. Both the 50 kN and 100 kN force generators gave consistent results between calibrations performed over a period of time.

Spring rate (stiffness) effects as measured were found to be within 0.01% of full scale for each generator, provided that the piston movement was limited to about 0.25 mm in the case of the 50 kN force generator and 0.5 mm in the case of the 100 kN force generator. These limits are within the anticipated limits of movement in a typical mechanical or strain gauge balance calibration system. Small deflections must always be expected in any loading system and the force generator spring rate, however, small, will affect the results.

Cyclic tests involving vertical force generator movement at fixed load points revealed hysteresis of up to 0.01% of full scale which increased with load but not proportionally.

Calibration of the steel bellows sealed force generator on the 50 kN force standard machine showed non linearity of approximately 0.1% of full scale but the results generally were not very reliable. In view of the excellent results obtained from this unit on the weighbeam rig this behaviour cannot be explained at the present time and warrants further investigation.

6 GENERAL CONCLUSIONS

6.1 Tests on the weighbeam test rig

Results from tests on the Type A1 and A2 force generator under the constraint of the weighbeam test rig showed repeatability, when temperature compensated, to within one part in 40000 (0.003%) of full scale reading. Full scale force in this case was 40 kN at a pressure of 2 MPa. Hysteresis and non linearity affected results by up to 0.02% of full scale value, the hysteresis accounting for half of this amount. Part of the non-linearity was due to flexibility in the test rig, which was mainly designed to be suitable for comparitive tests, while still being capable of resolving the readings to within the accuracy of the pressure controller.

Tests of the Type A3 force generator on the weighbeam test rig produced results consistent with those achieved with the Type A1 and A2 force generators, both having the same errors relative to their respective full scale output.

The Type B force generator was found to be almost hysteresis-free in testing on the weighbeam rig, and although non-linear, its characteristics were exactly repeatable within the accuracy of the experiment.

6.2 Tests on the NPL force standard machines

Dead load tests in the 50 kN and 500 kN force standard machines at NPL
013 provided a means of comparing the force generator performance to an absolute standard. The rolling diaphragm force generators with their low stiffness and

and relatively constant piston area gave results within 0.02% of the respective full scale output value of each generator. This interpretation of results was improved by fitting a standard curve to the distribution and when comparing one curve with another, differences were less than 0.01% of full scale reading. Cyclic tests applied to the rolling diaphragm force generators in a dead weight condition involving vertical movement at fixed load points revealed hysteresis related, but not proportional, to load within 0.02% of full scale reading. This could be largely eliminated by adopting a technique in which each loading point was approached from a lower pressure level.

Within the time scale available for development of the testing technique the type B force generator was found to be unsuitable for testing by dead weight loading even under conditions of restricted movement. The tests at NPL indicated that the absolute accuracy of the experiment was not quite as high as the consistency of the weighbeam tests would suggest. However, it might be unreasonable to expect the inherently different dead load tests, under conditions of virtually unrestrained force generator movement, precisely to repeat the consistencies achieved on the weighbeam rig.

6.3 Application

Force generators of this type have successfully been used in a heavy duty calibration machine[3] for the balances to be used in a modern wind tunnel.

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No.	Author	Title etc
1	E.C. Brown	A heavy duty balance calibration machine for the RAE 5 metre low speed wind tunnel. RAE TR forthcoming
2	Dept of Trade and Industry 1971 National Physical Laboratory Measurement Services	Mass, Force, Hardness, Viscometry and Density Section 3.3
3	L.E. Andreeva Translated from Russian by A. Baruch and D. Alster	Elastic Elements of Instruments page 268 (5.77)

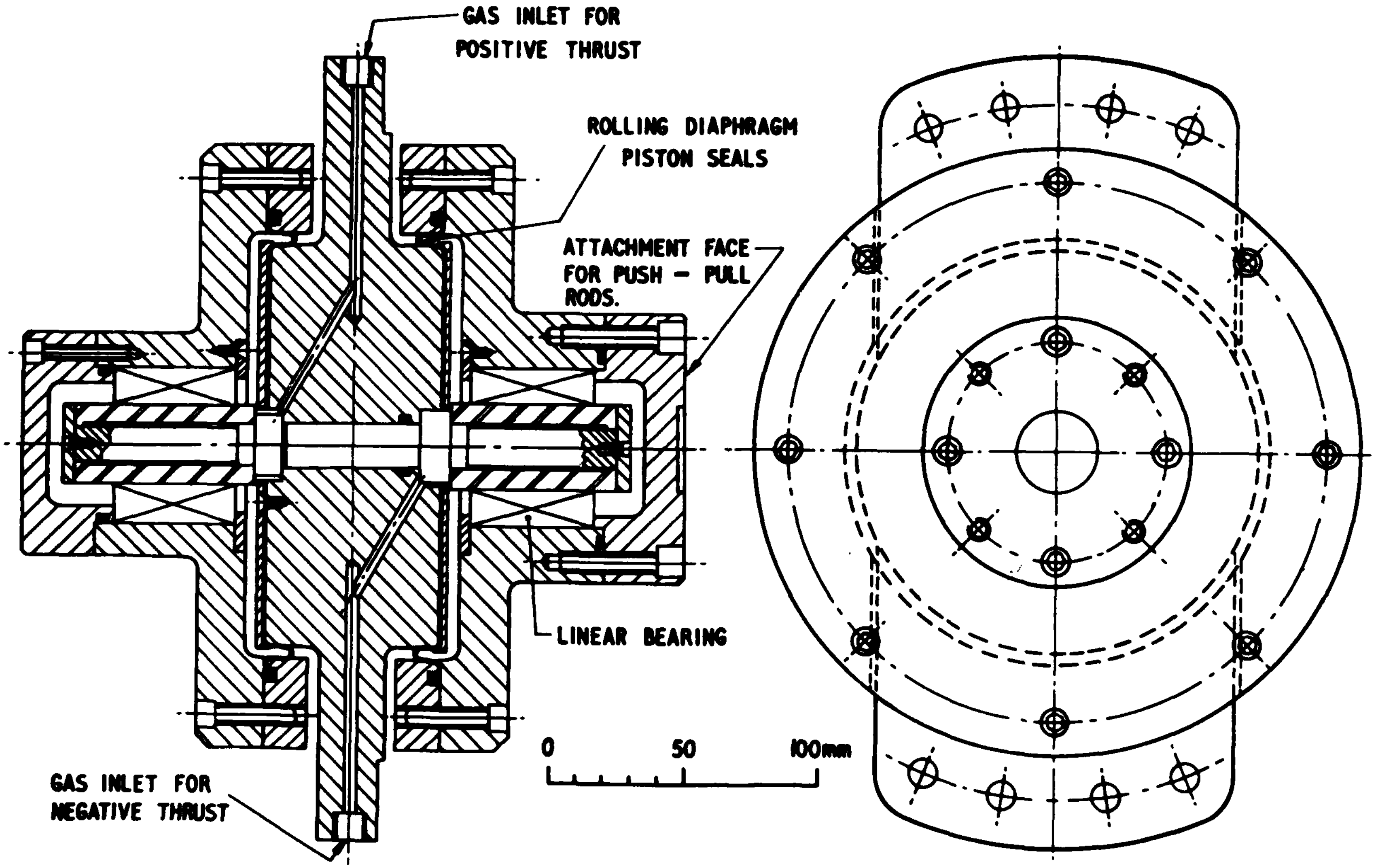


Fig 1 Arrangement of 50kN double acting force generator (Type A2)

