MANUAL AND AUTOMATIC LARGE-SCALE DIMENSIONAL METROLOGY

by

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(May 1969)

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Peter H Sydenham

Peter H. Sydenham,
Warwick.
May 1969.

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ABSTRACT

Current techniques for manual and automated determination of decametre-range are reviewed from information gained by extensive literature search and from visits made to a wide cross section of European establishments concerned with large-scale dimensional measurements. The reviews, which contain nearly 200 references, provide background information needed by systems designers.

A 12m steel measuring base is described which was length stabilised to within 3 parts in 10^7 for periods in excess of 500 hours. Temperature of the internal water flow is monitored by a contact thermometer which controls the heat input.

The theory and practice of tensioned-wire dimensional transducers are given which enables this new-class of dimensional measuring instrument to be designed. Two distinct groups of instrument described are those for transducing continuous length changes into electrical signals with better than 5 parts in 10^6 error and those for detecting changes of 1 part in 10^{10}, or smaller, of a nominally fixed length.

Continuous subdivision transducers with 12m and 1m range are reported which incorporate mechanical mechanisms for obtaining adjustable absolute length, reduction of in-scale accuracy errors, linear rotary output, rapid following response and simple temperature compensation. A method and practical apparatus are described which uses this type of

transducer for automatic control of the position of a workhea moved on a cartesian-frame manipulator. Actual two-dimensional position is measured on a trilateral basis, a technique which eliminates the need for a massive framework when machining or inspecting large workpieces. In-situ numerically-controlled machining is possible with this system.

A second frameless technique is described for automatically recording roundness variations of large rings or spigots. Repeatability of 5 parts in 10^6 or better has been proven to be possible with inexpensive equipment. This method illustrates the use of deformation wire-transducers for dynamic dimensional measurement. A similar type of instrument was used for creep determination of invar wires and carbon-fibres supported on the 12m base. Results are given which have shown that 1 part in 10^8 length stability is attainable over considerable periods.

It is shown that measurement of earth strains is possible with an invar wire tensioned by a simple beam-balance. Details are given of an experiment performed in a tunnel in which solid-earth tidal strains are recorded within hours of installation.

Several other possible applications are discussed for which tensioned-wire transducers seem suited.

The use of position-sensitive photocells in dimensional metrology is outlined with particular reference to wire transducers where linear and rotary movements may need monitoring. It is shown that they are a simple and economic way to measure small displacements of millimetre range.

PREFACE

This thesis is the result of work carried out in the School of Engineering Science of the University of Warwick, Coventry, England, during the period March 1967 to May 1969.

The author is indebted to his Supervisor, Professor J.L. Douce, for his guidance and criticism. Acknowledgement is due to other members of staff, in particular, Dr. V. Marples for the use of a laboratory under his care, Mr. D.L. Turner for discussions on mechanisms, and Mr. C. Vials for technical construction. Thanks are also due to the many persons who aided the writer during visits to their establishments. Dr.Davies of the Department of Geodesy, Cambridge University kindly allowed experiments to be performed in a seismic station of his Department.

Permission to study in the United Kingdom was kindly given by the Department of Supply, Commonwealth of Australia.

British Timken loaned the large bearing ring used for investigating the roundness measurement method. The manipulator described in Section 5.1 was constructed by the University Workshops.

The work was supported by two grants, the first being personal support from the English Electric Company,and the other being a Science Research Council Grant (reference B/SR/5029) which provided a technician for 18 months, a fund for travelling expenses and finance to purchase ready made equipment enabling more time to be devoted to new techniques.

Much of this thesis has already, or will shortly be, published. Copies of the four published papers and the two which were submitted recently, are given in the Appendices.

A 16mm, black and white, cine film record running for about 15 minutes, has also been made as a record. This is currently being edited (May 1969).

CONTENTS

1. INTRODUCTION

1.1 Previous Research at the University of Adelaide.

In January 1965 the writer began a fifteen month research project as required for the Master of Engineering Degree at the University of Adelaide. No formal lectures were involved being a research degree (1). This introduced the writer to dimensional measurement and is responsible for the topic of this Thesis. A brief account of the work is now given.

Initially, the project aim was to control trenching machines to cut a level trench, regardless of surface profile. A survey of suitable commercial transducers for measuring position showed that none was available. It was found that automated large scale measurement techniques were poorly developed. Even manual practice seriously lagged requirements when size exceeded a few metres. The project concentrated on techniques of measurement for the remaining ten months for this appeared to be a useful contribution. Two possibilities indicated were methods using flexible mechanical members, or optical principles.

Dimensional metrology has become sophisticated through years of development, but in almost all cases solid frames are involved in the measuring technique. The use of flexible wires or tapes for measurement had not been seriously investigated for general engineering purposes, the theory having remained virtually the same over the last thirty years. With regard to the optical methods, surveying instruments had clearly shown that high accuracies were possible in manual measurement and the need for automated processes was seen to be emerging. This is now becoming more evident with the recent release of at least four types of electrical output surveying instruments.

At first sight, a tensioned wire or cord appears to be incapable of accurate length measurement due to possible vibration and dimensional instability factors. The view was taken at the time that a short programme should be made to definitely prove their inadequacy before proceeding to optical methods. The first technique investigated, used a tensioned, recoiled wire acting as a retracting or expanding slide-wire bridge, voltage output being proportionate to the extended length. Knowledge of surveying practice made it clear that trilateration was probably a better method for measuring large scale position. Two 55ft. range potentiometric units were coupled to measure in trilateration and after conversion to cartesian co-ordinate equivalents, positional accuracy was checked and found to be about 1/4000 with repeatability about 1/15,000 over the 40 by 40ft. area tested (2).

A second method was theninvestigated in which the rotation of the recoiling drum was used as an indication of length. The potentiometric units were modified and incremental optical shaft resolvers attached to the drum shafts. This arrangement repeated position to about 4 parts per million (p.p.m.), standard deviation (3) showing that serious large scale measurements were in fact quite practicable with a wire device.

The resolvers used gratings made with a novel radial line generating machine developed in the same period (4.5). A fast bi-directional counter was also developed as part of this programme (6).

The digital output wire device, termed Digiwire, was subsequently tested at the National Standards Laboratory (Sydney) for repeatability and in-scale subdivisional accuracy, showing it to be within 1/100,000 at each of the subdivisions checked. The units, however, had many undesirable features that needed improving for practical measurement. The M.E. degree was conferred in 1967.

After submission a novel shaft resolver principle was tested and a paper published (7). This is submitted as part of this thesis and is included in the appendix.

1.2 Outline of Research at the University of Warwick

To continue large-scale dimensional metrology research, enrolment for the Ph.D. was made in March 1967, the salary being provided by an English Electric Company grant. The original intention was to investigate optical methods of large-scale position control envisaged in the previous research period. As the award included no funds for hardware, English Electric were asked to support an investigation for machining large components in situ using trilateral control. Although they were, in fact, considering the economics of such techniques the financial situation prevented them supporting the programme further and permission was given to try elsewhere. A number of visits to gain background and, perhaps finance, were made to relevant firms and group research establishments. All showed interest, but expressed the view that more research was needed to adequately prove the case. It became clear that further research with wire methods should be the first priority.

In September 1967 an S.R.C. grant was lodged for equipment, finance and a technician for 18 months. This was awarded in April 1968 and enabled the project to advance into application at a reasonable rate.

Previous to this award the time was spent making a more comprehensive review of large-scale dimensional transducers which resulted in a paper being published by the I.E.E.(8). A 12m, steel test bed was constructed for testing long length measuring devices in the Heavy Engineering Laboratory. Dynamics of the Digiwire method were investigated showing how response could be improved. A Digiwire II unit was subsequently designed on paper which would have improved responses, absolute length adjustment, in-scale error correction facility and linear digital output. A suitable incremental resolver design was selected and a bi-directional counter purchased, it being more economic than constructing one.

A study was made of tensioning methods showing that spring motors had been the correct choice, but the future form should be different to improve the response. To monitor the step response of the Digiwire unit a study of position sensitive photocells for rotary transient measurement was made. A paper was published on this research (9) for, although some 50 papers were available, few quoted experimental results. A brief review of the various types of cells was included.

In March 1968 a test was made to assess creep of the wire extended from a Digiwire I unit brought from Adelaide. Length stability within 1 part in 10^8 was obtained over a 15 minute period. It was then realised that a second type of tensioned wire measuring instrument existed in which very small changes in long lengths could be detected.

The S.R.C. award commenced shortly after this enabling two Digiwire II units to be constructed. A temperature measurement system and a recorder were purchased after considering various alternatives. At this time organisation of a study tour of Continental large-scale measurement establishments was started with the initial selection of suitable places. This tour was made in July 1968.

When the tour was completed in August, the first Digiwire II unit was ready for preliminary testing and it was decided to stabilise the length of the 12m measuring base by controlling its temperature in order to improve testing accuracy. This exercise proved successful giving a facility some twenty times more stable than the devices under test. It also showed that a different approach to temperature control of precision machines was feasible and economic (10).

To check the length stability of the base a simple beam-balance was installed for tensioning an invar wire and measuring relative movement between the wire and the base. Continuous records weremade of the base mean temperature and its length changes, both showing, by inference, that the nominal length of the base and the invar wire remained constant within 5 parts in 10^8 over period of up to 500 hr., this being the maximum duration tested. This also added knowledge on invar creep properties under constant stress conditions and on the stability of clamped joints in the system. As invar geodetic tapes are only calibrated to about 1 part in 10^6 at the best, these results led to an investigation of the tape procedure showing that only the state behaviour of the wire or tape, used in catenary had been investigated. Important factors such as bearing friction, mechanical hysteresis, tensioning methods and dynamic response do not appear to have been considered. A study was made of these factors and a number of different tensioning heads made to test the formulation.

In November 1968, it was decided to demonstrate trilaterial measurement at the forthcoming 1969 Physics Exhibition. The design of the manipulator needed for this method was given to the Workshops for construction. Good progress enabled automatic control of position to be shown at the Exhibition. This was the first of several applications, based on tensioned-wire measurements, investigated in this project.

Alarge bearing ring was lent by British Timken for proving a circularity measurement technique based on the tensioned-wire instrument capable of detecting small changes in large nominal lengths. Work commenced in February 1969 to set this ring up as a reference circle in the laboratory area. At the same time the use of this type of transducer for seismic strain measurement was discussed with the staff of the Department of Geodesy and Geophysics at Cambridge University. The method showed promise and permission was obtained to install a system in their seismic station in Yorkshire.

The seismic application was given priority over the circularity one due to the interest of the Geophysicists and as longer time would be needed to obtain results. The investigation of the roundness measurements was, therefore, not as extensive as originally intended.

The seismic application showed that the tensioned-wire method was capable of results similar to existing methods but was cheaper and more rapidly commissioned. A more reliable apparatus will be constructed and continuous records taken on the off chance that an earthquake recording may be obtained.

Figure 1.2.1. General view of area used for large scale metrology research and construction.

A general view of the laboratory area where this work was performed is given in Figure 1.2.1. The measuring base runs across the rear, from wall to wall. On the left hand side is the trilateral co-ordinate control system arranged for demonstration. A small plastic sheet room houses the reference ring equipment.

The findings of this twenty-six week programme have been assembled in this thesis as distinct groups although the work on many aspects was performed simultaneously. Figure 1.2.2. is a chart that summarises the aspects of the project. Sections 2 and 3 are relevant to large-scale metrology as a general discipline, Section 2 being concerned with manual and automated practice and potential. Section 3 describes the 12m measuring base which is useful for testing all types of decametre range length and alignment measuring devices. The theory of wires as a measurement medium is given in Section 4. Many aspects of this may need extensions to suit specific applications but the first necessity is awareness of pitfalls and possible solutions. Three applications have been investigated and are discussed in Section 5. The first described is a frameless machining system for controlling tool position at reduced capital cost. The second details the roundness measurement method, and the third, the results of various tests made in the disused railway tunnel used as a seismic station.

Some subject matter has already been published and the reader is referred, as necessary, to reprints given in the appendix.

Fig. 1.2.2. Chart showing topics encompassed in the research programme.

2. DIMENSIONAL MEASUREMENT PRACTICE

2.1. Current Practice of Large-Scale Metrology.

Large scale metrology may be defined as dimensional measurement of position within the range of one metre to several hundred metres. (The term 'dimensional' should be included with metrology but is usually implied). It is now becoming a discipline in its own right but as there are no general texts on techniques in this field a brief review of current manual methods of large-scale measurement is given in this sub-section. The following sub-section reviews automated methods for this range. Texts on the optical tooling techniques (11,12). the use of the auto collimator (13) and general surveying cover some of the aspects. Hume recognises this range of measurement in one of his metrology texts (15), but the contribution is very brief.

Accurate large-scale measurements that occasionally arise in mechanical engineering are met, as well as possible, by extending normal-scale metrology techniques. Traditional instruments used for length measurement are stick micro-meters, end bar and tooling tapes. Optical squares, jig transits, autocollimators, alignment telescopes, wires and bubble levels, are used to align or to extend the length measuring methods to obtain multi-dimensional measurement.

In civil engineering, measurement is mainly made with surveyors instruments. These have been developed for use with triangular methods of measurement rather than for the rectangular, cartesian methods of the metrologist. They include the optical level, theodolite, target staff, tacheometer, subtense bar and tapes. Recent additions are the electronic distance measuring devices such as Geodimeter and Tellurometer, and the shorter range versions using modulated gallium arsenide beams.

Some overlap of instrument usage occurs in the mechanical and civil engineering fields. For example, the bubble level and telescope are combined in survey work but are used separately in mechanical measurements. Optical tooling, used mainly in the aircraft industry, uses optical instruments generally for cartesian layout methods. Strangely, the theodolite was regarded as having little application in this field (11) even though it has been suitable in the production form for some years. Current models are available with 0.1 seconds of arc accuracy. The telescope optical-axis centring accuracy, instrument centring accuracy, telescope resolution and focus range have had to be improved to make the surveying versions usable for the shorter range precise engineering measurements. The trend for surveying instrument manufacturers to market accessories, such as autocollimation lenses, optical squares, and optical micrometers, as additions to standard instruments is increasing.

For continuous length measurement and subdivision of ranges to 5m (or more in some cases) the laser interferometer is second to none, given the ideal working conditions. Application in an industrial environment, however, reveals that the laser has many shortcomings, not the least being the high cost and relatively short life. Other techniques are being investigated that might prove to be superior. At the National Physical Laboratory (N.P.L.) the use of submillimetre-wave devices promises to greatly reduce the cost of interferometric devices. The research reported in this thesis shows that tensioned-wire measurement methods can equal laser performance in normal environments of temperature imprecision with greater translation rates and without the need for a guideway. (1°C uncertainty in a metal part or machine bed implies a length uncertainty of 1/100,000). Both wire and laser methods have digital readout (D.R.O.) of length making them simple to use.

As the applications of accurate large-scale metrology are only required occasionally by individual establishments, they rarely have experienced operators in this discipline. For this reason future development should aim at simplicity in operation and use. Thus a display, in meter or D.R.O. form is desirable. For recording and use in closed-loop position control a transduced output is essential. A dynamic continuous output is also useful for assessing the stability of a measurement which is time dependant, such as those involving temperature or instability. D.R.O. or meter displays are well known in metrological instruments but the larger commercial developers of surveying instruments have been slow to adopt them.

A small amount of research on large-scale metrology is apparent. For example, specific groups (though small in staff) exist at the N.P.L. (Great Britain), the N.S.L. (Australia) and the T.N.O. (Holland). The general situation is that industry relies upon these groupsto solve the too-hard cases, whereas these groups usually have a primary policy of improving standards. The apparent trend of research by industry and manufacturers indicates little interest in this area, the arguments being that only a few percent of all measurements made in mechanical engineering fall in this category and also that governmental laboratories should do the research anyway.

Development trends ascertained from published reports and trade releases are at least two years behind the policy decision, so it was decided that a study of expected future trends should be carried out throughout the project period by visiting a wide spectrum of establishments in Britain and on the Continent. The latter was covered by a 7week study tour of 33 places in Holland, West Germany, Switzerland and Italy, during the summer of 1968. This tour, partially sponsored by the Science Research Council, included surveying instrument makers, large machine tool builders, users of large-scale metrology, geodetic research institutes with instrument interests, metrological instrument makers and several national laboratories concerned with measurement. The selection of suitable places was difficult. Suggestions were requested from responsible officials at a number of British Governmental institutions. The total response resulted in only three suggestions, showing the need to establish the situation and made contact with the continental establishments. France was not visited as the preliminary research indicated insufficient density of places. Undoubtedly this was due to poor communication on both sides.

The final selection was made from a list prepared from the European Research Index (16) from the writer's experience, from the affiliations of known authors and from Embassy suggestions. It took about 7 months to organise the tour. At all places the purpose of the visits, of about 1 day's duration, was centred on large-scale metrology practice with accent on development policy and application of new techniques. It was said British visitors are rare. The following comments are based on this tour and are extracted from a detailed 8,500 word report. This report was circulated, but not published due to lack of demand. This outline portrays the current methods of measurement on the Continent but is typical of other countries. Further comments upon some specific British instances are detailed later.

Mechanical Engineering Measurements

The majority of the world's large machine tools are made on the Continent. Metrological problems on these tools are similar to smaller machines with the exception that ranges are greater. Most precision parts of large tools require straightness, parallelism, matched components and occasionally absolute magnitude.

Alignment in the vertical plane (often to lengths of 50 m) is mainly performed with taut wires viewed with the Leitz, cross-hair or double image, alignment microscope which resolves to 1 m, Sulzer have developed an electric contact-feeler for sensing a 300μm diameter alignment wire to within about 10μm with sag corrections being used for horizontal alignment. For shorter distances and horizontal plane alignment, bubble levels mounted on a 0.5 m. base, manual autocollimators (Leitz, Hilger and Watts) and alignment telescopes (Taylor-Hobson) are most used. Optical methods are, however, mainly mistrusted due to their atmospheric dependency. The electric level, Talyvel (Rank-Taylor-Hobson), is used occasionally for levelling plane areas. Water levels by communicating tubes are used extensively for this operation and a permanent 50 mm. diameter pipe surrounds a 25 m. bed milling machine at the Sulzer works to provide level checking. Alignment with the laser, zone plate and diffraction grating seemed to be virtually unknown in industry. Electric readout autocollimators and electric levels have also made little appearance but Leitz have recently marketed a photoelectric microscope which becomes an electric autocollimator by changing the objective.

Geometry of tools and products is checked by direct inspection of lengths and angles or by using the machine to gauge precision blocks with dial gauges. Inductive displacement transducers are sometimes used instead of dial gauges at Frorieps' plant. Theodolites are rarely used in mechanical engineering except, perhaps, for turntable rotational accuracy checking, optical tooling techniques being virtually unknown.

For long length comparisons, light structural beams, such as the triangulated tubular steel beams used by Waldrich (Coburg), are used in conjunction with similar length measuring machines fabricated from machined rolled steel joists. The one at Sulzers is 7 m. long and has been erected adjacent to their largest vertical borer. End bars used are of the usual stick micrometer design having a 6mm. diameter, spring loaded, internal measuring bar held in an external joining and thermal isolating tube. For external measurement at Sulzers, a thin walled steel tube (50mm O.D.) holds adjustable caliper legs which can be slid along for adjustment. A dial gauge or micrometer is used at the ends. The bars are stored with the measuring base to maintain equal temperatures. Handling of the bar is by special grips placed outside the legs to reduce heat errors. It was interesting to note, however, that the machinists rarely used this bar, a rough pine-wood beam having solid fixed caliper legs being used instead. It was agreed that no two operators really agreed on measurements made. (Brown-Boveri have a similar measuring machine at their Baden works).