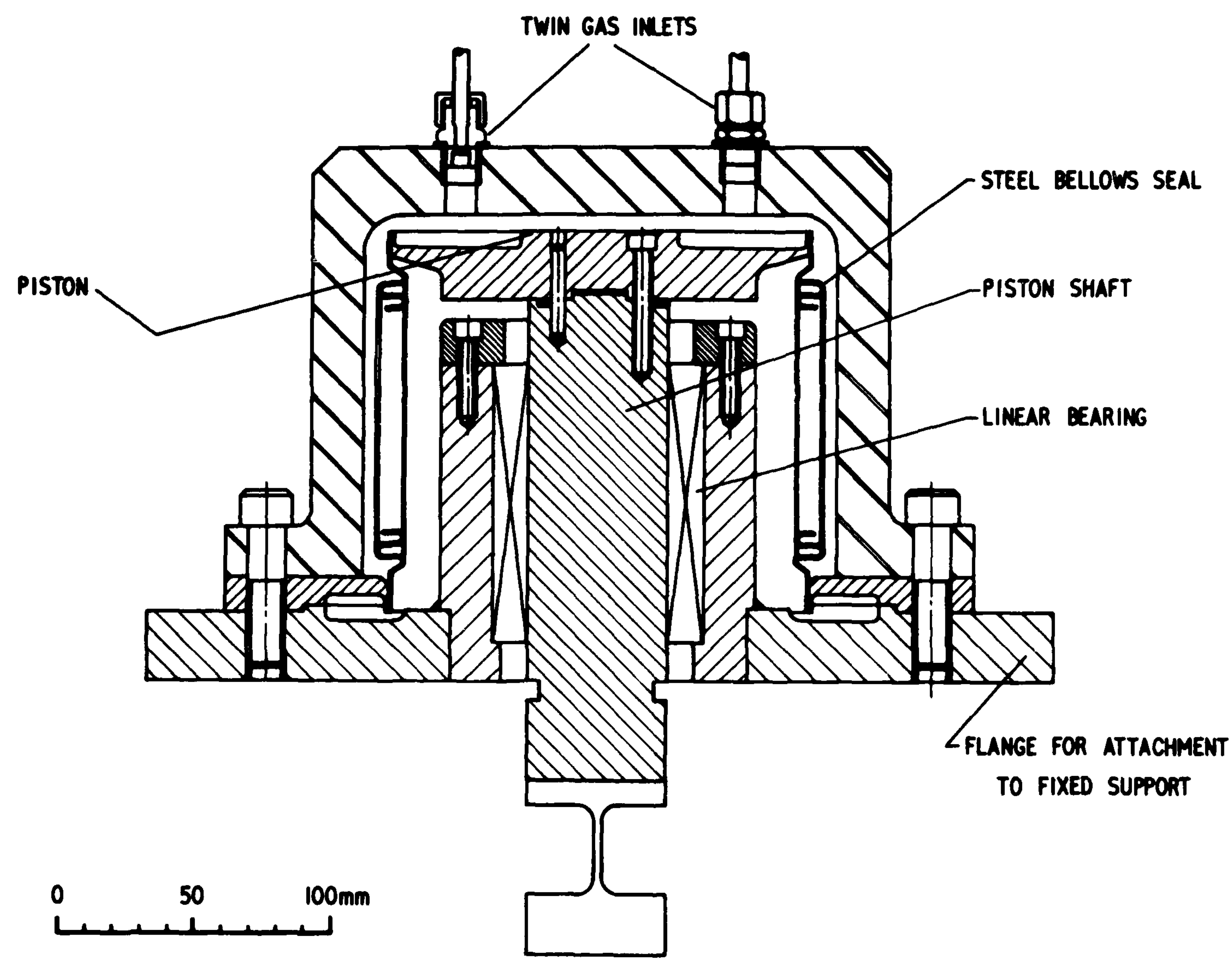


Fig 2 Steel bellows type force generator (Type B)

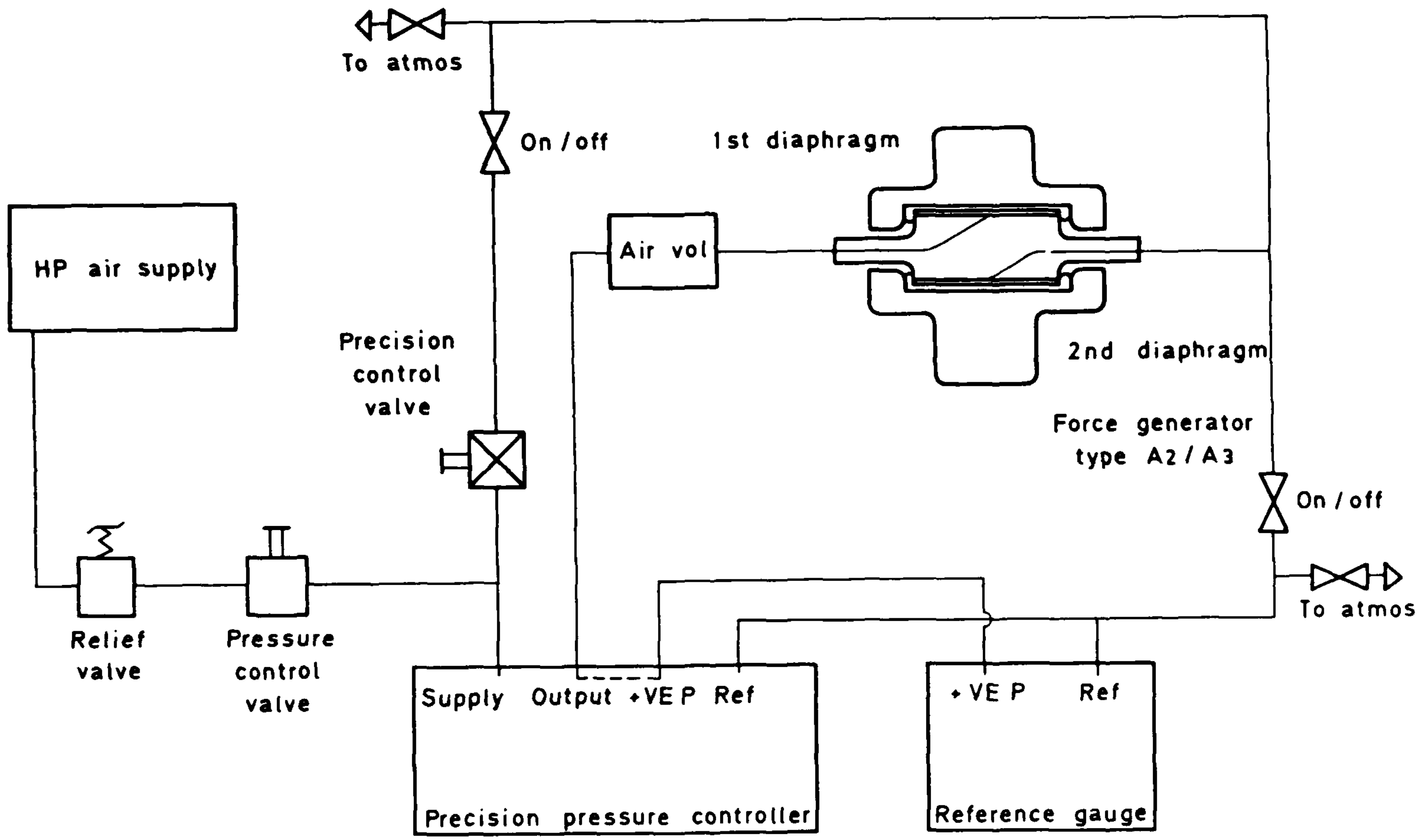


Fig 3 Pneumatic pressure control system

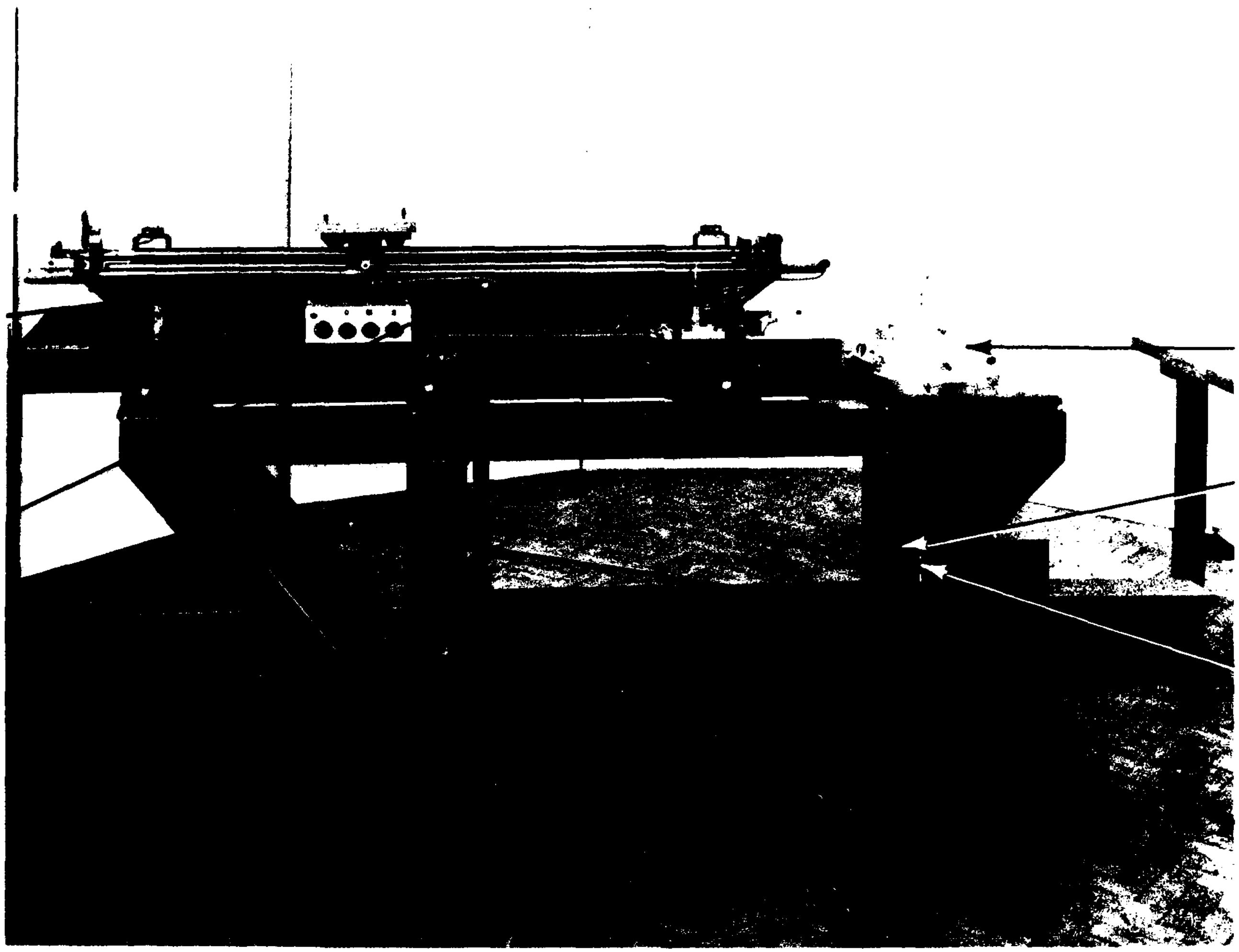


Fig 4 Weighbeam test rig with single acting rolling diaphragm force generator (Type A1)