Control of temperature continues as a major problem and various solutions have been adopted.

At SIP, the facility for line-standard ruling is housed in a 0.1°C tolerance room in which a further enclosure maintains the ruling machine to better than 0.01°C. All major machines are isolated from the room floor on seismic mounts. Few places have such facilities.

The basic standards at the Sulzer and Brown-Boveri plants are 4m. SIP axial measuring machines and these are housed in $\pm\frac{1}{2}$°C controlled rooms.

Fitting of transducer scales (Inductosyn, Gratings, Accupin, racks etc.) presents the most precise length measuring problem in machine tool construction. Scales are prepared in approximately 0.5m sections which must be fastened to the tool with correct alignment and phasing at junctions. This is usually accomplished by stepping the machine slide, end to end, along a 1m line standard bar of H section, adjusting scales progressively which requires temperature control to at least $1^{o}C$ as better than 10 p.p.m. relative error is desired. Adjustment of the scales at the works is made with the entire machine temporarily enclosed in thin-plastic sheets. The internal temperature is controlled with heaters and/or refrigerator units to about $\pm 1^{o}C$. At least 3-4 days are regarded as minimum for stabilisation, the adjustment of the scales taking about 2-3 days. Only air temperature is measured and at only a few positions. The machine temperatures are regarded as too difficult to interpret due to the vastly differing time constants of various machine sections. It seems that machine temperatures are seldom measured unless the design is new. The alternative method is to adjust the scales in the customers works, adjusting to the precision allowable by the machine environment. For assembly and testing of gear hobbers, Schiess have a large hall controlled to within $\pm\frac{1}{2}^{o}C$. Their temperature controlled metrology room houses an 8m lead-screw finishing and checking machine. This equipment enables the semi-finished screw to be hand-lapped using a, flexible band adjusted, standard screw for comparison. A 3m Zeiss (Jena) axial measuring machine is also housed in this room

Much time is lost during machining of large components for after each machine-cut considerable time must be left before temperature stability is reached and a measurement can be made. Up to a day in some cases as the sizes range to 7m or more. Ambient temperatures did

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not seem to be taken into account, the main reasoning being that the bed, machine and component were all equal. No actual tests checking this assumption seem to have been made.

Pininfarina, of Turin, are well-known as car body stylists and for their small volume, advanced styled, car production and have one of the most extensive automated inspection facilities for measuring and producing vehicle body shapes.

The facility available is a Digital Electronic Automation (D.E.A. of Turin, Italy.) automated inspection machine. This is a three-axis cartesian frame machine with digital read-out and digital positioning on each axis. The unit can take full size bodies. The axis-drives can be manually controlled with a pressure sensitive manual feeler head or can be programmed to increment and take plunge readings at preset variable intervals. Position coordinates are recorded on punched tape which when used with a correction tape, if needed, can be used to plot points on an automatic 6m by 2m plotting table. The points are manually faired. The system is reversible, i.e., the drawing can be read and a marker drill controlled over the subject to drill holes to the depth required in the correct position. The subject is then sculptured to produce a continuous surface. At the time only point-to-point was available but work was in progress to develop software to fair the empirical body curves.

The principle using a single column with ram projection has been applied to an inspection machine produced by Schiess. Digital readout is fitted to the two axis of each column which are used singly or in pairs to measure large components.

Recent additions to the Zeiss (Oberkochen) metrology products are the Multiprismat digital length readout and the Minor-Optic setting equipment. Multiprismat consists of prisms (about 25mm wide) mounted edge to edge between two steel clamp bars. An incremental length readout is obtained by electro-optical techniques. Minor-optic basically uses a d.c. connected, double photocell (a position sensitive photocell) to position a head onto scale lines. This is available as a separate setting head or as a system which can also sub-divide the coarse scale divisions by manual manipulation.

For checking vertical straightness an automated plumb-bob has been made by Froriep. The plumb-wire is supported from the cross-rail of the machine and passes through knife-edges (fastened to the slide) to a plumb-bob. The bob, immersed in oil for damping, is instrumented with four inductive displacement transducers giving two-axis electrical read-out of slideway linearity. It has 5m range and $\pm 5\mu$m/m accuracy was claimed.

Laser interferometers were seen at a number of establishments. Brown-Boveri have engineered their own and it was demonstrated at their new underground, metrology room at Birr. The unit was mounted on a 4m SIP axial measuring machine and repeatability of 0.1μm in the 4m range was seen. This unit used a Spectra-Physics stabilised laser with photo-multiplier detectors. Phase of the two signals was adjusted by slit movement. With its 5 mega.Hz counter circuits, a translation speed of 3m/min has been realised. Some 2μm difference in a 3.5m length existed for the absolute indicated value at the time and work was in progress to see if this was due to error in the scaling circuits. Its conception was brought about by the need for calibration of N-C systems and for shop-floor inspection.

The interferometer used by the P.T.B. (Physikalisch-Technische Bundesanstalt - the National Physical Laboratory of Germany) uses a Spectra-Physics stabilised laser and has movement to 1m.

Photo-multipliers view the finges via fibre-optic channels, deriving quadrature signals by spatial separation across the fringe field. At the time it was in use to calibrate strobe marks made on film which were a position-time record of an experiment to determine the gravitational constant. (This interferometer is similar in design to that available from Heidenhain, Tranreut).

A Cutler-Hammer interferometer was purchased by the R.T.M. (Instituto per le Ricerche di Tecnologia Meccanica, Turin) about three years ago. Little use has been made of it by member companies, Innocenti have decided to purchase their own.

At the Technical High School in Aachen, Germany, a Cutler-Hammer interferometer is operated in conjunction with radial gratings to check gears, screws and gratings. Deviations from the reference measurement was indicated as an analogue output. The interferometer unit was currently in the U.S.A. for modification, where the normal manual compensation controls for temperature humidity and pressure were being made automatic. An investigation of the long term behaviour of the laser was planned.

Short term repeatability of machine tool measuring systems must be close to 10µm which represents up to 1 p.p.m. relative precision for full scale lengths. Very little is known, however, about the absolute length stability of tools. Only one firm has a laser-interferometer on order for these adjustments. Generally it was considered that its utility, at present, does not warrant the cost. (About £15,000).

A recent acquisition by the metrology department of the Eindhoven Technical High School in Holland was a 3m Zeiss (Jena) axial measuring machine. Research aims were to produce ruled scales of up to 3m in length for Dutch use, there being no internal supplier.

The research programme originally was based on using the measuring machine as a standard but a second approach using a laser interferometer has been developed. Brass scales were being ruled on a self-made 3m machine which was enclosed in a temperature controlled enclosure constant to about 0.1°C. The scales were then calibrated on the measuring machine and errors recorded in punched tape form. The next scale was ruled by transverse control from the first scale using a P.E. microscope to position, errors being corrected by electrically moving the ruling head. The laser interferometer, using a Spectra Physics stabilised laser, was built to give a faster record of errors in a scale. Germanium photocells sensed quadrature signals by using the 90° phase-shift of a beam splitter. Counter rate was currently 50 kHz, Fine position control for correction and movement was by use of a closed-loop piezo-electric system. The interferometer bench is made from 25 cm deep, rolled steel joist about 3m long and is suspended from above by springs for isolation.

At Waldrich (Siegen) interest was shown in the problem of in-process measurement of turbine-blade diameter during outer diameter spark erosion. Such a case represents the growing need for in-process measurement methods as the machining process is unable to give accurate dimensional information about the part it is forming. Another example was seen at the Technical University in Berlin where plasma machining was under investigation. Plasma roughing enables parts to be roughly shaped without a cutting process and with little cutting forces. This process will also require in-process measurement of dimension as the plasma length is only a crude measure of size.

Whilst at the stepping-motor development section of Philips, Eindhoven, an automated inspection problem was discussed. The current method of testing stepping motor angle used an optical-lever equipment which was manually adjusted and read. With up to 96 steps to be tested on a motor this is slow. No method was available for satisfactory overshoot tests. The writer proposed a method using a position sensitive photocell to measure overshoot and phase-analogue angle measuring technique synchronised with the step positions to give electrical output of step angles which can be recorded for test purposes. The significant problem was that added inertia should be less than that of the rotors of the smallest motor (about 4mm diameter by 5mm long).

Numerical control (N-C) is now fitted to most large machines supplied. This has made the designers more aware of dynamic performance of their machines. N-C equipment is not produced by the tool-maker but is selected from available units such as AEG, Siemens, General Electric, Brown-Boveri and Westinghouse. Few British equipments are used on the Continent. Systems are generally continuous-path as the larger machines mainly produce continuous profiles. Due to their own peculiar problems it has become necessary for the firms to have their own software expertise and to adapt the electronic systems to better suit their own peculiarities.

The SIP optical jig-borer which uses line-standard scales for measurement of 3D shape up to several metres in length, has been fitted with SIP N-C and read-out. Positioning is accomplished using a P.E. microscope to position over a scale line, with driven synchros being used to sub-divide each millimetre. One model available has a magnetic drum store which records dimensions as the first part is manually made. Subsequent parts are automatically reproduced.

Due to the considerable cost of large-machine tools (often near £1 million) it is not easy to make drastic changes in design. Each new tool is in fact, the prototypes for new ideas. For the reason concepts such as concrete frame machines and the use of automatic closed-loop alignment to correct geometry were still considered too advanced for commercial inclusion. Fabrication is used a little but casting is still more economic for basic frameworks. (Welded fabrication would increase the requirement for better large-scale metrology during construction)

2.3 <u>Civil Engineering Measurement and Geodesy</u>.

As surveying methods are applicable to large-scale industrial metrology a number of geodetic instrument makers were visited to ascertain if future development might favour industrial application. Although industrial application of these products was known to the larger concerns the small proportion of existing sales does not seem to warrant radical changes in production. It was also pointed out that most industrial sales require a heavy company loss to train the buyer to use the instruments. A definite conflict exists between the technical advisors and the commercial sales decision makers who feel that current lines are sufficiently profitable and that radical changes are risky and would give low return. These industries have long experience with fine mechanical and optical techniques but must combine, perhaps reluctantly, with electronic expertise to produce the instruments of the future. Little was said of the precise details of future development for commercial reasons. It is clear, however, that each firm follows its competitors closely. It seems radical future development will come from the smaller firms who can make special equipment at realistic profits as they operate faster with less overhead cost. No firms seemed interested in producing non-traditional forms of instruments which could possibly be more economic. For example, in alignment applications the telescope has been improved in accuracy and resolution (at increased cost) whereas a semi-electric method such as laser beam alignment or zone-plate technique appears to be cheaper.

In a round table discussion with three Professors of Geodesy at the Berlin University the case for large-scale metrology was discussed. It was thought that automation in geodetic work was not needed as surveyors strive for precision regardless of the time taken. The geodetic surveyor seldom has to measure dynamic movements as does the industrial metrologist. The view was given that Distinvar of CERN and the Mekometer of the N.P.L. would not radically displace the Tellurometer and Geodimeter as these were, in the main, adequate for present trilateration. Similar remarks were applied to the Viasala interferometric method described below. It was apparent from this, and similar discussions, that Geodesists are generally unaware of the relevance of their skills to industry.

As American style long-barrel telescopes and transits (open vernier scales with four levelling screws) still compete strongly with European instruments on the U.S.A. market a small quantity are still made in Europe for this market although European design is said to be superior.

The number of production surveying instruments useful to automated engineering metrology is increasing and now includes the code-theodolite, the gyrotheodolite and the incremental digital readout theodolite. Sales of the Fennel gyrothcdolite are about twenty per week. Most designs originated at local Geodetic Institutes.

The code-theodolite records the three-angles of the theodolite by transferring an absolute code disc reading onto 35mm film. The film is read in a central processor. Fennel claim the method is economic for larger survey teams where a number of field units can support the expense of a central processor needed to interpret the records.

Kern have developed a code-tachometer which records angles and information of range using tachometric principles.

The gyrotheodolite is useful for surveys underground and where datum points cannot be easily transferred by line of sight techniques. Readings, taken from pendulum oscillations, require about 20 mins. to obtain the maximum 30 sec. of arc accuracy. (The unit produced by the British Aircraft Corporation gives greater accuracy,)

The Digigon theodolite (name derived from digital goniometer) is probably the more useful readout theodolite to industry as the response is of millisecond order and the electrical output signals are directly useful for recording on punched tape or for inclusion in a closed loop control. The prototype model, made by Breithaupt, uses a Leitz incremental radial grating readout system on the horizontal axis. The method, and its need in surveying was suggested and developed initially by Dr.Ing. Zetsche of Bonn who has investigated readout theodolites. Values cycle through 400g as the theodolite is continuously rotated. Resolution is currently 10 new-seconds of arc but facility for 1 second resolution is in-built for future modification. The complete system; theodolite, counter, display, preset and punched tape recorder was costed at about £3000. (The 400 new-degree system is supplied in half of the sales of scales on the Continent). Plans by Breithaupt were, however, to exploit the surveying fields and not to develop industrial sales. A meeting with Dr. Zetsche revealed that he started development of the Digigon method at the same time as Fennel commenced the code-theodolite but due to lack of adequate backing was delayed some three years. He was currently studying the direct use of commercial resolvers developed for the N-C industry. The Geodetic Institute of Bonn also have a semi-automated tape bench for calibrating engineering grade tapes. The bench consists of a 20m length of structural section steel with double, 30mm diam., rollers mounted every 0.5m. The sub-standard tape (calibrated at P.T.B.) is placed on one roller set; the other tape to be calibrated on the other set. The standard tape is then moved by an electric drive until the two divisions of both tapes are coincident (detected by a simple magnifier). The movement needed is readout by a Multiprismat system with punched-tape records. The system has about 10µm resolution with 30µm repeatability at present.

The Spectra-Physics alignment laser head is sold as an extra by most companies. It was stated that Wild were not satisfied that the beam is sufficiently stable with respect to the cavity for alignment of precise order. (At least two British alignment lasers have been designed to reduce this error).

A number of modulated gallium-arsenide distance measuring units, operating in the near i.r., have been released by the larger firms. The range is typically 1000m with centimetre resolution making them suited only for large-size civil projects.

At CERN, in Geneva, extensive precise metrology (better called Engineering Geodesy) is necessary to accurately set up the 200m diameter proton-synchrotron ring and the 300m diameter intersecting storage ring (I.S.R.).

The original accelerator ring survey used angles and length measurements. A special theodolite tribrac (base support) enabled the invar wire reglette to be used through the optical centring facility. The ISR survey is to be entirely by lengths.

Computer programmes are used for calculation from measured data. To improve and speed up the length measurements an automatic invar wire device, Distinvar, has been developed. Basically, the standard length, 1.65mm diameter, invar wire is tensioned at 10kg, by a beam balance, correct tension occurring at the reference position of the balance arm. The first prototype used a circular bubble level to indicate arm position moving the other end of the wire until the bubble was central; this could resolve to 10μm satisfactorily. The unit was improved by sensing the arm position with two contact switches. If the beam is incorrectly placed the base support is moved accordingly by an electro-mechanical feed - this removes the need for two operators. Movement of the base plate is measured by a potentiometer or digital method for recording. Snap-action connectors enable the wire to be attached in seconds. Distinvar is calibrated on a SIP geodetic base before and after each measurement on the ring and a demonstration on the base showed 10μm repeatability over the 37m length.

CERN have approval to make Mekometer units and they are to be used for establishing a reference grid covering the entire CERN estate.

The use of time-rotation transformation for angle measurement has been studied at the Geodetic Institute in Bonn. So far investigated is a method whereby a laser beam is reflected by a rotating mirror from one end of a subtense bar to the other. A photo diode detects when the beam passes each end of the fixed 2m distance. Only 1:2000 accuracy was achieved in this study, the main errors being due to rotational non-uniformity. (Inertia rotational smoothing was not used). The next alternative to be tried will be to measure mirror angle by incremental pulse generation instead of rotational time. Time-angle transformation has also been studied by Dr. Zeichen, whilst at the Hannover Geodetic Institute. The prototype produced, was capable of 0.1 seconds of arc resolution and achieved about 1 second of arc accuracy under field conditions. This principle is used in the MTIRA diameter measuring equipment.

Professor Bray of the Institute Dinametrico in Turin, heads research related to force measurement and calibration. Work on l.d.v.t. and laser measurement was in progress. One recent task of the Institute was to instrument the tilt of famous Leaning Tower of Pisa. A liquid circular pool surrounds the base. At diametrically opposite sides are floats driving l.d.v.t. units whose outputs are continuously recorded. A back-up, second, system using a Talyvel electric-level is mounted on a wall. This is not entirely satisfactory due to short base of the Talyvel responding to short term variations.

An automated project in progress at the Institute of Applied Physics, Delft, was to record position of a ship model as it moves in a 60m. by 60m. test tank. Two coordinates will be computed from the angles (and a base-line) of two tracking heads that track the ship continuously. A circle of corner cubes will be attached to the model. A similar two-axis tracker has been previously made for measuring a radiation source position to within 10μm in an area of movement 200 by 200mm. Four cadmium-sulphide cells form a position-sensitive detector which tracks the source.

The majority of the work of the above Institute is concerned with large-scale metrology for the civil engineering industry in Holland. Advice only is given to the mechanical industry who normally do their own instrumentation. This has resulted in considerably more expertise in the larger civil sizes as feedback of industrial information is sparse. The late Professor A.C.S. Heel pioneered most of the alignment methods used, these being diffraction effects due to circular zone plates and spherical optical elements. (This group was visited by P.W. Harrison (N.P.L.) in 1967 and a report of his visit is available from N.P.L.). Zone plate alignment has been used in numerous civil constructions all over Holland. Notable applications mentioned were:

1. Alignment of a rising, water lock used to bodily lift the ship and the lock tank up a 5% gradient over a 300m movement. 80 wheels support the unit.
2. Optical guidance of the nominally 200,000 ton tanker being made in Amsterdam. This had to be guided through a relatively narrow canal to the North Sea. The pilot was aided by a series of slits and lights.
3. Squareness of the joining of the halves of this ship which was made in two sections due to length restrictions in the dry dock. The cross-section shape of each half did not seem to have been measured with high accuracy.

4. Measurement of dyke movements where large disturbances are created by excavating or building close to the dyke wall.
5. Vertical control of liners in hollow-pile foundation construction.
6. Paper mill roll alignment.
7. Deformation measurement of the Eindhoven Exhibition building during construction.

Zone plates are mounted in two axis adjustable plates which mount to the bench mark using a taper plug not unlike a morse tool-bit taper. Repeatability of 10µm for the taper joint was claimed. The zone plate has also been used instead of the normal theodolite objective lens. This, as in autocollinator telescopes for theodolites, has correct focus from zero to infinity for sighting and, therefore, avoids telescope optical axis errors due to the focusing lens movement. (The N.P.L. are using the zone-plate method with laser illumination inside an evacuated 500 ft. tube to produce a reference alignment bench for testing alignment devices. Theodolites are used frequently with readings being recorded directly on IBM data sheets ready for computation.

In the past it has only been considered necessary to have long-length stable bases to test length measurement accuracy and a number of such bases were seen. The other necessary quantity, angle, can usually be checked with relatively inexpensive equipment but the need for a reference alignment bench for testing alignment methods has been recognised and will be filled by the project of the N.P.L.

In the basement of the stately Bavarian Academy of Sciences in Munich is mounted a base for investigating the Viasala interference comparitor, long-distance measuring method. The base is 30m long and remains constant to within 2-3°C all year round. This base was used to calibrate the tapes for the Hamburg accelerator survey. It consists of concrete blocks spaced at 6m intervals. The velocity of light has also been determined here.