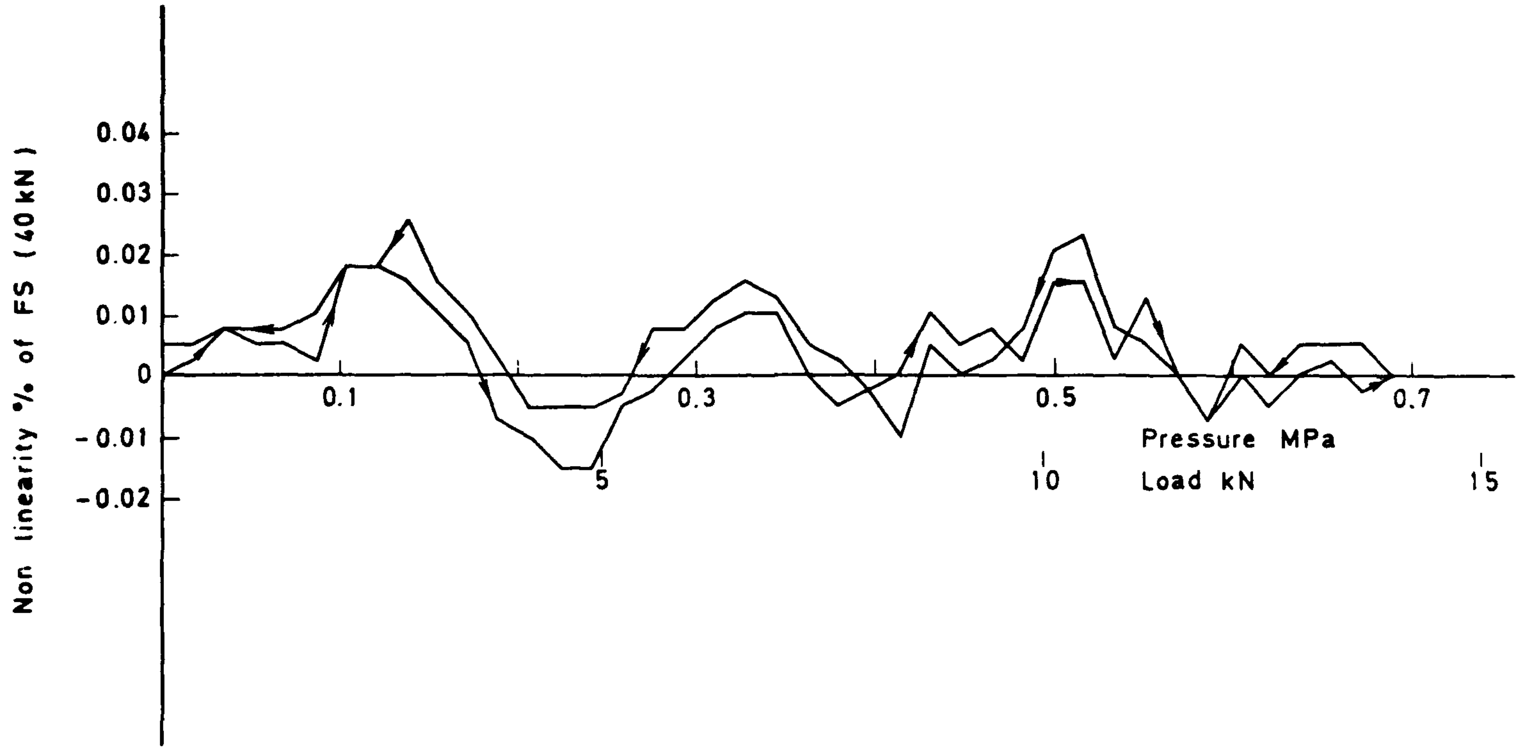


Fig 5 Partial calibration of 50kN single acting rolling diaphragm force generator (Type A) on weighbeam rig

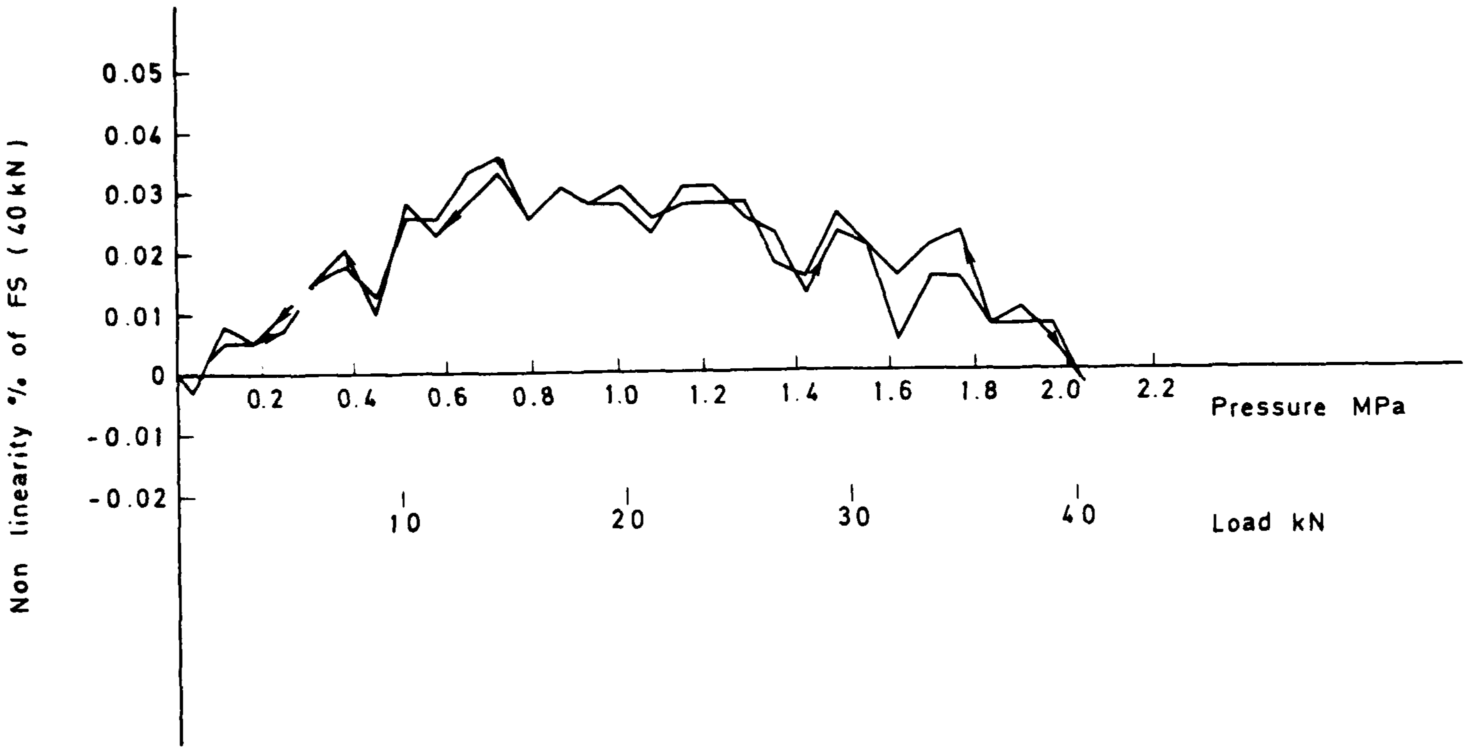
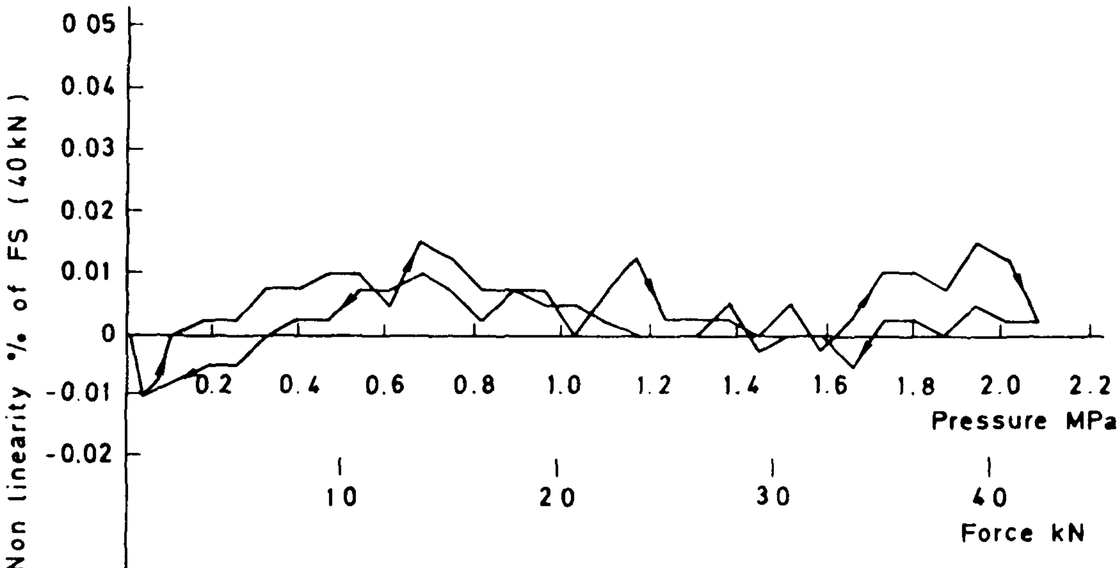
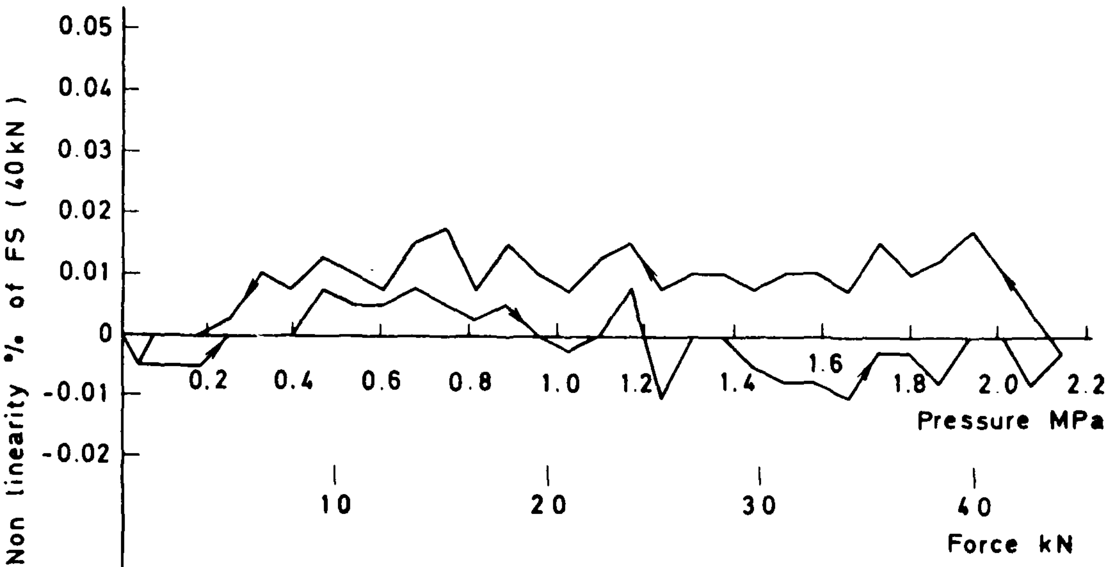


Fig 6 Sealed bellows force generator (Type B) on weighbeam test rig



a Readings taken after overshoot of one increment



b Plot of overshoot points

Fig 7a&b Single acting rolling diaphragm (Type A1): hysteresis tests on weighbeam rig performed simultaneously

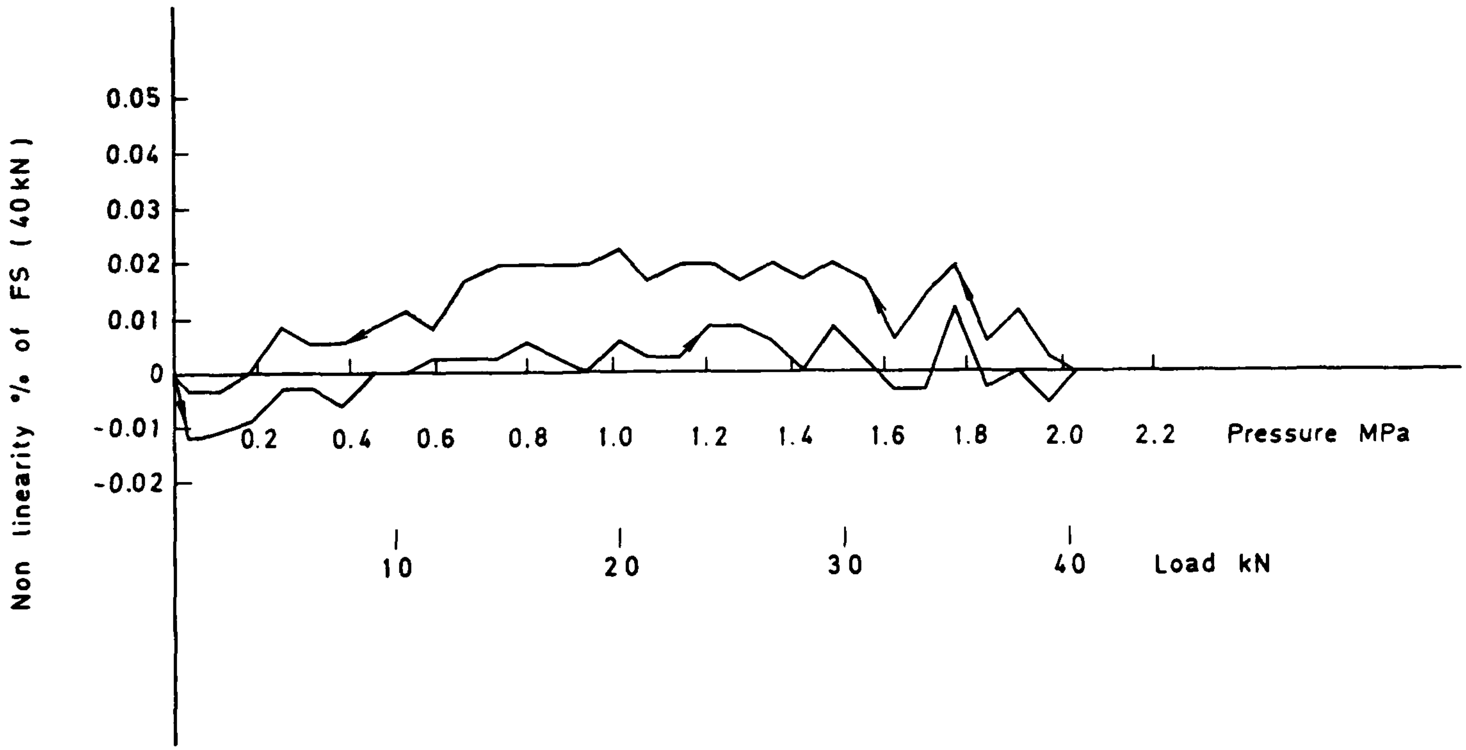