The Viasala method is briefly as follows. A one metre quartz bar with polished and calibrated ends, is standardised from the fundamental standard. The bar is placed into the apparatus with one end touching a mirror and the other just clearing a mirror at the other end. The next base point is prepared by placing an adjustable mirror approximately in place. Radiation is passed through the bar and also along a path adjacent to the bar. The adjacent path length is made to be a multiple of the internally reflected path in the quartz rod. By interferometry this can be used to multiply the rod length to the next base point with high precision. This has been used to establish an 864m base. In the laboratory the precision is about 0.1 p.p.m. and in the field about 1.p.p.m. The actual measurement is comparatively rapid but the setting of base points must be performed many weeks before to ensure stability..

For exacting calibration of tapes and wires the geodetic comparator is used. The SIP version is the most used and consists of vertical pillars set, usually every 4m upon a solid foundation. Each pillar carries a microscope having 0.1μm resolution and a range of movement of a few millmetres. For calibration a four metre standard bar is placed under each pair of microscopes using a light supporting railway. The tape or wire is erected under the microscopes and compared with them. The base is then recalibrated for a check. SIP have supplied over 20 bases to date, the most recent being at CERN in Geneva and N.S.L., Sydney. The CERN base is unique as it has a scale and microscope system which enables the end 4m bay to be sub-divided and the reglette to be ruled on the base. The CERN base is instrumented with a 100m invar sag wire. The centre of the sag is connected to a L.d.v.t. transducer whose output is recorded. It is sensitive to less than 1μm and to reduce drifts due to staff movements, the sag wire is encased in a 4in. diameter galvanised sheet-steel pipe. It was also learned that construction has started in Turin of a geodetic comparitor base for Italy.

From the limited experience gained in the previous research project of the writer (1) it was possible to propose areas of application where improved measurement of large-scale positions would give economic return. A list of these was published in a paper which is included in appendix 7.5. It is interesting to note that recent uncollaborated work by Gosling gave a similar list (17) . During the last two years many visits were made to British industry, research institutions and conferences, in order to expand the writer's experience and to provide assessment of current problems and capabilities in order that original research could be directed towards useful application. A few of these problems are now described.

Through the writer's association with the English Electric Company, it was learned that insitu machining of large (60ft) diameter turbines was thought to be more economical if a satisfactory way of controlling a workpiece supported machining head was available. This would allow the part to be assembled from rough castings or by fabrication and be machined to final tolerance without need for transport and disassembly. One aspect of this research has shown that this is now possible using the trilateral control technique described in Section 5.1. The fundamentals of triangulation are given in the following review on transducers (Appendix 7.4) and by a paper given in Appendix 7.5.

A recent metrology problem at their Rugby Works was to mark out mounting holes on the vee-block shaped frames used to support a turbine stage. The requirement here was to locate holes on the upper horizontal faces of the 30 odd feet sections which were placed evenly about the framework centre-line lying some 15ft lower in the vee centre. This was performed with cartesian measurements but could have been more easily measured by a trilateration method. A similar problem was seen at the F.H. Lloyds plant in Birmingham where two fabricated gearboxes (about 20ft by 15ft by 15ft) had mirror-image dowel holes arranged in a triangular layout. These required 2in. diameter dowels to fit with .005in. tolerance, the centre-lines being about 12ft apart. The holes had been bored with a large ram borer but did not match upon assembly. This was put down to borer scale inaccuracy but temperature error was probably more correct. Harland and Wolf (ship builders at Belfast) have introduced quality control of the size and shape of weldments which came as large as 50ft in dimension. This will ensure that fabrications taken to the assembly berth from the fabrication shops fit with reduced re-work. This departure from traditional practice of cut and fill will require improved 3 dimensional measurement of the weldments. Another recent trend is to one-side weld stock plates to produce an enormous sheet from which ship-sections are cut directly. Control of flame-cutters to 200ft ranges could be needed. The above examples can be solved, in the writer's opinion, by continuous wire measuring devices as described in Section 4.

Another class of measurements are those where small changes in a nominal length must be measured. Whilst at Lloyds the problem of assembling the teeth of an 80ft diameter fabricated gearwheel of a drag-link excavator was discussed. A possible solution of this is given in the roundness measuring method investigated. (Section 5.2). After publication of the transducer review paper (Section 2.3) the writer was consulted on the problem of measuring turbine movements in a generating power station. The ideal requirement here was to continuously record the 3 dimensional movements of all bearings (about 12 spaced along 100ft) as the load and temperature change. The vertical component is already measured with relative ease using water levels but the two horizontal movements present a more difficult problem and the method earlier considered by the staff of the C.E.G.B. was to use laser beams passing through light path shield tubes. A more economical solution was formulated during the discussion in which triangulated tensioned wire deformation transducers could be arranged to measure small changes from the bearings to a temperature controlled framework supported from the roof. (This method provides a reference plane of measurement which needs no precision location relative to the building provided all lengths are measured simultaneously). The initial knowledge needed to solve this problem has been proven by this reported research, see Section 4 for deformation transducers and Section 3 for the framework. With wires a cost of about £100 per measurement, giving absolute analogue readout in electrical form is realised, compared with probably £500 per measurement from the laser system. This application is still under review by the C.E.G.B.

A final application of note is the measurement of seismic strains in which strains of 10^{-9} must be recognised over periods in the range of 20 seconds to many weeks. The quest for a cheap and portable strain meter for earthquake prediction and geological studies may be solved with this method. The application resulting from this project is described in Section 5.3. It is clear from above that accurate and economic large-scale measurement has become a necessity. Out of the many solutions suggested by the writer, the only request for immediate assistance was the seismic application. In all other cases an obvious reluctance to spend any amount of money was apparent. The usual remark was that the bill for any preparatory research should be footed by governmental sources. To enable the potential to be demonstrated, therefore, a number of applications have been constructed in the laboratory being selected to include a wide variety of known problems. The results have been widely circulated (Section 7.6) and it is now up to industry to apply them to their particular applications.

The next sub-section covers a review of automated large-scale transducers which completes the possibilities for measurement in this new discipline. Considerable overlap is evident for in fact most transducers can be used for manual measurement with advantage.

2.2 Transducers for the Decametre Range

The initial period of this project was devoted to a literature survey to ascertain the availability of established principles and instruments suitable for large-scale position control.

An extensive review was eventually compiled which covered over 200 different tests and published articles. Due to the interdisciplinary nature of measurements and tothe lack of a suitable journal for the publication of metrology in its own right, the material was collected from extremely diverse sources. Experience gained during less extensive searching of the previous research degree also helped to broaden the scope of the review.

The conclusion was drawn that although numerous suitable principles exist, few have been developed to a usable stage suitable for a systems designer. It is especially characteristic of the measurement discipline that theoretical studies are insufficient in themselves as only practical investigation can discover all the necessary assumptions.

During preparation of this review cartesian and triangular co-ordinates systems were compared and it was realised that the latter was more applicable to larger sizes. It is hoped that all methods for measurement are included and in several instances principles giving only low accuracy at present are detailed to ensure that the review user is aware of the possibilities. The majority of the paper is concerned with the measurement of lengths but as pointed out many measurements have more than one dimension and the technique of length transduction must be chosen to yield multi-axial information. They may also be supplemented with alignment sensing methods, which measure small angles and extend a line into space, and also with angle measuring transducers that give rotation of the extended line or number. Due to the length of this paper, a reprint of the published form is given in Appendix 7.4, to avoid repetition.

There have been a few developments of note since the printing of the review which was brought up to date at proof stage. These follow.

Measurement of the effective diameter of flexible rings forming part of the new jumbo-jet engines has been investigated at Rolls Royce, Derby. They have developed a roller circumference measuring instrument for this purpose which is to be marketed.

Laser interferometer research at the N.P.L. has now raised counting rates to 10 Mega Hz with reduced signal to noise ratio requirement. This work has two aims, being to provide a more rapid method of establishing geodetic lengths (50m) in their tape calibration tunnel and secondly to detect earth strains in seismic studies.

The latter investigation is in collaboration with the Department of Geodesy and geophysics, Cambridge University. (See also Section 5.3). Laser interferometers are finding favour for this measurement (18) . The Rank Organisation is at present evaluating its recently developed industrial interferometer in field trials and it is to be released shortly. New models are now available from the American manufacturers of interferometers. The cost of such equipments is definitely reducing.

International agreement now exists about the stability of the helium neon laser and its use as a standard of length is becoming apparent (19) .

The N.P.L. Reference Alignment bench is nearing completion and when commissioned, will be able to verify the alignment behaviour of established instruments and enable investigation of optical path effects to be carefully studied. This unit generates a precisely straight line using a laser beam passing through zone plates arranged in boxes at intervals along the 100m length. The total light path is contained in an evacuated aluminium tube.

The N.E.L. absolute displacement transducer system using compounded "diffraction" gratings is now available commercially at a cost comparable with incremental systems. In general, industrial demand has forced the size of radial gratings down and 2in. diameter radial gratings having 5000 lines have been used in several commercial applications.

It was interesting to find that the British Calibration Service are considering the use of a large calibrated three dimensional gauge-block for checking multi-axial measuring systems. Previously traceability was proved by independent checks of translations and angles.

The survey generated many new ideas, especially the use of optical methods. These had to be put in obeyance for fear of broadening the project beyond the capabilities of the limited time and manpower.

The technique of triangulation offered great promise for the larger sizes and as wires were able to realise it, the project applications side concentrated on their use as continuous length measuring devices. This broadened as the demand and possibilities of deformation measurements became apparent.

A short review paper covering length measuring transducers .. ranges to a few metres was delivered to a conference on digital techniques. This is also bound in the Appendix 7.6. It contains a few additional references to the main review paper.

2.3 Electrical Gauging Techniques for the Millimetre Range.

In tensioned-wire transducers it was necessary to measure small axial movements, usually not exceeding a few hundred micrometres (Section 4) in deformation methods and to be able to produce an analogue transient signal of the rotary oscillations of the measuring drum in the continuous units.

Three available alternatives were the position sensitive photocell (psd), the linear differential voltage transformer (ldvt) and the capacitance displacement probe. At the time it was thought that the first method would be applicable to all requirements with the use of special, but simple, optical elements.

Available literature on these cells gave little quantitative information regarding stability and practical detection limits. An investigation was made to produce instrumentation using these cells for recording drum transients and measuring linear movements. A paper has been published on this work (9) (Appendix 7.4). In this, the literature has been reviewed (some 45 papers have been published on the cells) and the design and applications of the simple dual-cell to one-axis measurement is given. It was found that linearities of 0.5% were realistic with stabilities of around 1μm over a period of a few days. By the use of the optical lever and parallel plate principles, rotary measurement from seconds to degrees of arc could be made. Direct linear measurement of movements across the cell and perpendicular to it are also described.

In the early stages of the project these methods are satisfactory but as the deformation measuring aspects of the project developed with the successful construction of a temperature controlled measuring base the need for 0.01μm resolution with hundreds of hours stability become apparent. Position sensitive cells could possibly have provided the resolution needed by using more expensive cells and a longer optical lever path length but the stability beyond several days was not established.

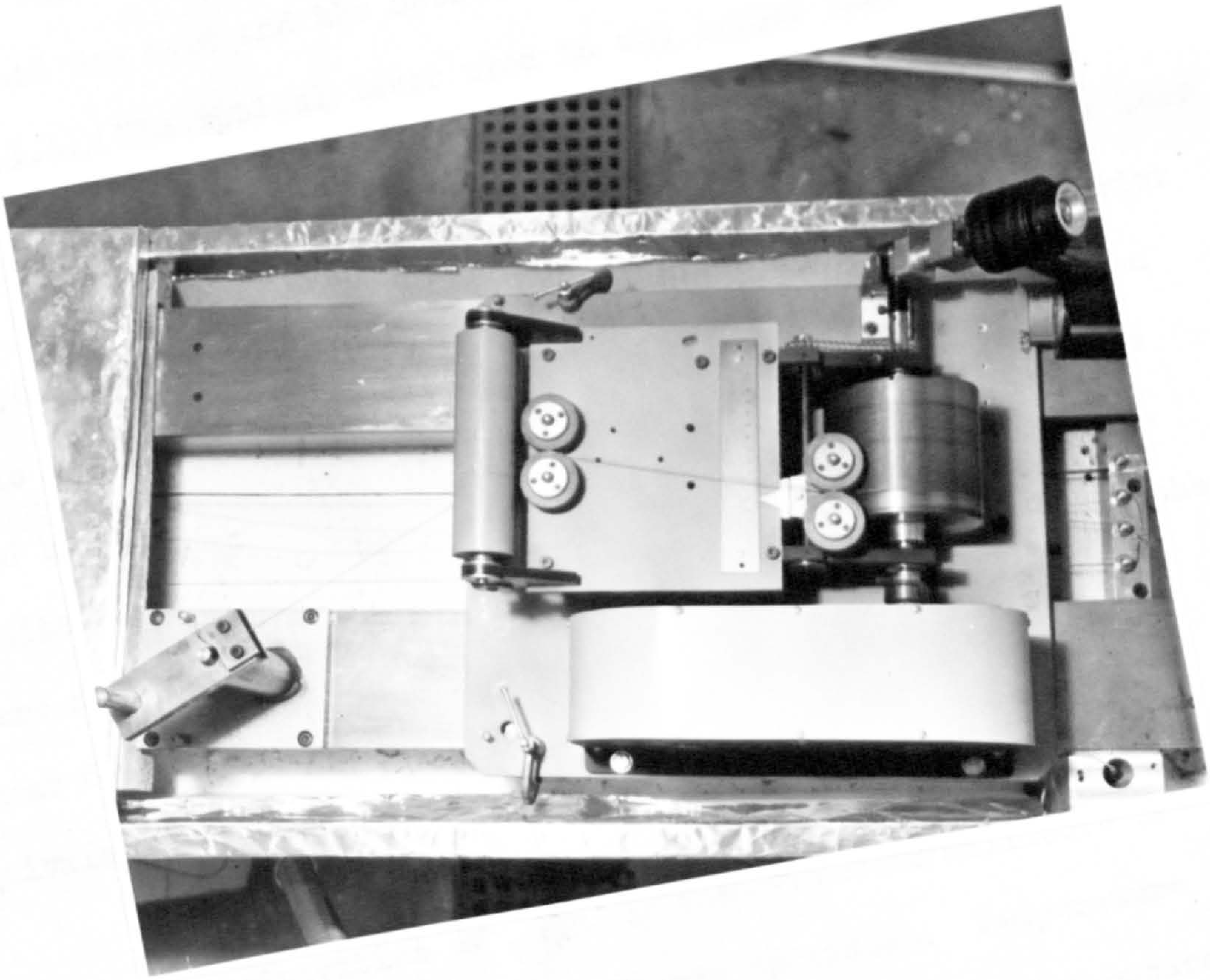

Figure 2.3.1. Digiwire I mounted on test base with analogue output for transient measurement.

Further investigation of other alternatives was made in which ldvt and capacitive probes were utilised. Photocells were found to be suited for response testing of the large-range cartesian wire transducers and for repeatability tests of a 1.5m range unit. (Section 4.8). In the former case the parallel plate method was used and the method of use is illustrated in figure 2.3.1. The optical lever used in the latter case is shown in figure 4.7. Further figures are to be found in the reprint.

The sensitivities of the constructed beam balances were less than 0.01μm (Section 4) and in such cases linear probing is superior as this measures directly to the wire end. In any shaft rotation method bearing errors enter into the measurement. Originally the capacitance probe (Wayne Kerr) was applied to this measurement to ensure non-contacting operation. It was later established that the linear differential voltage transformer (ldvt) probes could give equivalent performance if roller ended probes were used.

By amplifying the capacitance probe electronic output, recording sensitivities of .01μm of wire movement/millmetre of chart were easily obtained with linear operation. Temperature drift (about 1μm/°C) and time drift (about 2μm/day) were apparent in this unit. Tests were made using a 0.005in. range probe. As the gap clearance was limited to 0.1mm when measuring with such sensitivities the probe adjustment was critical and it only allowed small movements of the balance.

Tesa gauge heads contain an integral ldvt system with the moving element supported on a ball bearing spindle. The electronics directly display movement, have electrical zero shift, and can be switched to obtain sensitivities of 1μm f.s.d. with a corresponding

200mV recorder output. The probe can be moved over 2mm. 4000 hr. stability of no greater than 1% of f.s.d. is quoted. These probes and the associated electronic unit are shown in a later figure, 4.4. Most measurements could be made with these units unless a frequency response above about 10hz was needed. The capacitance probe is useful to about 10 kHz with the position sensitive photocell going to above 1 Mega Hz.

3. LENGTH TESTING FACILITIES FOR THE DECAMETRE RANGE.

3.1. Installations in General.

As 90% or more of all engineering measurements are said to be within 300 mm capacity it is not surprising to find few installations for checking long-length measuring devices. The requirements include stable length to better than a part in 10^6, rigidity, a calibrated scale over the entire length and good temperature control. These are nearly met by geodetic survey bases of which there are about 20 throughout the world. These are used to calibrate tensioned tapes and wires by a technique traceable to the agreed National standard of length. With the exception of the base at CERN in Geneva which has a facility for subdivision of one bay, these bases only give in-scale locations at about 4m intervals over their 50m lengths. Current work at the N.P.L. is aimed at using a laser interferometer to subdivide the base length.

In industry, usersof large machine tools have constructed bases for comparison purposes using a solid metal structure. Lengths to 8m have been reported. These are usually placed by the machine tool to equalise temperatures. High precision measuring machines, up to 4m range, are available which hold scales of line-standard accuracy.

As no suitable base was available locally it was decided to construct a relatively crude base made from continuous steel. This was subsequently temperature controlled by internal water flow and now appears to have better stability than any other manufactured base in existence.

3.2 The University of Warwick 12m Base.

Previous testing of the repeatability of continuous length wire measuring devices had been carried out using coupled steel bars to give 14m distances. In November 1967 a section of one of the school's Heavy Engineering Laboratories was equipped as a large-scale metrology research and manufacturing area. Metrology facilities up to about 500mm were available in a small metrology room.

As there was no good reason for insisting upon 14m range a metal measuring machine was built across the 12m width of end of the laboratory. This base has no calibrated scale or absolute length calibrations but provides a constant reference length for testing the repeatability and long term stability of tensioned wire transducers. As these can repeat to about 4 parts in 10^6 or better, temperature control of the steel's length was needed. This was added about August 1968 being completed by October. Since that time it has been operating continuously. The details of this base have been published and a reprint is given in Appendix 7.6 where the method of testing and the performance are also described.

A general view is given is figure 3.1. For repeatability tests of continuous devices, two pins project through the insulation giving an external controlled length. These can be seen in the figure.

Figure 3.2 shows the transformer and low inertia heater (mounted in the glass tube), the mercury switch relay which switches the heater and the pump motor, with contact thermometer demands and the two pipes that couple the two sides of the base through this

Figure 3.1. General view of 12m measuring base.

Figure 3.2. Underneath view of right hand end of base.

heating and circulating equipment. A top view, showing the contact thermometer, can be seen in figure 4.4.

Although satisfactory for continuous device checking where inherent errors limit precision to a few parts per million, the length stability is apparently still inferior to that of the tensioned invar wire limiting creep determination to reasonably short periods. (Section 4). Further work is continuing in a disused railway tunnel at Queensbury in Yorkshire in the hope of obtaining extensions to this knowledge on creep. (Section 5.3).

The base operates in a normal environment of about $\pm 3^{o}C$. Hundred hour stabilities of 10^{-8} have been obtained when the laboratory conditions were within a degree or so indicating the possibilities of this technique in a more suitable location, such as a basement or tunnel. The current stability obtainable is probably an order of magnitude better than any other manufactured facility in existence, although similar performance is possible in some deep rock tunnels.