Fig 8 50kN double acting force generator (Type A2) on weighbeam rig

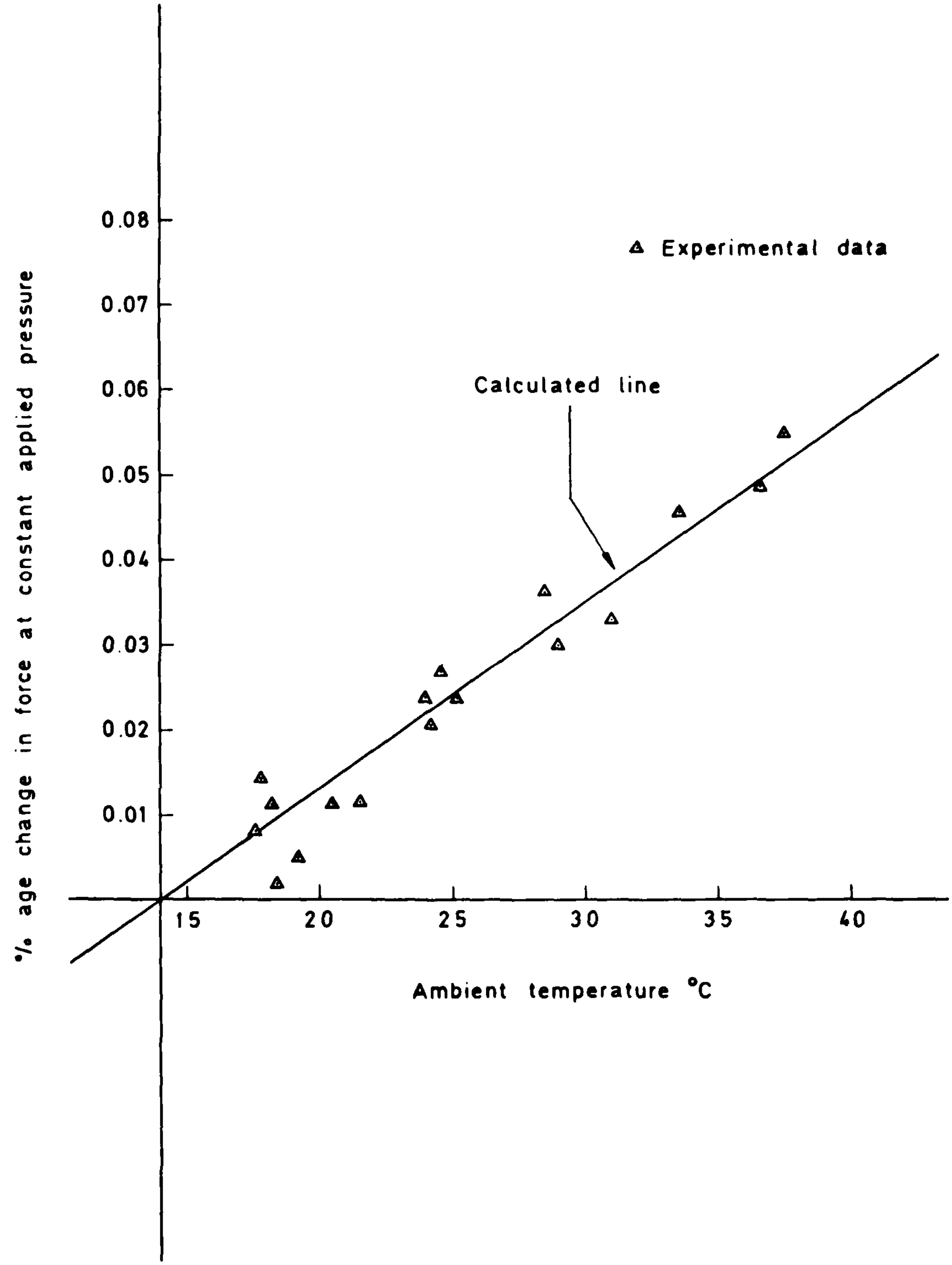


Fig 9 50kN double acting force generator (Type A2): temperature effects

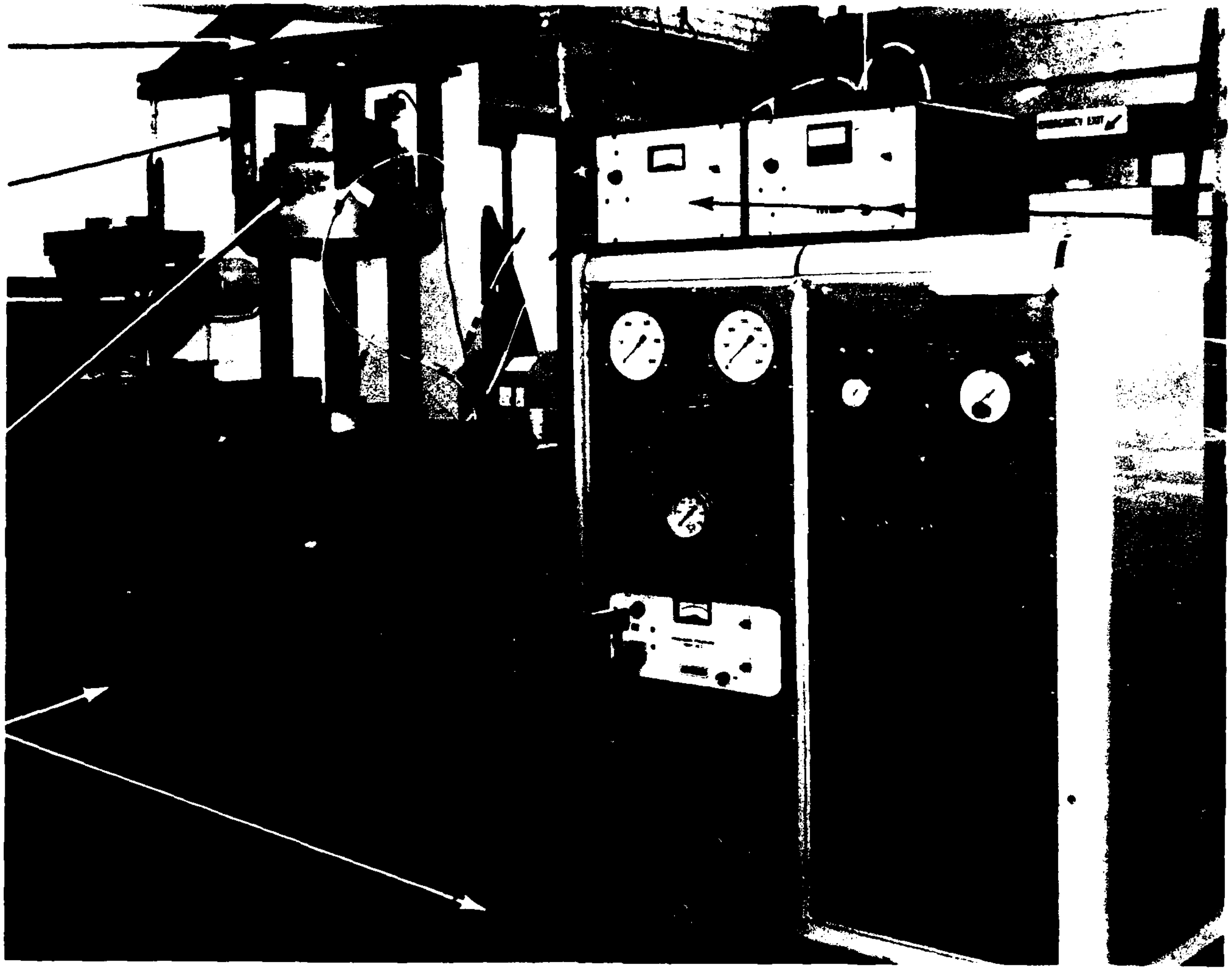


Fig 10 Double acting force generator (Type A2) undergoing preliminary dead load tests