Bending of the base has been measured with an autocollimator (Hilger and Watts, two axis) which was directed through the internal air-space. The image was stable to within its 0.1 second of arc resolution. Over a week period the maximum variation was about 4 seconds of arc implying alignment to at least 0.25mm. Rotation of the mirror bracket was monitored with an electronic level (Talyvel by Rank) and was always within 1 second of arc. Special brackets were needed to hold the equipment and it was considered that this contributed error due to creep in welded joints.

4. FUNDAMENTALS OF TENSIONED-MEMBER DIMENSIONAL TRANSDUCERS

4.1 INTRODUCTION

Tensioned flexible mechanical members have been used for precision surveying since 1784, when Roy experimented with a steel chain. About 1885 Jaderin introduced the continuous wire method which has been retained. The discovery of invar in about 1896 overcame temperature variation difficulties and precision base lengths were measured with wires and tapes until about 1955 when electronic devices enabled long bases to be directly measured in a greatly reduced time. Tapes and wires are still used to establish both short lengths (where electronic methods have insufficient resolution) andalso long bases for comparison purposes.

Although used almost exclusively in surveying, numerous engineering measurements can be made by tensioned-member transducers, especially if electrical output is produced. Measurements fall into two groups, the first being to determine small changes in a large nominal length and the second to provide continuous measurement of length over the entire range varying up to a hundred metres or more. These will be referred to as deformation and continuous methods respectively.

Deformation tensioned cord transducers have applications in recording of movements of large civil and mechanical engineering structures, for instance, concrete erections, buildings, power-station foundations and power-set movements, deflections of aircraft frames, machine tool structures and ships, under both static and dynamic conditions; in calibration and use of survey wires for base measurement and engineering geodesy; in creep testing and temperature coefficient evaluation; in setting up of rolls where parallelism is vital and for mechanical transfer of small movements to remote locations.

Applications investigated in this project include, long-term length stability of a 12m measuring base; creep testing of the wires and fibres; a strain seismometer and measurement of the circularity of large rings. It is shown below that relative movements of 1 part in 10^{10} can be detected with a tensioned wire held between two end supports and that stability to a few parts in 10^{8} is attainable over periods of several hundred hours.

The second group of applications includes those where position along the full extent of the wire is needed. Examples include, readout and control of position ranging from millimetres to decametres, for instance, in machine tools, gantry cranes, plotting tables, flame cutting machines, microcircuit master production and for manual marking and inspection of precision components of sizes up to several hundred metres. In many cases wire transducers enable trilateration to be used (Section 2.2) with advantage as an alternative to the conventional cartesian method.

Investigated designs include 15m and 12m range units, the latter being mechanically linearized and including mechanical absolute length and temperature error adjustment, a 1m unit with partial range readout and a 1.5m range model which will be linearized by electronic computations. The 12m units have been used to control position in closed-loop mode using both rectangular and trilateral coordinates (Section 5.1). Repeatibility of about 4 parts in 10^{6} (standard deviation) is achieved with the larger units and 1 part in 10^{6} (s.d.) for the smaller versions. The accuracy compares with the repeatibility. Such performance compares favourably with the laser interferometer working in a normal industrial environment. With wire methods, however, these are considerable advantages, for the measurement is mechanically absolute, resolutions can be matched to range to yield maximum translation speed when incremental readout is used, scaling and inscale errors can be corrected mechanically (the method is not affected by humidity or pressure), life is expected to be considerably longer and finally no guideway is necessary to control the measuring system translation path.

Formulation of static conditions of wires and tapes has reached great sophistication during the years 1890 to 1940. This work has been summarized by Bomford in 1952 (20). His review includes sag, temperature, tension, slope and end scale corrections and the effect of wet, dirt, wind and pulley eccentricity. Friction effects have been studied by Hotine (21) but results quoted are relevant only to actual tests made on a pulley and weight system. His study did not directly consider bearing and hysteretic frictional errors in the tape.

Further work by Clark of the N.P.L. (22) has considered the choice of cross-sectional area for a given tension and span, effects of gravity variation, stresses in the tape or wire and effects of additional loads.

Little has been reported regarding the other important factors, namely, effects of friction on the detection limit, methods for applying tension, dynamic behaviour assessment, effects of temperature and suggestions for compensation, creep and material hysteresis, types of materials, readout methods, choice of scale of magnitude for the system and applications to other areas of dimensional measurement. These are the subject of this paper. Although the term wire is used, most remarks are relevant to tapes and cords.

4.2 SOME TENSIONING METHODS

Four methods have been investigated for tensioning the wire, in this research study. These are, pulley and weight, beam balance, constant torque springs and electric motors. As the choice depends upon the angular rotations needed, the non-absolute, latter two, are most relevant for continuous transducers as many revolutions are generally needed. These methods are shown diagrammatically in figure 4.1.

In surveying work tension has traditionally been applied by using a weight held by a cord passing round a pulley. This provides constant tension at any angular position. If absolute tension is needed over a limited rotation, for example, where movements are small or where the tension head is moved physically to restore balance, a beam balance may be used eliminating the oscillations of the hanging weight and frictional errors of the cords. (Recent work at CERN in Geneva has resulted in the development of a null-seeking beam — balance known as Distinvar(23)). As the dynamic performance depends on the rotational inertia of the unit (see section 4.3) it is desirable to reduce the inertia to a minimum. This raises the natural frequency of the system, reduces transient stresses in the wire and reduces the possibility of the system vibrating in its transverse, less controllable, mode.

For pulley tensioning the inertia consists of components made up from the weight virtually rotating at the pulley radius plus the inertia of the pulley which is approximately equal to that of the weight.

For a beam balance the inertia is similarly due to a weight acting at a radius. In this case there is no additional pulley component and the weight and radius can be varied to minimize the inertia whilst maintaining the same torque. (Inertia being proportional to the square of the radius, torque proportional to radius). Even so, a beam-balance constructed to have reduced least inertia for a given torque by using a large mass rotating at a small radius has considerably greater inertia than that of spring or electric methods

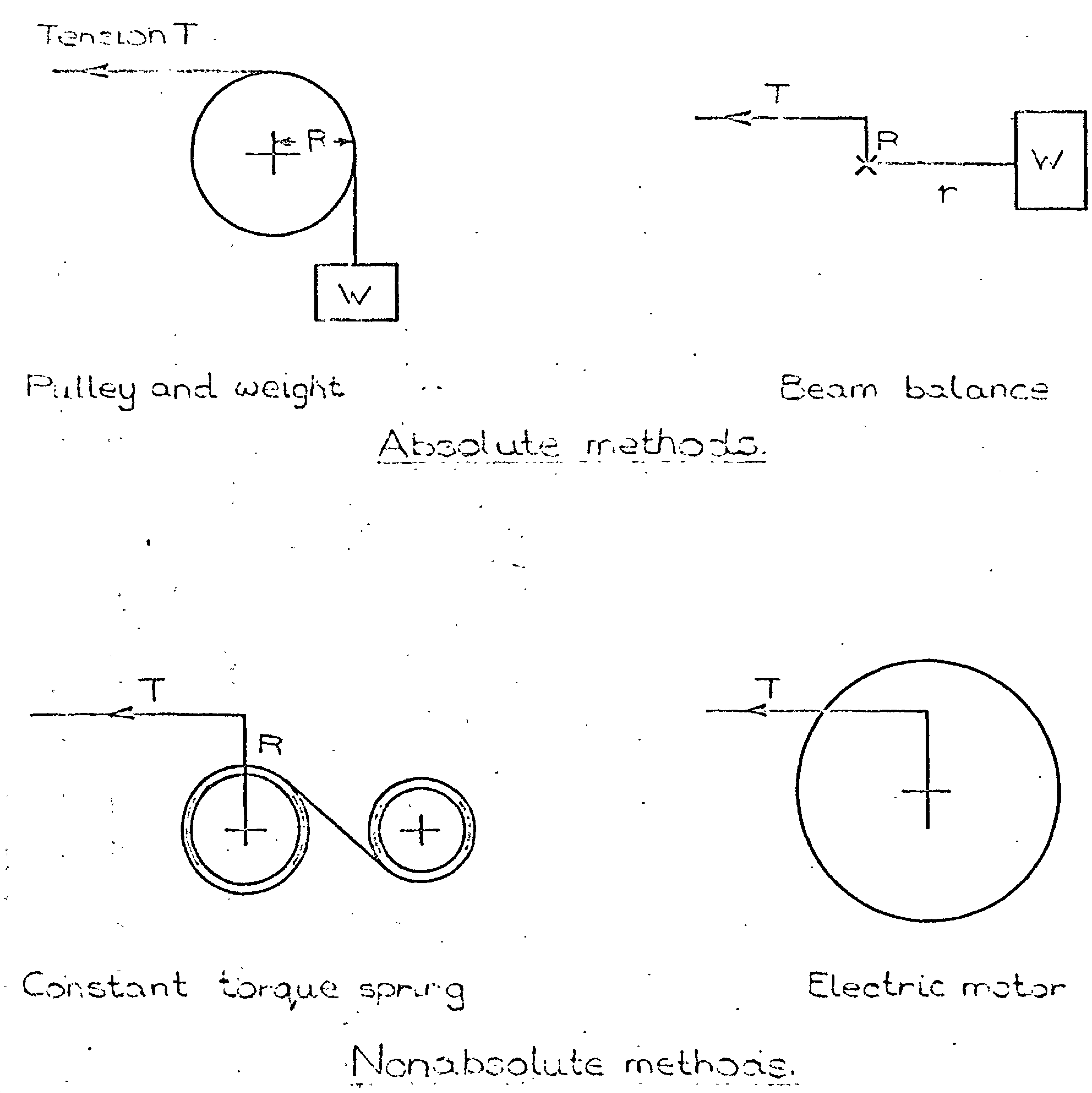

Fig.4.1 Investigated tensioning methods

of tensioning. A comparison of the torque and inertia of various designs is given in the table 4.1.

Large displacements can be achieved with absolute methods by allowing sufficient travel for the weight or by translating the head to a null. The use of gears to reduce the mass displacement increases the inertia as the square of the gear ratio, the torque being increased proportionately.

For continuous transducers neither absolute method is satisfactory as lengths of many metres must be accommodated and low inertia is important. Two alternative solutions are to use constant torque springs and electric motors.

The rate at which the system recoils or releases the wire is decided by the inertia as the tension is virtually constant. The tensioning mechanism of continuous transducers is often required to rotate a drum of significant inertia. West has shown (24) that the ability of a torque producing system to accelerate a matched load inertia is best assessed by the torque^2/inertia ratio, or power-rate, a term recently applied to electric motor terminology (25). If the inertia coupled to the tensioning head is negligible, as is the case for deformation transducers, the torque/inertia ratio is the measure of acceleration ability.

It has been found that the constant-torque spring motor gives highly repeatible, continuous, smooth torque with low inherent inertia. Static analysis of these motors was reported by Votta in 1952 (26) from which torque output, life, size and spring stresses may be calculated. For dynamic designs an estimate of the inertia is needed.

It is shown in the appendix 7.2 that the inertia of these motors can be approximated by assuming it is produced by a cylinder of spring material with inner radius that of the output

ABSOLUTE METHODS

	Torque (kg.m)	Inertia ($kg.m^2$)	Remarks
Pulley and weight			
10 kg. on 100mm rad.pulley	-	$1.0\ 10^{-1}$	Pulley inertia ignored. Supplies 10kg tension.
10kg on 150mm rad.pulley	-	$2.3\ 10^{-1}$	
Beam Balance			
1 kg at 300mm rad.	0.3	$9\ 10^{-2}$	Each supplies 10kg tension at 30mm radius.
10kg at 30mm	0.3	$9\ 10^{-3}$	
100kg at 3mm	0.3	$9\ 10^{-4}$	
5 kg at 15mm	0.075	$1.3\ 10^{-3}$	Comparable fi[illegible] for 2 kg tensio[illegible].

NON-ABSOLUTE METHODS

	Torque (kg.m)	Inertia ($kg.m^2$)	Remarks
Spring Motors (20,000 cycle life)			
70 Turns			
.05mm spring thickness	0.075	$7.3\ 10^{-5}$	Digiwire II possibilities.
.07mm "	0.075	$2.8\ 10^{-4}$	" " "
.10mm "	0.075	$7.2\ 10^{-4}$	Digiwire II - actually used.
.3mm "	0.110	$1.2\ 10^{-2}$	Digiwire I motor
10 Turns			
.05mm "	0.075	$1.0\ 10^{-5}$	Suitable for shorter range continuous transducers.
.07mm "	0.075	$2.4\ 10^{-5}$	
.30mm "	0.075	$3.8\ 10^{-4}$	
Electric Motors (Supplied with rated current).			
Printed armature, air cored	0.085	$1.6\ 10^{-4}$	
Cylindrical, air cored	0.022	$3.4\ 10^{-6}$	
Best quoted in 1955 of comparable size (24)	0.070	$6.8\ 10^{-3}$	

Table 4.1 comparison of inertia and torque of torque mechanisms having several turns output.

bush giving:-

$$I_s \doteqdot \frac{\pi}{2} b\delta((r_3 + N_0 t)^4 - r_3^4).$$

N_0 is the number of output turns available, t the material thickness, δ the material density, b the material width and r_3 the radius of the output bush upon which the spring is coiled. As inertia depends upon r_3^4 it is greatly reduced by using a wide spring on a small bush. Votta has shown that the torque output is

$$T_s = \frac{E\ b\ t\ Sf^2 r_3}{24}$$

where E is the material elastic constant and Sf the stress.
The inertia has been measured for a number of the spring motors listed in the table 4.1 and was found to agree to within some 20% of the calculated value.

These springs are also useful in deformation transducers which require larger excursions or faster response. They are independant of gravity and orientation is unimportant. A simple cantilever, precurved, spring strip is probably sufficient to provide tension and a measuring surface, if movement is small. Inherent damping of spring motors depends upon the rolling surface area of the spring moving upon the bushes. Low inertia designs, therefore, have improved damping.

High-performance direct-current electric motors may sometimes be suitably applied. For tensioning applications, however, a number of disadvantages exist which generally exclude them from precise tensioning. Firstly, the torque output varies with angular position. Printed armature d.c. motors have about 1/200 variation. Brush friction significantly increases backlash errors (see section 4.4). Brushless motors are generally a.c. types and have considerably larger inertia for the same torque. The basic cost is larger and a stabilized current supply is also needed. From the comparison table it can be seen that for limited rotation applications requiring torque, the spring motor power-rate is comparable with electric motors operating at continuous current rating in an open-loop mode. Tension may also be controlled using tension feedback to control the motor torque. This increases the complexity and does not seem to offer any accuracy or response improvements over open-loop spring motors.

4.3 DYNAMIC PERFORMANCE

A wire supported freely between a rigid support and a tensioning head will have two basic vibration modes. These are the transverse vibration, moving perpendicular to the wire axis, and the longitudinal mode which vibrates along the axis.

The transverse mode is produced by interaction of the restoring force exerted by the longitudinal tension and the transverse inertial force of the wire. The fundamental frequency is given by

$$f_t = \frac{1}{2l}\left(\frac{Tg}{w}\right)^{\frac{1}{2}}$$

where l is the span length, T the tension, w the weight per unit length of the wire and g the gravitational constant. This can also be written in terms of material constants giving

$$f_t = \frac{1}{2l}\left(\frac{S_u g}{\rho N}\right)^{\frac{1}{2}}$$

where S_u is the ultimate tensile strength of the wire, ρ its density and N the ratio of maximum tensile to actual stress in the wire.

For highest transverse natural frequency at a given length, the material should be tensioned as high as possible consistent with allowable stresses. For a 10m span of invar, stainless steel and carbon fibres of equal cross-sectional area and static stress ($N = 8$) resonate at 4.4, 6.5, and 18Hz respectively, showing the potential of carbon fibres in this work. It is also possible to further raise the transverse frequency with these fibres, as the elastic limit is nearly equal to the tensile strength allowing a lower N value to be used.

The transverse frequency is independant of the tensioning unit inertia. It is the tension magnitude that is important. It is shown below that the transverse oscillatiocan often be eliminated in a well designed system. Clark has also shown (22) that vertical sag changes are about ten times greater than the end movement producing them,indicating that transverse vibration amplitudes are not serious as might be thought.

The longitudinal mode is produced by energy exchange between the longitudinal wire extension and the inertia of the tensioning head. As a first approximation (usually sufficient) the wire may be regarded as a linear lumped spring of spring rate

$$K = \frac{l}{AE}$$

where A is the cross-sectional area and E the elasticity modulus of the wire. The resonant frequency is

$$fl = \frac{1}{2\pi}\left(\frac{R^2 l}{AEI}\right)^{\frac{1}{2}}$$

where R is the radius at which the end of the wire rotates on the tensioning unit having inertia I.

For a distributed wire hanging horizontally in a catenary the spring rate is more correctly the rate of length change with tension which includes the subsequent change in catenary shape. Hotine has shown (21) that this is given (in material constant form) by

$$\frac{dl}{dT} = \frac{l}{T}\left(\frac{Su}{N} + \frac{\rho^2 l^2 N^2}{12Su^2} \right)$$

For a catenary hanging with ends not level, the sag term needs correction for slope but for frequency calculations the sag contribution is negligible unless the span is long or the tension very low. Clark (22) has shown that there is an optimum area for the tape or wire which maximizes the stiffness by balancing the elastic and catenary rate. This occurs when

$$A^3 = \frac{6T^3}{E\dot{\rho}^2 l^2}$$

but as the function is slowly varying considerable deviation is allowable.

Survey tapes and wires are stressed to have N between 8 and 10. This allows a wide stress variation during transients and handling that might otherwise exceed the elastic limit. During these investigations similar N values have been used, there apparently being no exacting criteria for choice. The longitudinal frequency is, therefore, largely decided by the tensioning unit inertia, the radius at which the wire acts (as also is backlash discussed in section 4.4) and the stiffness of the wire which depends upon span, material and its cross-sectional area. A compromise must be made when choosing the latter as this also affects the transverse frequency. Longitudinal frequency is not dependant upon tension magnitude to any practical degree as this only changes the catenary contribution of the stiffness.

From the discussion of tensioning methods given in section 4.2, it can be seen that absolute methods have inherently large inertia compared with springs or electric motors and will, therefore, have lower longitudinal resonant frequency.

Normally expected dynamic dimensional movements will occur along the wire axis. This directly excites the longitudinal vibration mode and may excite the transverse mode if the energy transferred into the transverse directions exceeds the damping dissipation of the wire. The magnitude of this energy transfer is related to the degree to which the catenary shape changes during a transient. This is related to the displacement magnitude and velocity, steady state tension, degree of static wire sag, inertia of the tensioning head, the mass of the wire and the transverse component of the gravitational pull. The effect has been studied experimentally by inducing step displacements to the free end of the wire.

Step responses obtained with Digiwire I (3) at maximum range, were found to occur as beating of the two, approximately equal frequency vibrations producing a damped semi-sum frequency envelope modulated at the semi-difference frequency. In this case the inertia was large allowing the wire to grossly sag before the unit could recoil the released wire. In the improved units, Digiwire II, described in section 4.8, the inertia has been reduced separating the two modes (the transverse frequency remained at 2 Hz and the longitudinal was raised to 8 Hz for a 10m span) reducing the energy transfer into the transverse direction due to improved response rate. Typical step responses of the two units are shown in figure 4.2.

4.4 EFFECT OF TENSIONING UNIT FRICTION

As the wire is elastic, static friction of the tensioning device introduces stiction errors which limit resolution and repeatibility. which appear as backlash.

For frictional forces to be overcome, the wire must elastically change length until sufficient force is generated. This length change is given by

$$l_f = \frac{fl}{AE}$$

where f is the frictional force component along the wire axis. The friction of the tensioning heads discussed in section 4.2 can be

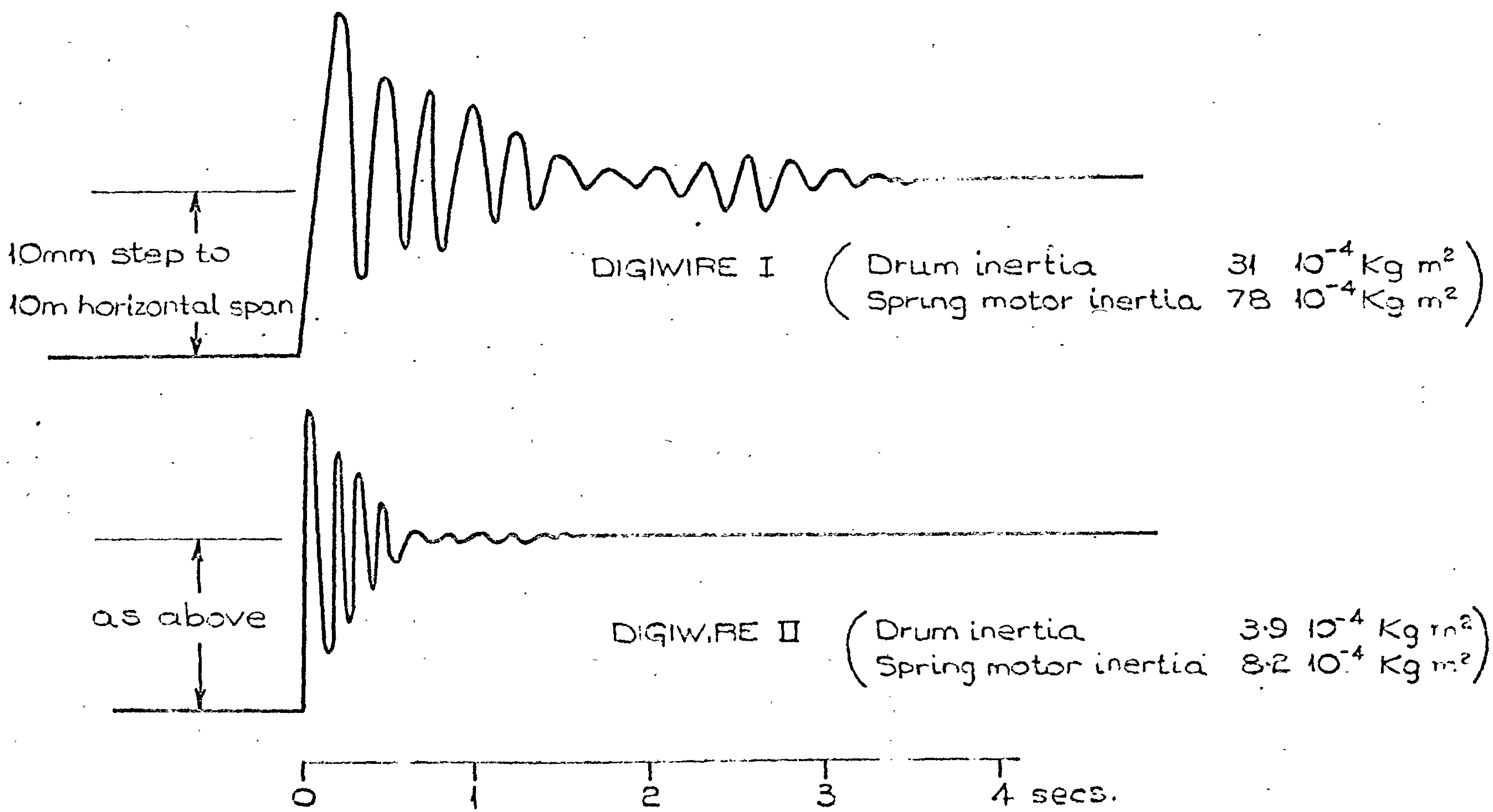

Fig.42. Step responses of Digiwire I and II at 10m span.

regarded as torque, M, acting about the mounting pivot. For ball-bearings, an estimate of the friction torque can be made using

$$M = \frac{\mu \quad PB}{2}$$

where μ is the coefficient of friction of the bearing acting as though it occurs at the diameter B of the bearing bore. The total load P is approximately equal to the wire tension, T. The lowest friction coefficient occurs for self-aligning bearings where $\mu = .001$. Expressing backlash in relative terms we have

$$\frac{l_f}{l} = \frac{1}{2} \cdot \frac{T\mu B}{RAE}$$

where R is the radius at which the wire rotates.

Study of manufactured bearings shows that $B/T \doteq 0.11 \text{ mmkg}^{-1}$ for bearings with static capacity lying in the 4 to 80 kg range. For smaller bearings no general ratio appears to hold. It is of interest to calculate some examples. A small beam-balance deformation transducer has been used to monitor length stability of a 12m measuring base (Section 3.2). It is illustrated in Figure 4.3. This balance applied 2.5 kg tension to a 0.11mm^2 area invar wire. The effective bearing diameter was 1mm and the wire was attached 30mm above the bearing centre. From the above formulation, backlash was estimated to be 2 parts in 10^8, or $0.2\mu\text{m}$ in the 12m length. Experiments showed this estimate to be conservative as observed backlash was some $0.05\mu\text{m}$. Improvement probably occurs due to background vibration. If carbon-fibres were used instead, a larger area could be used for the same mass per unit length, the elasticity modulus is doubled and with a larger radius for wire attachment, sensitivities to 10^{-10} or better are possible with a longitudinal resonant frequency of at least 100Hz at 10m span. (This has led to the initiation of a study of the use of deformation transducers for seismic strain.

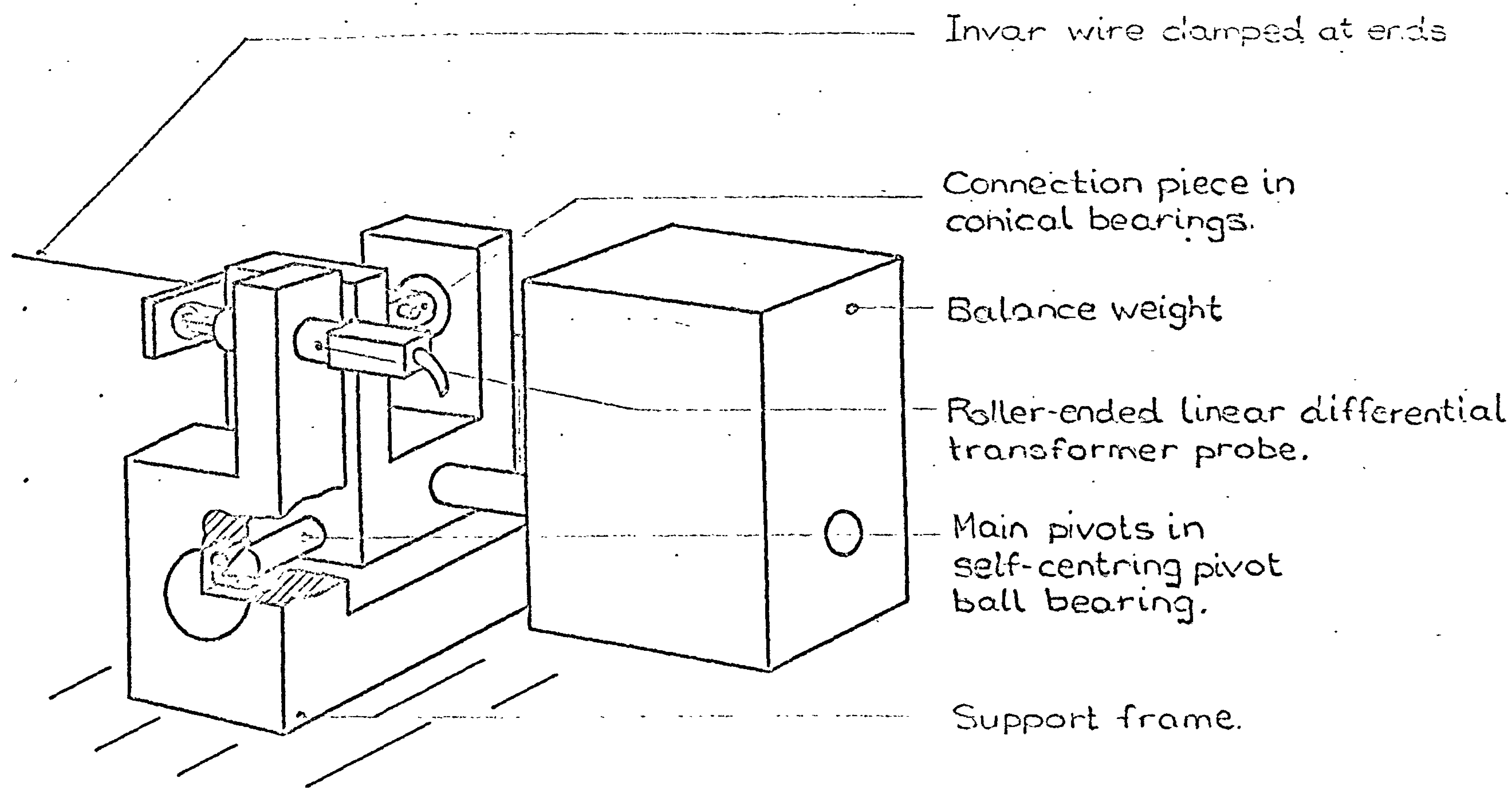

Figure 4.3. Adjustable parameter beam balance.

recording, section 5.3)

A study of the surveyors base tensioning method is also relevant. The tape is typically tensioned with 10kg weights held by a cord passing over a 150mm radius pulley, supported on 12mm bore ball-bearings. Two pulleys are used, one at each end to simplify movement of the tape marks in both directions and to enable push-pull techniques (21) to be used for estimating friction errors. The bearings have a static load of some 240kg and from backlash considerations should be made smaller. Even so, the calculated relative backlash is about 1 part in 10^8 for a single pulley tensioning normal tapes. The N.P.L. metrology centre have kindly supplied actual readings for a double-ended tensioning, single 30m catenary. Of 12 settings, the recorded backlash was as high as 5 parts in 10^7. As base repeatibility is probably about 5 parts in 10^8 over a several minute period, frictional effects appear to be contributed by other causes such as cord friction and material hysteresis.

Other bearing methods such as flexure pivots, air and hydrostatic bearings and knife edges may be capable of lower friction if necessary. The Distinvar unit (23) uses knife edges set onto the inner surface of radial bearings. The bearing tolerances and the repeatibility of the translating head support are greatly in excess of the errors of the knife edges in this case. The standard deviation for complete measurement with this method was found to be a little better than 1 part in 10^6.

4.5 EFFECT OF MATERIAL PROPERTIES

The precision of measurements made with tensioned wires depends upon the dimensional stability of the material under the conditions imposed upon it. There are long and short term effects.

Long term effects - Creep is the term applied to length changes that occur when a material is stressed at a constant value for prolonged periods. The general theory is that creep passes through an initial, relatively rapid, primary stage followed by a much slower rate called secondary creep. Failure occurs at the end of the final rapid, tertiary stage. Current views are that all materials exhibit creep to some degree and that the rate is increased with increased temperature and stress. Creep data, however, must be obtained experimentally and most data have been compiled for severe conditions of high temperature and stress.

Long term changes not fitting the creep theory are termed secular effects. For example, opinions on the behaviour of invar tapes over periods of many months vary widely from one extreme to the other. It is said they lengthen or shorten and abrupt rapid changes have also been observed. Bar standards, which have no applied axial stress, also exhibit unaccountable and unpredictable changes of small magnitude.

Short term effects - If a material is initially stressed to a chosen strain condition and the stress varied about this datum the length does not return to exactly the same strain for the same stress, but exhibits mechanical hysteresis which appears in the measurements as a backlash error which increases in magnitude with increasing stress excursion. Again this is not a quantitative theory and experiments are needed to evaluate magnitudes. In geodetic tape calibration the stresses during calibration and subsequent storage vary considerably implying that mechanical hysteretic friction may, in fact, account for the diverse opinions of invar stability. It also suggests that improved precision may be obtainable if the tape could be kept tensioned throughout its life to obtain less stress variation by a more precisely controlled push-pull procedure or by a vibration technique (see below).

For deformation measurements in engineering the tension is not released during the measuring period and under these conditions hysteretic errors should be negligible provided accelerations are small. Creep and secular changes are of interest in this case. Some useful, but limited, figures on the long-term constant-stress behaviour of invar have been obtained from experience gained from monitoring the length stability of the temperature controlled ($\pm$ .02°C) measuring base (10). In this application the 0.11mm^2 area annealed, Invar 36, wire was tensioned at 2.5kg with a beam-balance. Changes in relative length between the invar and steel base were recorded along with the average base temperature. The maximum recorded variation during a 500hr test was $\pm$ 3 parts in 10^7 with the variation being correlated with the base mean temperature changes. Stability of temperature measurements (.01°C) enabled this variation to be corrected showing that stability over this period was a few parts in 10^8. On several occasions, when favourable ambient conditions existed in the laboratory, similar stability has been directly recorded for 100hr durations.

Stainless steel wire of equal crossection has been tested for shorter periods. As steel has a temperature coefficient of expansion some twenty times greater than invar the experimental resolution was limited to 2 parts in 10^7. Over a period of 100hrs no unidirection creep was observed within this resolution. The variation deviated by 2[illegible] parts in 10^6 agreeing with measured mean temperature variation.

Stranded stainless steel wire cord is used in continuous transducers and as on some occasions the units might be used for deformation measurement, or require zero stability, over prolonged periods, stability is important. Tests of a fully extended Digiwire unit showed no change in the nominal 12m length over a period of one week, the resolution being 3 parts in 10^6 during this test.

Carbon fibres have many of the essentials needed for deformation measurements, these being high rigidity, low specific gravity, reproduceable and negative temperature coefficient of similar magnitude as Invar, good high temperature properties and they may exhibit good stability and low mechanical hysteresis. Experimental evidence on this material is limited. Some tests have been made on a 11m length of continuous filament carbon-fibre roving, bound with light shellac. Definite unidirectional creep was observed in the 1mm diameter bundle. After about 100 hrs of constant tensioning at 2kg this reduced to approximately 0.8 μm/hr for the 11m span. The material was difficult to handle due to its extremely low shear strength. End connections were made by impregnating the fibre ends with epoxy resin which could be clamped under a bolted joint. As this test included a joint in the bundle, the creep of the fibre may be better than indicated.

As the limiting factor of the above tests was temperature variation, further tests are in preparation using invar and carbon fibres to measure seismic strains on the Cambridge University/ N.P.L. seismic base. (Section 5.3). It is hoped that more defineable temperature conditions will enable seismic strains (magnitudes 10^{-9} to 10^{-7}) and material creep data to be obtained.

Some data on the magnitude of mechanical hysteresis is available (appendix 7.3) and is conventionally quoted as the ratio of the width to length of the hysteresis loop. For steels it is some 2%, implying that backlash as large as 1/50 of the strain change can occur during a procedure where the strain is entirely or partially changed. A stainless-steel wire of 10m length was tested and 0.5% hysteresis was measured. For invar of similar crossection the value was 1%

and for the carbon fibre bundle only 0.1%.

In tape calibration a procedure suggests itself in which the tape is initially strained to double the static value and then released to vibrate to rest in the centre of the hysteresis loop after completing a large number of reducing stress cycles.

The invar wire ($0.11mm^2$ area) was vibrated in this manner and when oscillated to rest over some 50 cycles the repeatibility was found to be $0.1\mu m$ s.d. for a strain change of 1mm (The maximum strain was 10mm). Assuming linear interpolation of the error this indicates 1 part in 10^8 s.d. repeatibility may be possible for tape calibration.

Special materials have been developed with hysteresis as low as .02%. These have a lower temperature coefficient than steel but still higher than Invar (27).

Vibrated and slowly released tests were made on the carbon fibre cord. As hysteresis was measured at 0.1% maximum, little difference was obtained by either method both repeating to about 5 parts in 10^8 s.d. Further tests are needed to establish the relevance of these tests to actual tape calibration and field use.

4.6. EFFECT OF TEMPERATURE

At present there appears to be no known material that does not change dimension with temperature. The most significant advance in this direction was the discovery of the nickel-iron alloy Invar. Carbon fibres and fused silica fibres have a similar coefficient. Some typical values are listed in the appendix.

For exacting applications in engineering measurement the full sensitivity of tensioning heads cannot be realised unless temperature effects can be satisfactorily eliminated. A number of possibilities are listed for reducing and assessing temperature error, the choice depending on application and accuracy needed.

a. Discrete Measurements with Probes

Discrete thermistor or thermocouple probes can be placed along the wire in order to measure an average temperature regarded as a reasonable estimate of the mean. Thermistor probes lend themselves as they can be interconnected to directly indicate the mean temperature. This method appears to be the best for continuous transducer temperature correction.

b. Direct Measurement by Electrical Methods

The wire temperature can be measured by monitoring changes of resistance of the tape or wire. Mean temperatures accurate to $\pm$ 0.2°C have been measured by Nottarp (28) using a compensated bridge to measure resistance. An alternative approach is to apply a constant voltage to the wire, measuring the current changes which can be directly used to indicate length error without knowledge of the temperature coefficient of the material (2).

c. Self-heating of the Wire

If the wire is electrically heated to retain the same resistance, correction could be eliminated. The improvement, however, is limited by the extent to which heat input offsets the actual loss distribution.

d. Dual Wires in Parallel

Colby used coupled brass and iron bars to establish a stable length for base survey before invar was discovered (20). His apparatus may be seen in the Science Museum, London. The reading points were taken on the two end links at such proportions that their unequal temperature coefficients cancelled out. This principle can be applied easily to tensioned wires over a much larger interval. For example, if an invar wire and a carbon fibre cord are tensioned side by side between two measuring points, the two outputs can be directly subtracted as coefficients, approximately equal and opposite in sign, can be obtained by selection. A temperature coefficient of about $10^{-8}/^{\circ}C$ seems possible by this technique. For materials with unequal coefficients electronic summation with the appropriate weighting is needed.

e. Wires in Series

It is common practice to correct measuring scales by using a reentrant shorter length of higher coefficient material. Opposite sign coefficient material can be used directly in series. For long lengths however, the method only averages for a local area of the span and the wire should ideally be a chain of alternating materials each short enough to give overall mean compensation.

The above are suggestions only. As temperature distribution and magnitude vary considerably with the problem, experiments are needed to ascertain those best suited for the task.

For exacting applications the differential thermal expansion of the tensioning head must also be studied. This is minimized by using correct lengths of components and carefully choosing the mounting points. A second temperature effect often overlooked is that the elastic modulus of materials is temperature dependent. The thermoelastic coefficient gives the rate of modulus change with temperature change. Invar has a slightly higher coefficient than that of steels being about -500 $10^{-6}/^{\circ}C$. Alloys exist which show almost zero change (27). Typical values, where available, are listed in the appendix 7.3. For measurements of less than 1 part in 10^{6} accuracy, this effect can usually be ignored.

The temperature time constant of the wire is also important. For metal wires of about 0.1mm diameter it is of the order of two seconds and for a 1.0mm diameter some twenty seconds.

A short thermal time constant is desirable as electrical filtering can be used to obtain a longer time constant with simple adjustment.