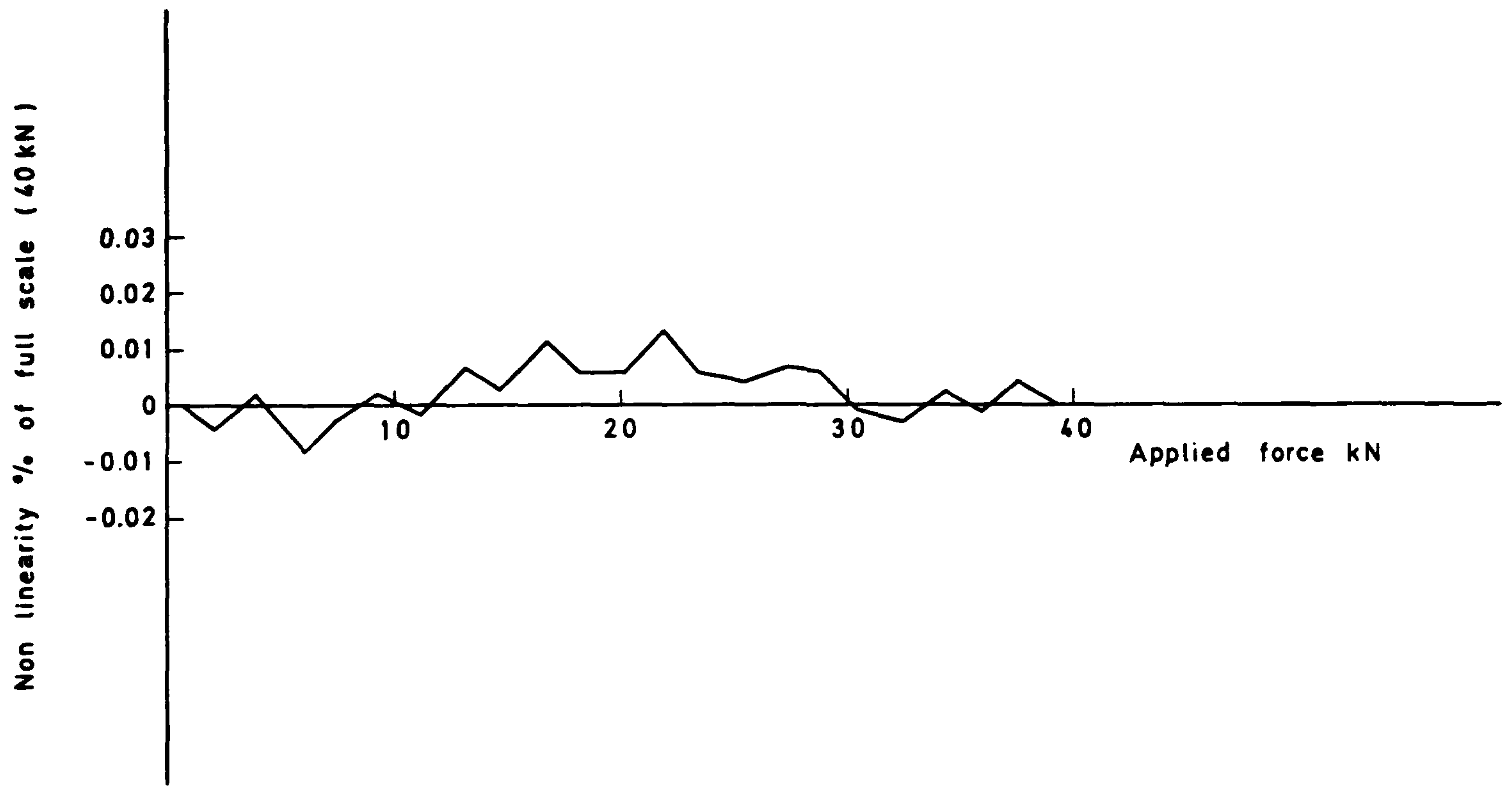


Fig 11 50kN double acting force generator (Type A2) on the 50kN force standard machine at NPL

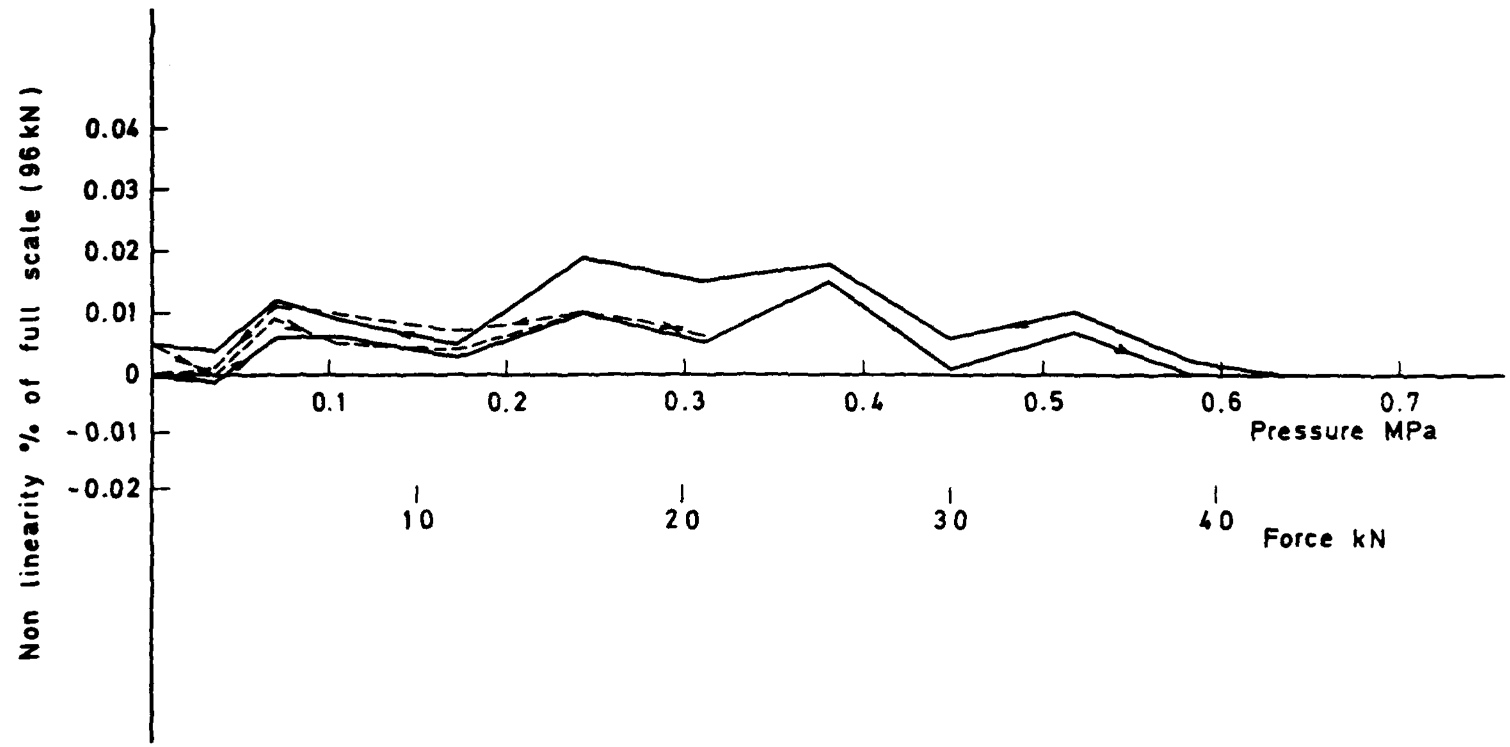


Fig 12 Reduced range test on 100kN force generator (Type A3) on the weighbeam rig