4.7 DEFORMATION TRANSDUCERS

A number of deformation transducers have been constructed and are now described.

The beam balance shown in figure 4.3 was originally built to verify the formulation for friction errors and dynamic response. It has adjustable tension and inertia. The beam rotates on self aligning pivot-type ball bearings. The wire connection point is also held in similar bearings and is made of sufficient length to cancel differential thermal expansion in the structure. A bored socket holds a linear differential voltage transformer (l.d.v.t.) probe (or capacitive probe) which measures the wire end movement relative to the support frame. A miniature ball race is used to reduce surface friction between the probe end and the slightly translating surface. The inertia of this unit was typically $3.2\ 10^{-3}\text{kgm}^2$ and tensioned the wire at 2.0kg.

Four simplified units based on the above were made for simultaneous creep testing of various materials. These units, shown in figure 4.4, used the same bearings for the main pivot. The beam is made from a single steel bar with the wire or cord being directly connected to the upper face.

A constant torque spring tensioning unit was also made to verify the behaviour of force methods. The unit, shown in figure 4.5, is based upon a standard stock spring. Inertia has been reduced by lightening the support bushes and may be further reduced by using a wider spring strip on small bushes, as shown above. The calculated inertia of this unit was $1.5\ 10^{-4}\ \text{kgm}^2$ which agreed closely with the measured value, and is considerably lower than that of absolute

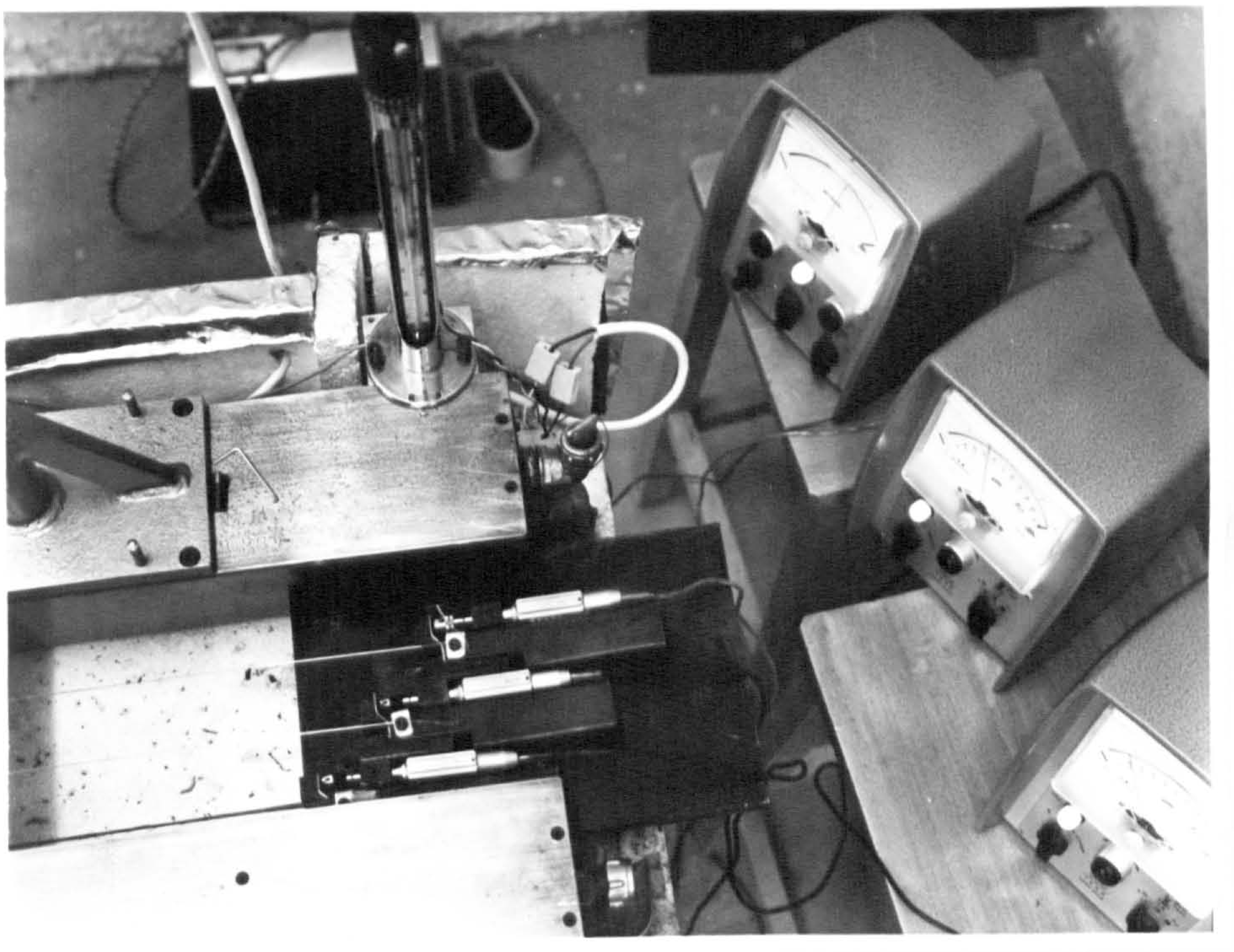

Figure 4.4. Simplified beam balances for creep testing.

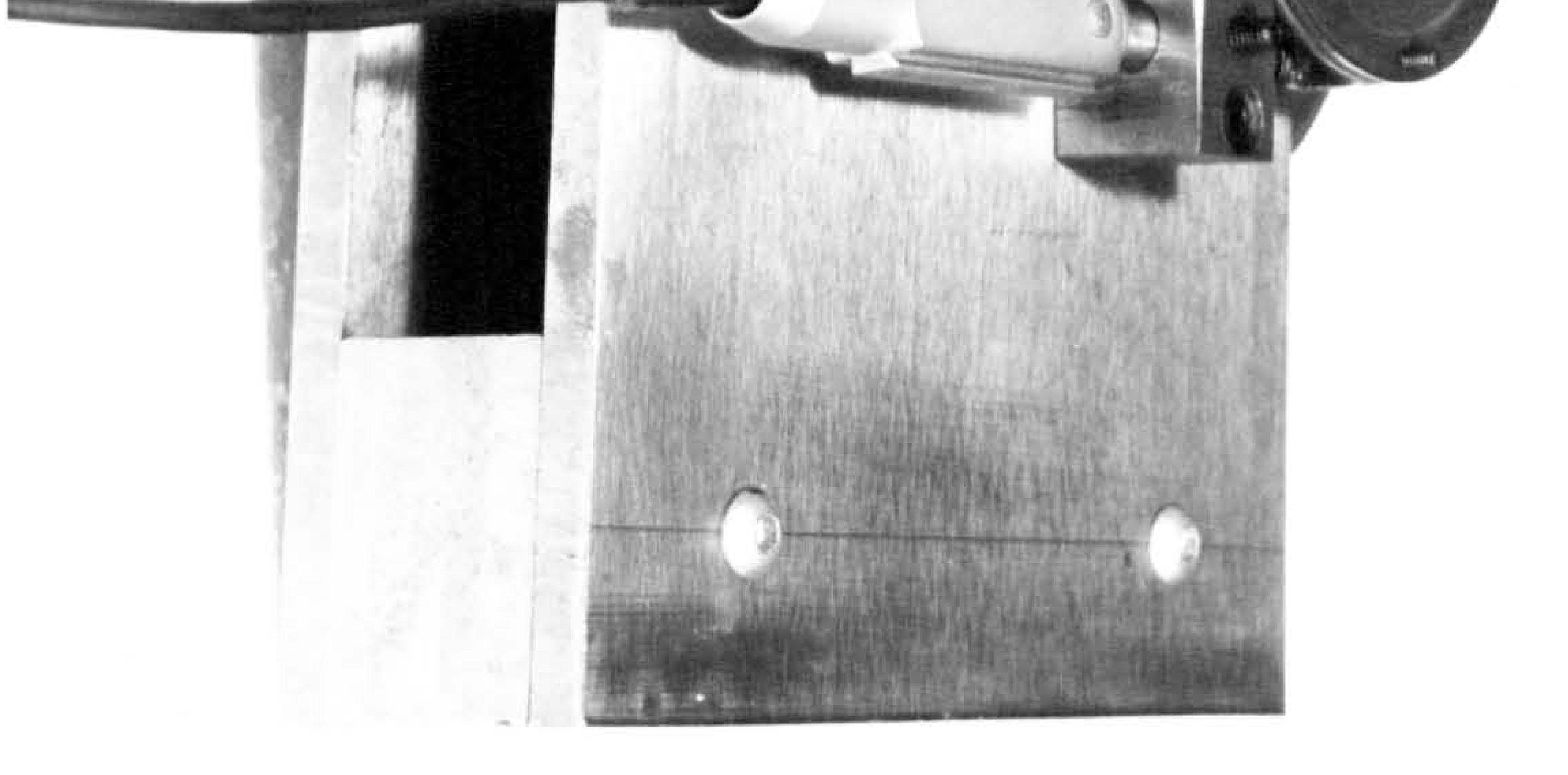

Figure 4.5. Spring tensioned, deformation transducer.

balances. Poor alignment of the radial bearings used for support, led to large frictional errors in this unit. A similar unit using pivot bearings is described in the next section.

The movements of the tensioning unit can be measured by linear gauging techniques or by measurement of the supporting shaft rotation. The former is preferred as it is relatively independant of bearing errors. Although non-contacting methods are desirable contacting spring-loaded gauge heads of the l.d.v.t. type used in metrology have been proven to be suitable provided roller ended probes are used. Non-contacting capacitive displacement probes have been used but the temperature and long-term stability were found to be inferior to l.d.v.t. probes for which 4000hr stability is guaranteed.

An alternative method is to measure rotation of the pivot by an optical lever and position-sensitive detector. The simple dual cell has been proven to have about 1μm stability over a period of several days (section 2.4). Increased sensitivity is available with cut-quadrant cells (.02μm drift) or by using a longer path length in the lever. Sophisticated optical levers, for example, those reported by Jones (29) could give extreme sensitivity.

4.8 CONTINUOUS SUBDIVISION TRANSDUCERS

The design of continuous transducers involves further considerations as accurate measurement is needed over the full range. Dynamic performance is also important as application in closed-loop control requires rapid response.

The wire must first be tensioned with the required accuracy and then used to produce a continuous rotation as the wire moves in and out of the unit. A capstan wheel may be rotated by the wire; this was investigated and it was found that datum shift occurred presumably due to the minute differences in the mechanical linear to radial conversion for each direction. An alternative, not exhibiting this error, is to secure the wire to the tensioning drum and measure the drum rotation. A wire is more ammoniable to this method as a constant diameter, threaded drum can store large lengths of wire in a small volume. A recently marketed device uses a narrow tape laid on a cylindrical drum in this manner. Good reproduceability is claimed. Wire, however, can also be directed in any direction without twisting, making it suitable for trilateration measurement.

In 1967, Digiwire I was reported (3) showing that repeatibility of about 4 parts in 10^6 (standard deviation) was possible by this method. This unit, modified from an earlier potentiometric length measuring device (2), had large inscale errors due to the winding mechanism, had no adjustment for absolute length or temperature error and was not suited to automatic control because of intolerable inertia.

An improved version, Digiwire II, has been built and is illustrated in figure 4.6. This has a 12m range with 10μm resolution from an incremental resolver. Winding error is eliminated by moving the feed pulley parallel with the drum axis directing the wire along the same axis. To minimize friction effects, a commercial grade, 15mm diameter, recirculating ball screw and nut carries the pulley. One drum revolution gives a wire movement equal to its circumference plus the pitch of the drum helix, the total being 200 mm in this model.

To effect coarse absolute length adjustment the lead-screw assembly can be inclined to the drum axis causing a proportional change in the distance from the drum centreline to that of the feed-pulley as the feed translates. This effectively changes

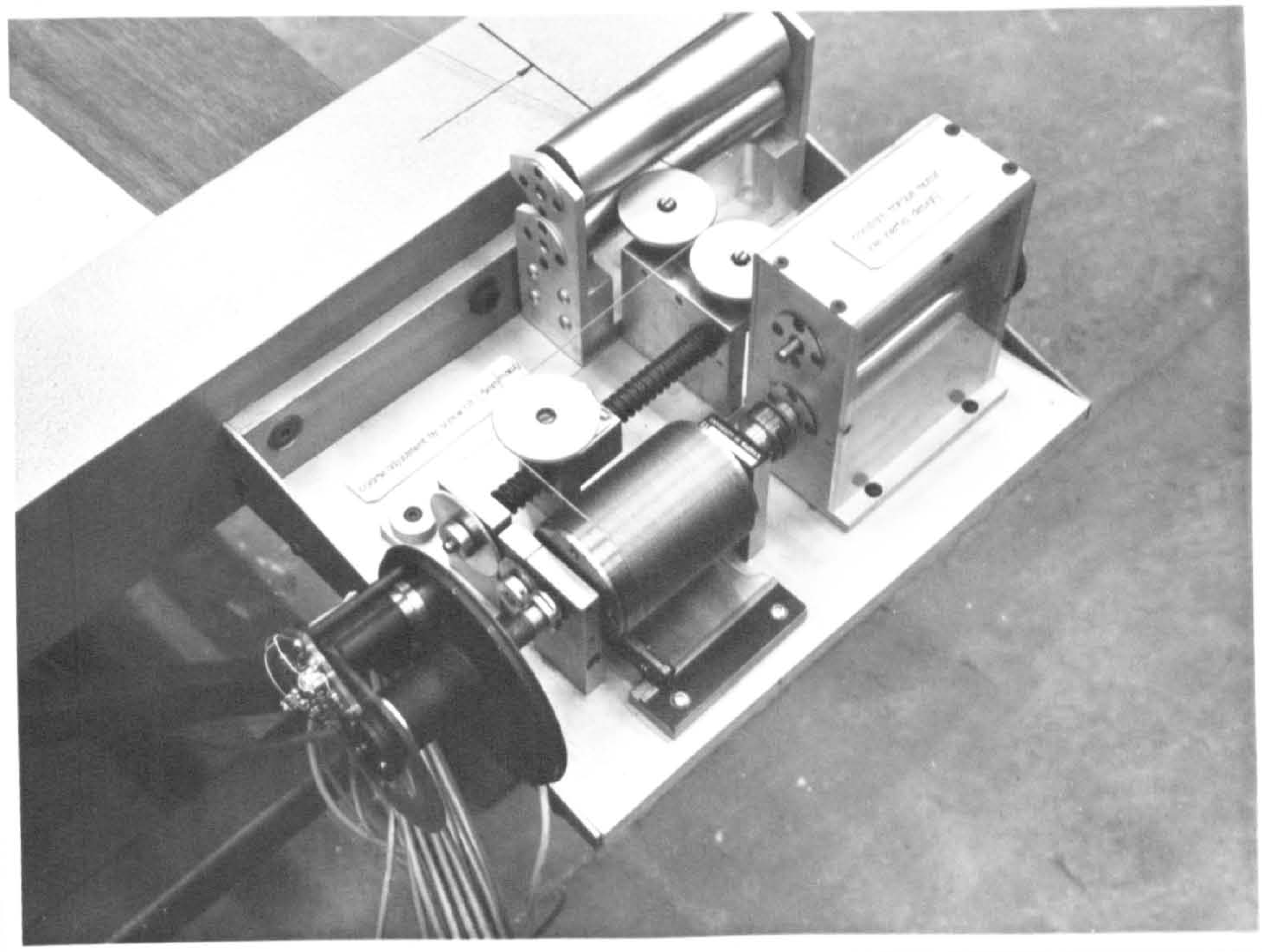

Figure 4.6. Digiwire II, 12m range, linearized continuous transducer.

Figure 4.7. Digiwire III, 1·5m range experimental transducer mounted on measuring machine.

the drum diameter and can correct about 0.5mm/m relaxing the manufacturing tolerance of the drum. Finer adjustment is obtained by profiling the cam plate carrying the end of the arm used to control nut rotation. Non-linear errors, such as catenary sag (about 100μm at 10m in this model), lead screw pitch errors and tension variation errors can be reduced this way. An amplification of five is obtained by passing the arm underneath the measuring drum. The cam plate can also be inclined vertically to give further adjustment of absolute error and to make adjustment for temperature variations. The range of this fine adjustment is 100μm/m which corresponds to about $\pm$ 4°C temperature error for the stainless steel wire used.

To limit bending stresses in the coiled wire a multi-strand cord is required. In general the ratio of strand diameter to bending diameter should be 1/300 or less to obtain virtually infinite life. The 35 by 0.1mm diameter stainless-steel cord is directed out around a single pulley. This arrangement is designed for trilateration measurement where the wire angle varies as it leaves the transducer. For rectilinear use the arrangement can be simplified.

The tensioning motor produces 2.0kg tension in the wire and rotates through 70 turns. The spring strip is 100mm wide and 0.1mm thick stainless-steel, to obtain low inertia [illegible].

The initially assembled unit must be cycled a number of times to work the wire into its stable form. The repeatibility of Digiwire II was found to be similar to the previous model, there being no apparent improvement by having a precision ground helix. Backlash was found to be 4 parts in 10^6 of extended wire length.

Step response tests were made and it was verified that the transverse natural frequencies were as predicted at various extensions and that larger steps could be tolerated before the transverse vibration was excited than in the Digiwire unit. These units have subsequently been used in closed-loop position control measuring in cartesian and trilateral coordinates (section 5.1). The total inertia of this unit could be reduced at least fourfold in subsequent models raising the longitudinal frequency mode to 15Hz for a 10m span.

In these units incremental, radial grating resolvers are used to measure shaft rotation giving 20,000 pulses per revolution which are counted by a bi-directional counter displaying metre units directly.

A further experimental model, Digiwire III, was constructed to assess the possibilities of this technique for shorter range measurement. In this model, shown in figure 4.7, a seven strandby .05mm diam. stainless steel cord is stored and tensioned at 200gm on a 75mm diameter drum having 5 turns placed as close as practicable. Pivot-type bearings support both shafts carrying the drum and constant-torque spring. A large diameter drum was used to reduce backlash and the cosine winding error. The resolution was found to be less than 0.1μm, as predicted, The cosine error is $\pm$ 3μm for the 1.5m range. An optical lever using a position sensitive detector was used to repeat rotation position to within 0.5μm of wire movement. Tests of repeatibility over one revolution were made using a SIP MU 412 B measuring machine and it was found that the wire unit could repeat to 1 part in 10^6 s.d. The improved precision was attributed to closer temperature control and to the larger ratio of drum to wire diameter than had previously been used. This study proved the application of wire transducers to shorter length measurement. A 1.5m range unit having .0001in. resolution per pulse is currently under investigation for automated numerical controlled machine tool checking by a local machine tool manufacturer. In this unit it has been decided that the control of inscale linearity and absolute length is best achieved by electronic correction as a computer will be attached for processing the results. A wire transducer hasbeen selected as it is easily attached to the existing machine table.

The long-term stability of measurements made with continuous wire transducers has been studied. The Digiwire I unit has been used to measure the length between two datum pins mounted on the 12m test base. Over a period of the 6 months tested to date the mean values of groups of twenty measurements made at intervals during this period has not varied more than 5 parts in 10^6. Some 350 full cycles of the units were made during these tests.

It is not surprising that good stability exists, for the wire merely transfers a linear interval onto the drum measuring surface. It is, therefore, the wire diameter that must remain stable and not its length or the applied absolute tension, during short interval measurements.

A further stability test of the absolute length has been made using the Digiwire III unit. In this test, the linear interval corresponding to one exact rotation of the measuring drum has been recorded on the measuring machine. The absolute length varied about 3μm in 300mm and this was attributed to temperature variations during the two week test period.

As the 12m units have adjustable absolute length it was necessary to decide upon some way of obtaininga calibrating standard. To realise the full accuracy of 10 p.p.m. would need a special installation, such as a laser interferometer on a temperature stable measuring machine or a geodetic-tape base. A compromise is to use a standard of 1m lengthto obtain sufficiently accurate placement of the coarse adjustment.

Normal one metre standardsare either line or end standards and a method of transfer is needed. With wire devices, measurement is direct between two mechanical locations so a 'pin' standard is useable. A 1m normalised steel bar was made and precision ground. On this two, 10mm diameter, pins project, one being adjustable in position. The standard is shown in Figure 4.8. The pin separation was adjusted with reference to the SIP MU 214 B measuring machine by stepping along the bar three times. Its length was established as 1.000007m.

At each end a thin spring strip enables the bar to be held without causing bending. To use the bar, the wire end is fastened into the plate, shown in the lid, which has a good clearance hole over the pin. The bar is butted to the transducer and aligned to within cosine error requirements. The interval can then be measured and the transducer adjusted until the correct 1m length is indicated.

The accuracy of this procedure is limited by unit resolution (10μm) to 1/100,000 but experience showed that repeatability was never much better than about 50μm due to electronic errors. It was verified that the pin and hole repeatability was within 5μm, the wire tension removing backlash errors.

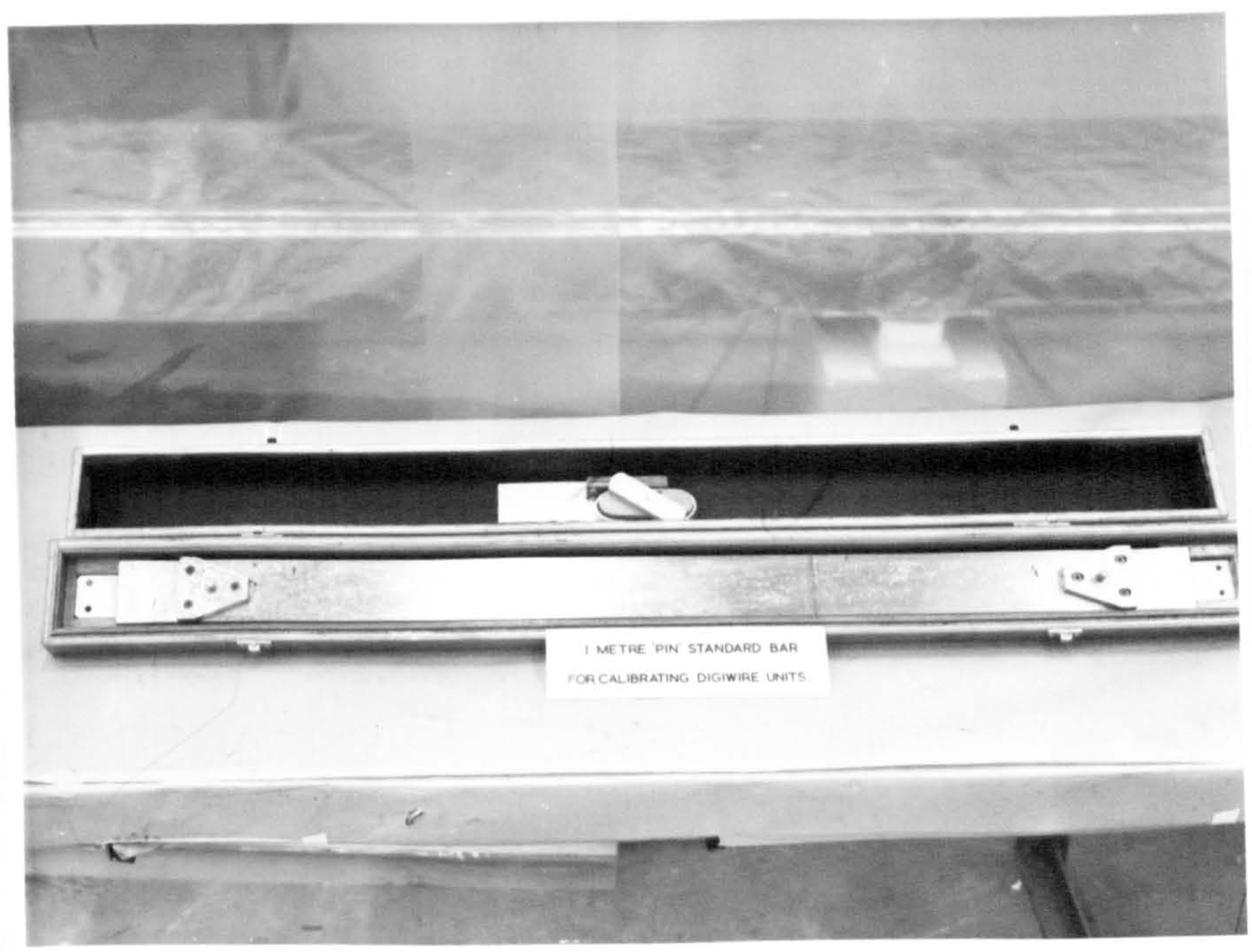

Figure 4.8. 1m pin-standard bar for calibrating Digiwire units.

5. APPLICATIONS OF TENSIONED-MEMBER TRANSDUCERS.

The fundamentals of the design and construction of dimensional measuring transducers using tensioned wires and cords have been outlined in the previous section. A number of specific applications were chosen at successive periods throughout the programme, the section being influenced by requirements discovered from the study of the literature and industrial practice.

The first sub-section reports the use of continuous transducers for closed-loop control of two-axis position. This apparatus demonstrates the automatic and manual capabilities of tensioned wires and the use of trilateration co-ordinate control of a cartesian co-ordinate manipulator.

Sub-section 5.2 is concerned with a industrial application of deformation transducers, this being the measurement and manufacture of large circular rings or spigots. Only circularity was measured as continuous wire transducers, circumference rolling wheels or stick micrometers could be used to measure diameter magnitude.

The final sub-section reports the use of deformation transducers to measure earth-strains. In order to investigate creep properties more precisely the writer requested that he be allowed to install some beam-balances and wires in the railway tunnel recently converted into a seismic station by the Department of Geodesy and Geophysics of Cambridge University. It was learned that such an experiment could possibly detect seismic strain by an independent method to their laser interferometer giving an independent set of geophysical results. A brief review of current strain seismometers is given. As the installation wasmade only a few weeks before compilation of this thesis the reported performance is restricted to 100 hr. duration records.

A fourth application using deformation measurement was made when testing the length changes of the 12m measuring base. This is covered in the published paper describing this base(Section 3 and Appendix 7.4)

5.1 Numerically-controlled position using trilateral coordinates

In mechanical engineering most measurements of two or more axis positions are made on a cartesian coordinate basis. In this rectangular method, location is defined by projecting perpendiculars from each axis to the point in question. Error in this procedure arises from the non-orthogonality of these projections with the respective axis, from non-orthogonality of the reference axes and, finally, from lack of straightness of the axes themselves.

For small sizes, measurement devices have evolved around this principle as the coordinates do not interact, giving simple operation and it has been proven that satisfactory elimination of errors is practicable. The frame involved also constrains the unwanted degrees of freedom.

With the need for precision measurement and manufacture of increasingly larger size workpieces, cartesian frame machines have grown with time, and tools with 20m traverses are now commonplace in heavy industry. To maintain the same relative accuracy as their smaller counterparts, the frameworks must be disproportionately heavier to control sag of the members due to their own weight and weight of the toolbox, and also to withstand negligible deformation with workpiece weight. The cost rises sharply with size. Typical figures for a large milling machine have been given by Umbach(30) in which he quotes data for a 37m length machine. It weighs 600 tons, takes a 220 ton workpiece, sits on a 2500 ton reinforced concrete foundation, costs £200,000 or thereabouts and needed about two years to manufacture. Cooling a casting for such machines takes up to six months. The high cost results from the necessity to obtain both roughing and precision performance from the same machine.

Study of the utility of large machine tools showed that actual machining takes very little of the machine time associated with a component. The majority of the time was required for setting up the workpiece, allowing time for temperature equalization and for rigorous manual inspection of the critical cuts. In many cases the machine was used mainly for marking out and for machining only relatively small areas at different locations on the workpiece.

Research of continuous subdivision tensioned-wire, measuring devices (Section 4) has shown that lengths to several hundred feet can be rapidly measured with accuracies of better than 10 parts in 10^6. This closely matches the requirement of the best measurements being comparable with inaccuracies caused by $1^\circ C$ temperature uncertainty (which is the closest tolerance maintained in industry). These transducers, not needing guideways, can realise the surveyors technique of trilateration, enabling a different approach to the measuring and machining of large objects in mechanical engineering and other disciplines.

If two-dimensional position is required, a base line of known, fixed length may be established relative to the plane from which all other positions will be uniquely defined by the distances from the point in question to the ends of the base line. For three dimensional position a base triangle is sufficient. For plane measurement, therefore, only the fixed distance between two points and two precise varying lengths are needed to define position compared with three perpendiculars, two precision straight lines and two precision varying lengths needed with cartesian coordinates. As well as improved accuracy other benefits exist with trilateration.

For measuring or machining large parts there is no need for a frame as the workpiece itself can support the two transducers and a small machine tool placed at each location in turn. This procedure allows insitu machining, saves time delays of transportation and temperature equalizing, eliminates the need for a permanent massive workshop, allows more than one simultaneous precision machining operation on the same workpiece, enables construction of precision large objects for low capital outlay, previously only possible by those firms with large machine tools, enables a new approach to construction of large objects as transport and available tools are not a consideration and, finally, the method is inherently more accurate and reliable as members taking cutting forces are not used for measurement.

Continuous wire transducers lend themselves to form the variable sides of the triangle as they do not need guideways. A manual system using trilateral techniques has previously been demonstrated by the writer using a potentiometric tensioned-wire method (2). In that demonstration the trilateral analogue signals were converted to their cartesian equivalents by an analogue computer in which accuracy was limited to about 1 part in 4000. With the change to the Digiwire method (described in Section 4) the improved accuracy required some 100 fold more accurate computational requirements if the same procedure were used. A simpler solution eliminating the interaction of trilateral signals has been developed. A diagrammatic view of the system to be described is shown in Figure 5.1.

In conventional cartesian position control the magnitude of a given coordinate is compared with the actual position producing an error signal which directs the position servo.(31) Errors produced in this way with the trilateral lengths S_1, S_2 in figure 5.1, are not directly meaningful due to their interaction. Manual direction from one location to another is difficult and time consuming; automatic control is not feasible unless the interaction is removed and suitable signals produced to drive a manipulator. As most machine tools have cartesian axes the preferred transform should generate cartesian error signals enabling trilateral control to be used for component-supported (frameless) machining techniques with a small tool or for control of existing machine tools where

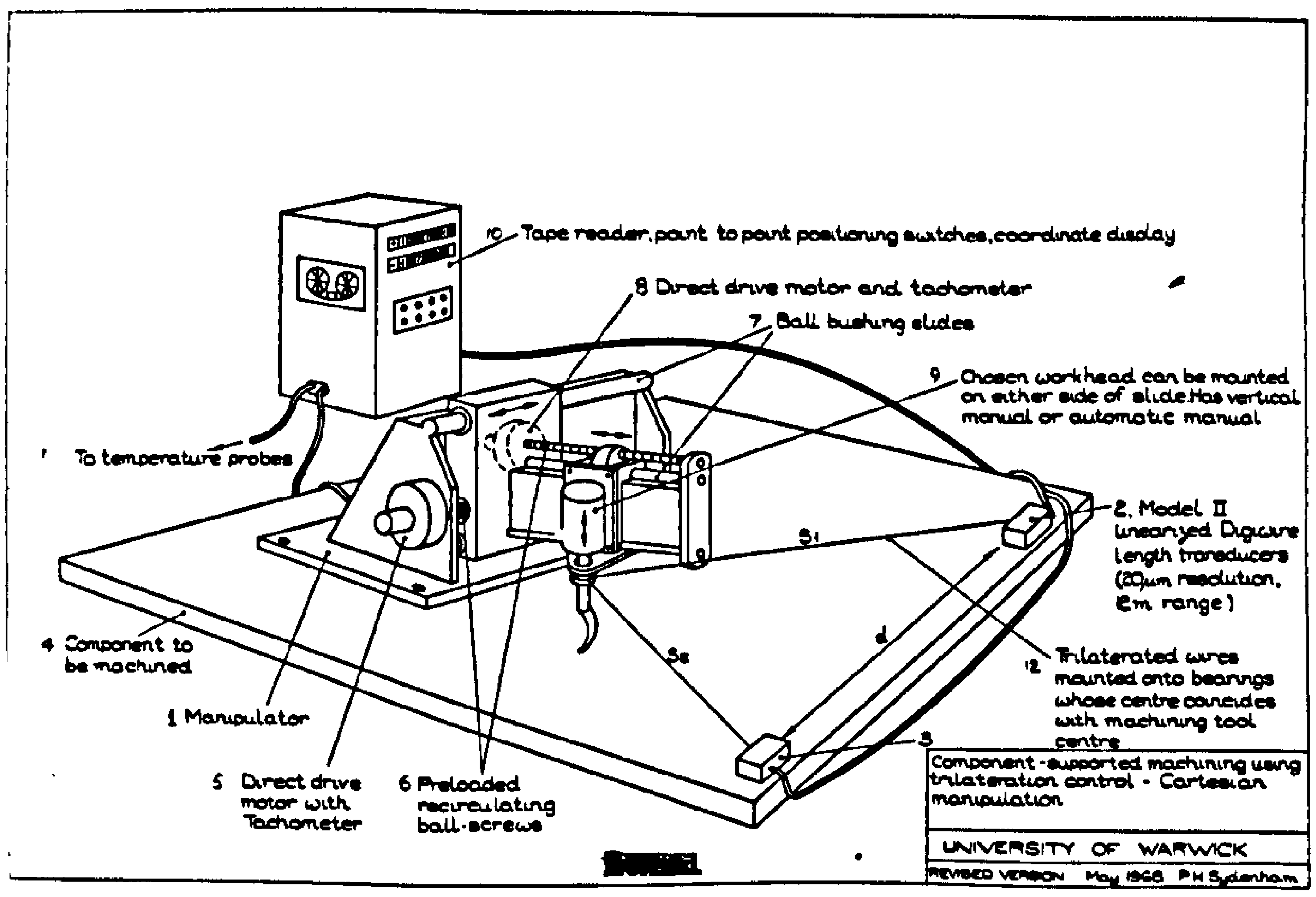

Figure 5.1.1. Schematic view of complete frameless machining system.

improved accuracy or position readout is needed as retrofit.

Two alternatives may be used to produce useful error signals. The first procedure would be to convert the S_1, S_2, lengths into the cartesian equivalents using a special purpose on-line digital computer this being similar to the analogue method mentioned above (2) where the necessary expressions were developed. These equivalents can then be used in the normal manner, if cartesian demanded information is given. The computer would need at least 6 decade capability implying high cost and relatively slow computational speed for each coordinate.

A less expensive solution is to transform the <u>error</u> signals (derived from the trilateral actual and demanded lengths of S_1, S_2) into cartesian equivalents. If necessary, the demanded lengths may be precalculated from cartesian coordinate drawings at the drafting stage using a preprogrammed desk calculator. A transformation is now described.

If the two transducer locations on the ends of the base-line are considered as foci, curves of constant sum of S_1 and S_2 are ellipses about these foci and curves of constant difference between S_1 and S_2 are hyperbolae. A normalized set of such curves is drawn in Figure 5.2 in which sum and difference curves are equally spaced at 0.1 base length increments. The important feature is that the sum and difference curves intersect at right angles giving a pseudo-cartesian system. Movements may, therefore, be expressed in sum and differences of the S_1, S_2 lengths. For example, if the initial position is at P_1, a move to P_2 requires an increase in the sum of S_1 and S_2 of 0.3 units and an increase in the difference of the two of 0.2 units.

A suitable procedure, therefore, to make trilateral signals useable, is to form the sum and difference of the trilateral <u>error</u> signals and use these to direct a cartesian manipulator which is placed with its axes coincident with those of the transform.

A number of other characteristics may be seen with this mapping.

Fig. 5.12. Graphical representation of trilateral to cartesian transform

Firstly, transformed signal magnitudes represent about 60% of the actual cartesian errors enabling the magnitude of error signals to be estimated. It can also be seen that sensitivity of the x,y axes depend on position in the useable field. Sum increments are relatively constant whereas difference increments vary by a factor of two. Areas where the difference exceeds a magnitude of 0.9 and where the sum is less than 1.1 should be avoided. If a direct path is desired between two points the feed rate of the difference signal (y by the convention used) should be varied relative to that of the x signal, depending upon manipulator position. The degree of rotation of the cartesian frame can be estimated. The rotation can be achieved by physically turning the axes or, if this is not possible, by effectively rotating it by gain changes of the x and y signals. Accuracy is not important in this procedure as measurements are within the control loop. No measurements are made with the cartesian axes. It can also be seen that the linearity of a given magnitude path length improves with increase in the base length for the transformed 'squares' become physically larger whilst retaining the same geometrical shape. This implies that larger steps can be tolerated with the same sagital error (produced by inherent curvature of the transform) if a given size part is made with the largest scale base-line possible. A compromise, must be made however, between this improvement and the allowable inaccuracy of length measurements. (The Digiwire units have been shown to have repeatibility limited by the replacement error of the wire onto the drum. This is proportional to the length of wire moving on the drum during measurements and is not dependant upon extended wire magnitude.) The shaded area shown in Figure 5.12, has been directly plotted using the equipment described below. Straightness of the outer difference lines of the square was found to be 0.6% and about 0.8% for the sum lines.

The foundations for the realisation of a two-axis positioning system using trilateral measurement have been established above. To investigate and verify the principles a closed-loop control system, capable of rapid positioning within an area 15 by 10m has been constructed using two 12m, linearized, Digiwire units to measure position of a small general purpose manipulator. A machine tool application was chosen as this represents the most demanding need for accuracy. The technique is obviously applicable to other disciplines, where position control is needed. The remainder of this section describes this system.

A photograph of the complete system is given in Figure 5.13. In this demonstration assembly a 1m base-line is mounted on one end of a frame which simulates a large work piece. The manipulator is fastened at the other end with its axes roughly aligned with the transform axes. The wires, pulled out from the two Digiwire II units, are attached to large-bore ball bearings which effectively project the wires so that they intersect at the true apex point of the triangle. The tool centre, therefore, coincides with the triangle apex if mounted concentrically in the bore. Vertical movement, not shown in this photograph, would be arranged to move through the bore. Actual position of mounting the apex point onto the manipulator is not critical provided it moves in the plane of the wires.