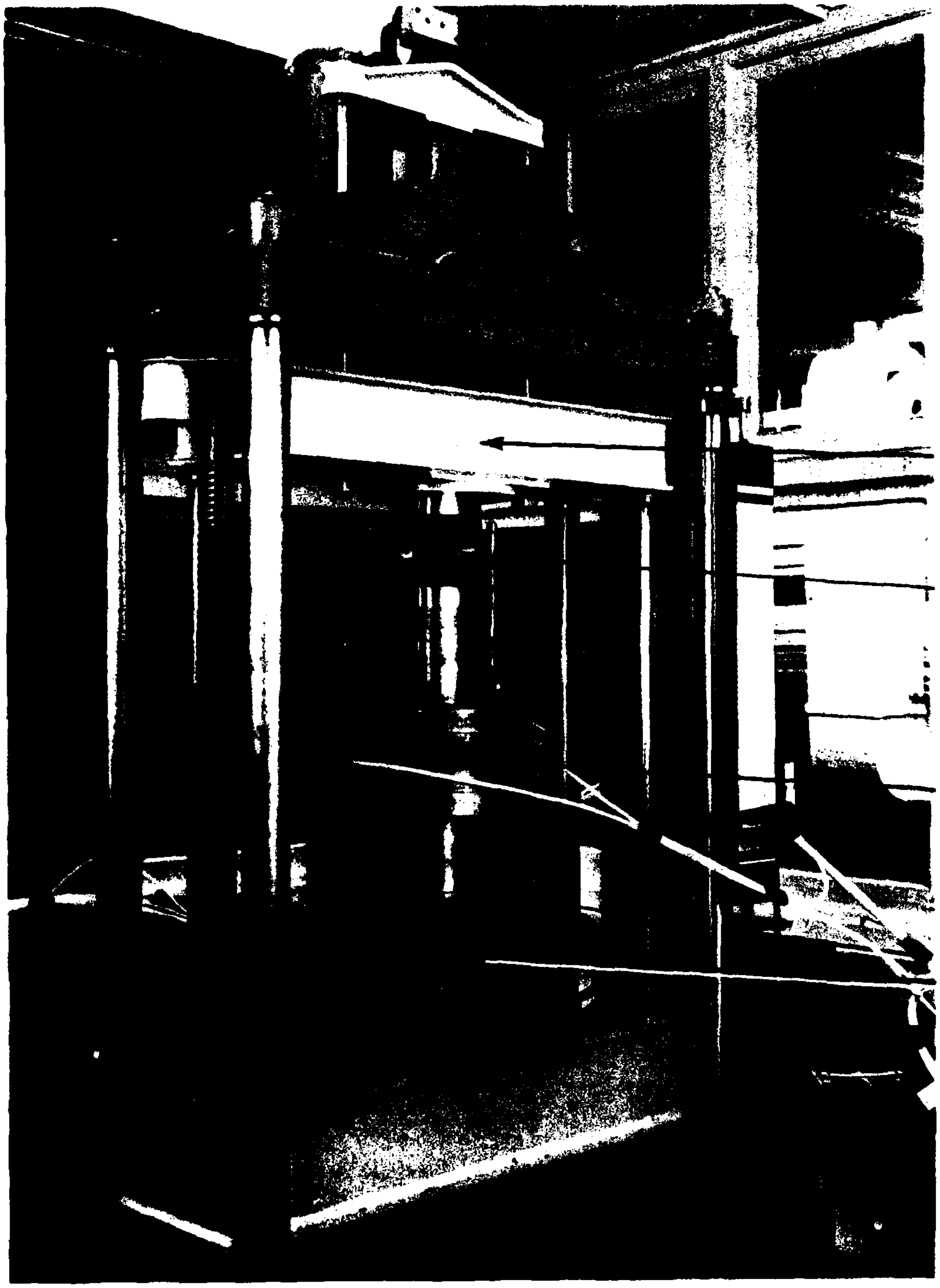


Fig 13 50kN double acting rolling diaphragm force generator (Type A2) mounted in the 50kN force standard machine at NPL

Fig 14

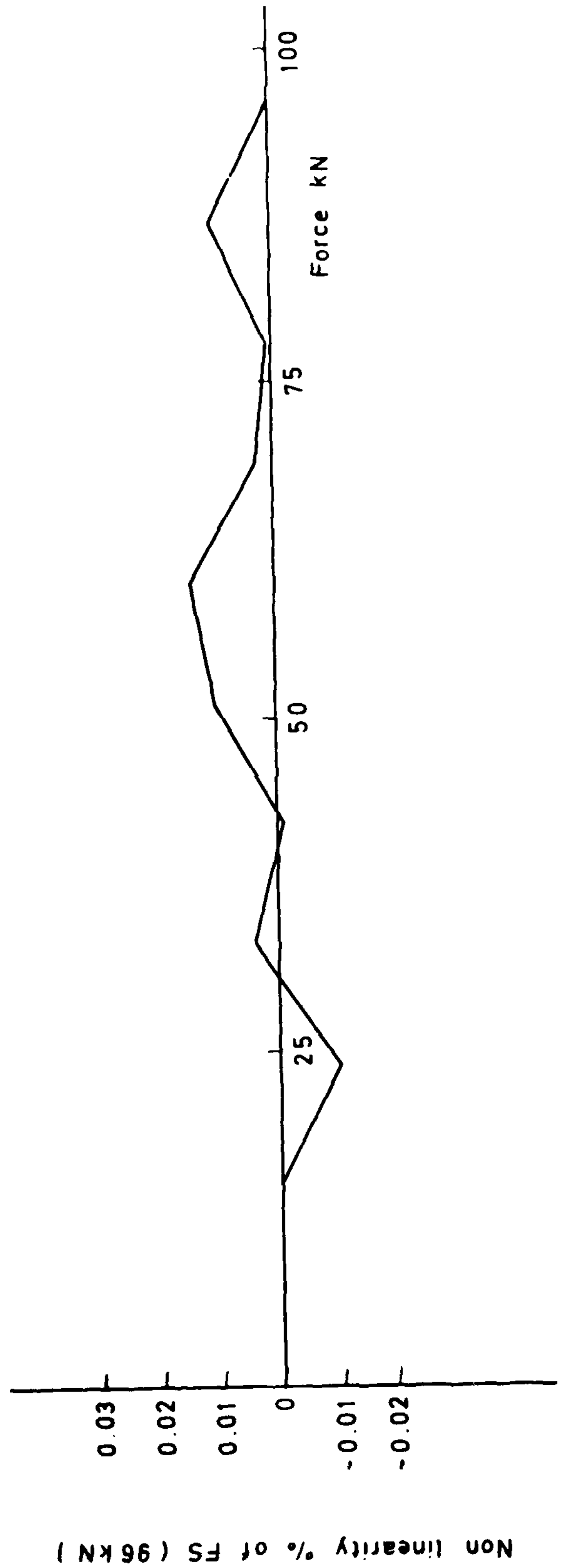


Fig 14 100kN rolling diaphragm force generator (Type A3) tested on the 500kN force standard machine at NPL

REPORT DOCUMENTATION PAGE

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17. Abstract

An assessment has been made of the performance of two different types of pneumatic force generator, covering forces up to a 100 kN, with a view to their use in balance calibrations in the RAE 5m wind tunnel. This Report describes tests performed on the force generators using a precision pneumatic control system firstly in conjunction with a static weighbeam test rig, followed by a series of tests to check the overall accuracy of performance against the 'dead-weight' Force Standard Machines at NPL Teddington.

It has been shown that force generators using a rolling diaphragm seal can produce forces to an accuracy within 0.01% of maximum output assuming a linear calibration. Individual values of force output could be repeated to 0.003% of maximum output when checked against a simple weighbeam under fixed experimental conditions.

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