As the investigation was concerned with closed-loop operation of wire transducers and the use of trilateral techniques, it was imperative that the manipulator characteristics did not deteriorate the overall-loop performance. A cantilever arm manipulator was constructed using high performance components. An illustration is shown in Figure 5.14. The 600mm long cantilever boom and its moving tool box mount are carried on 1.25in diameter ball bush slides. Friction is negligible with this method, a desirable feature in a closed loop system. Axis movements are by precision recirculating ball screws preloaded to remove non-linear backlash which might lead to instability. Stiffness of the screw assembly need not be improved by preloading as they are not used for measurement. The screws are directly driven by 150 watt printed armature motors (25)

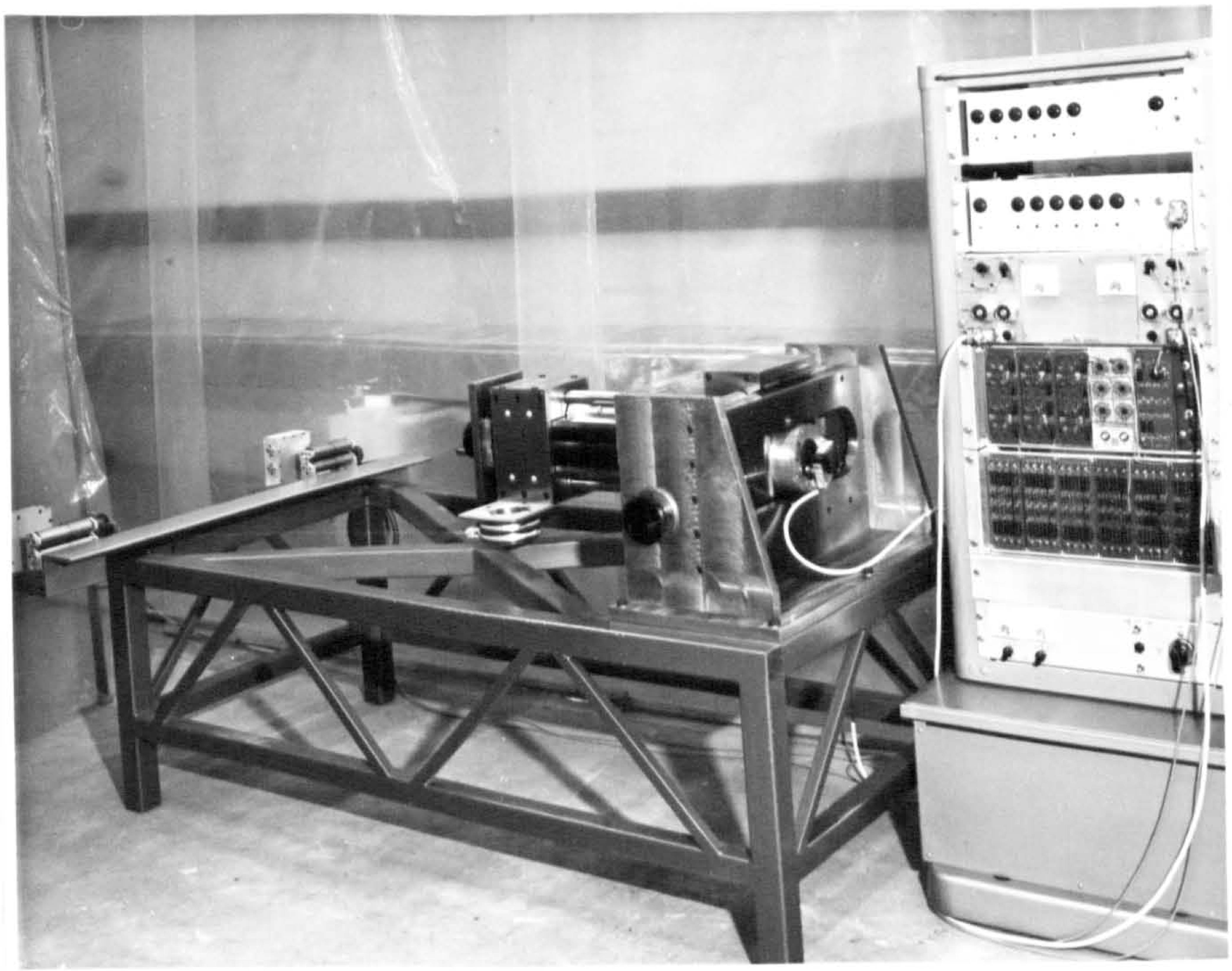

Figure 5.1.3. Experimental trilateral control positioning system.

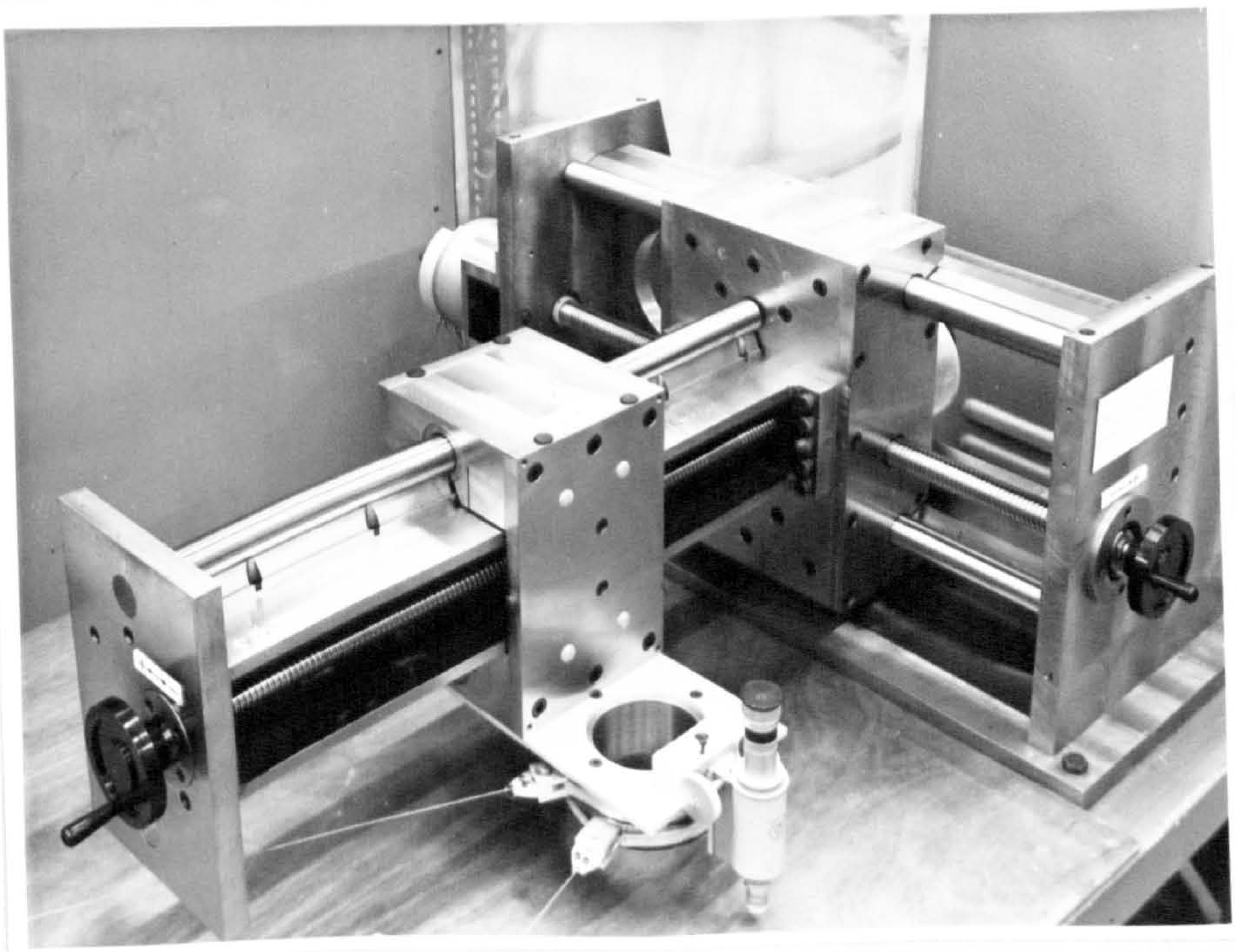

Figure 5.1.4. High performance, electrically driven, manipulator.

each driving a coupled tachometer for damping and feed-rate control. The unit was designed to give axial thrusts of 30Kg.

Friction torques of the bearings carrying the wire-ends cause the wires to deviate from the ideal lines joining the apex to the baseline ends. The effective length between the bore centre and the wire connection point decides the degree to which this cosine error is controlled as a restoring transverse component is produced by the wire tension. The two transducers are mounted at the same elevations as the bearings. The lightest available, large bore, bearings have been used but their capacity greatly exceeds the 4Kg maximum tension exerted by both wires. Incremental pulse outputs from the transducers are counted by the bi-directional counters shown at the top of the electronics console (Figure 5.15). The two analogue d.c. servo amplifiers and summing points are mounted below the counter. Heat sinks for the power stages are at the rear. Using tachometer feedback the feedrate of the axes is controllable from 1-200i.p.m. Adjustment for servo gain and velocity feedback is provided. On this panel can be seen two meters which display transformed error signal magnitude. These enable the operator to direct the cartesian controls toward the desired location. The above electronics are of conventional design and need no further explanation. Power requirements are supplied from lead acid cells. The remainder of the electronics have been specifically designed for this application and differ somewhat from normal numerical control philosophy as the transformation is necessary.

In conventional analogue motor drive systems the digital error signals, derived by subtraction of the demanded and actual coordinates are converted to analogue form in a digital to analogue converter(31). Saturation of the error signal can occur for relatively small error magnitudes, allowing simplification of the converter as the more significant decades need only be interpreted as zero or otherwise. In trilateration it was shown above that a transformation is needed to produce

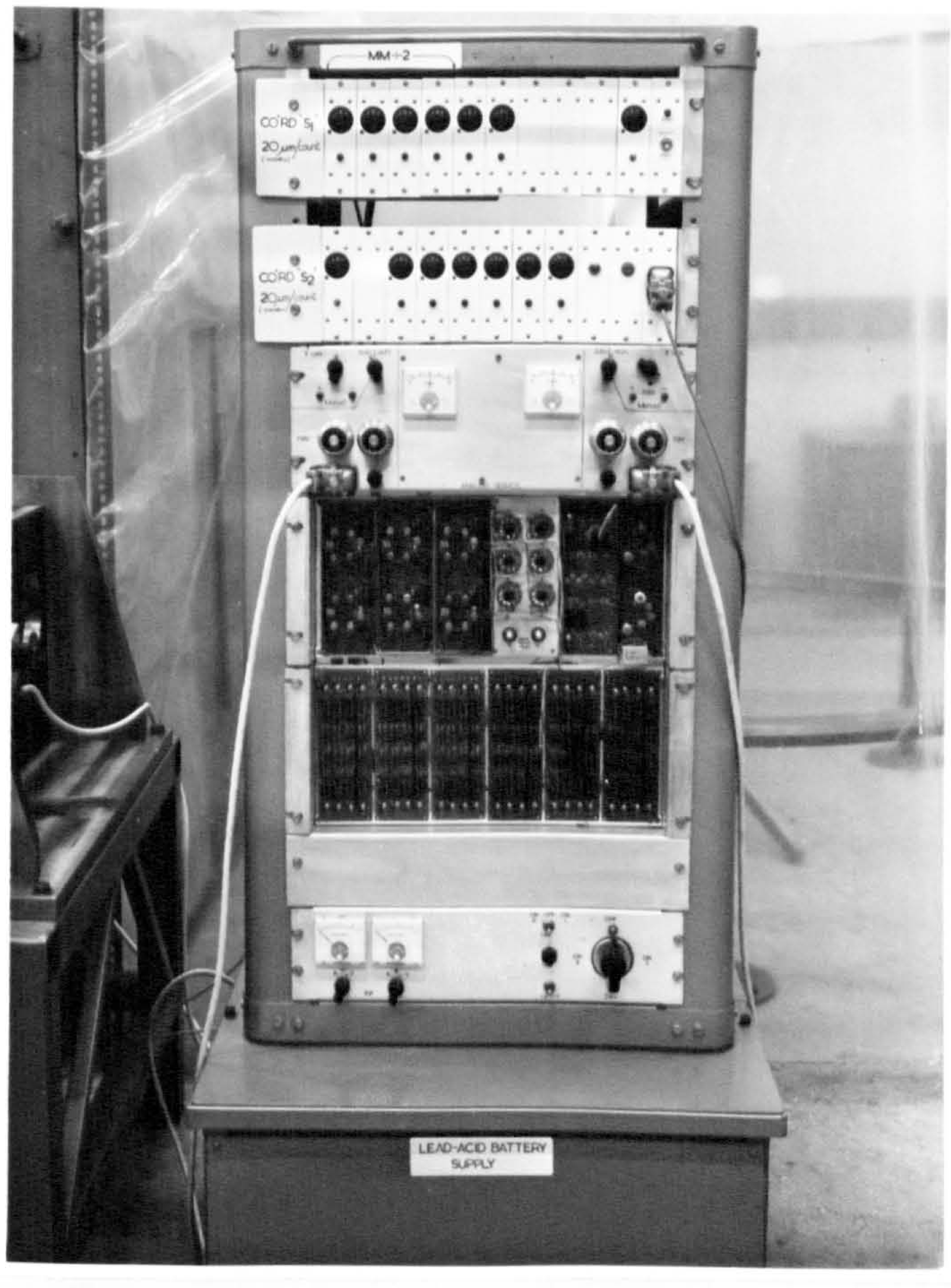

Figure 5.1.5. Experimental electronics for bilateral control system.

effectively cartesian, error signals. This transform was to produce the sum and difference from the two original errors. As error magnitudes may be as large as a full scale displacement, the sum and difference must be calculated before any saturation is allowed. To produce a truly linear sum and difference of six or more decade magnitude numbers, digital methods would have to be used. There seems to be little point in doing this as this transformation produces a non-linear path. A more economic solution has been developed which performs the transformation with anologue elements.

A schematic block diagram of the electronics is given in Figure 5.16. Each counter consists of six decades storing instantaneous digital error magnitude and a sign unit. The four binary outputs of each decade units (1-2-4-8- code) switch reed relays, each having two normally-open contacts. These connect binary weighted resistors to a common stabilized voltage supply giving a current summation as the equivalent anologue error. The sense of the sign units decides the applied reference voltage polarity. This much is more or less as found in conventional converters of this type, the exception is that all binary states drive relays. By connecting the two converters resistances to a common output, the sum and difference of the two numbers is produced directly. Identical sets of resistors are used for each function, the voltage polarity being chosen appropriately. The common outputs are connected to an integrated circuit operational amplifier corrected for summation. Stability of d.c. analogue circuits and tolerances of components only allow conversion to about 0.1%. As linear control is not necessary for any but the lower error signal magnitudes a technique of non-linear selection is used. Above the lower three decades, where linear conversion is made, decades are treated in pairs. For each, similar position, decade pair, the sum and difference is produced using switched resistors (which need only 2% tolerances). The sum and difference outputs are then quantized with schmidt triggers into zero for zero outputs, maximum positive for any degree of positive

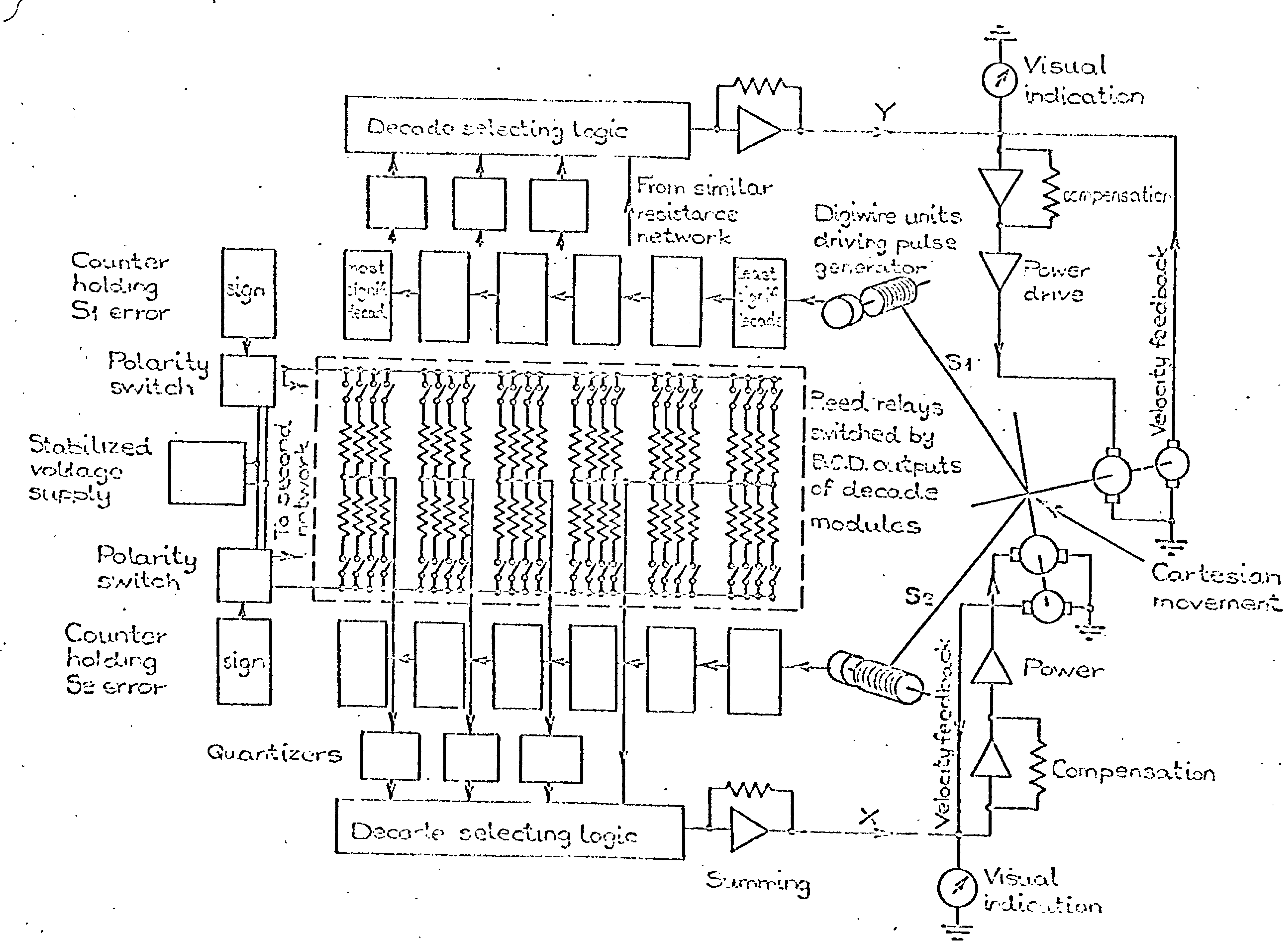

Fig. 5.16. Schematic layout of two-axis trilateral control system

error and maximum negative for any degree of negative error. Higher significant decades are identical. Logic is provided to test the presence of a zero from these units and progressively switch to lower significant pairs in search for an error until, finally, the linear converter is selected. Outputs of the converter drive the x and y power amplifiers of the motors and are displayed on the meters giving cartesian errors for manual observation.

With this system initial errors greater than the capacity of the linear units will saturate the drive giving maximum feedrate which reduces the error until the linear operation regime is entered. For large initial errors on both axes, the path will start at 45° (equal x,y saturated feed rates) moving until one of the error signals becomes zero where the path changes following the sum or difference curve equal to zero. A more direct path would be achieved if the x and y feedrates were maintained in constant proportion.

With 10m extended wire lengths some reduction in loopgain was found necessary to prevent oscillation due to the transverse wire vibration. The system was able to position from the maximum translation rate (150ipm) directly, without recourse to non-linear speed reduction. Positional error for rated axial thrust was less than 1/100,000 of the range. For shorter lengths, such as shown in Figure 5.3, the response could be improved as higher gain was possible. Stability limitation at wire extensions of 1m was found to be produced by the uncompensated servo design and not by the transducer performance. Typical step response has approximately two cycles of overshoot. With reduced feedrate, as would be the case in continuous control, the positional error is less. The same apparatus can be used to demonstrate cartesian control by holding the error on one axis at zero.

This investigation has shown that wire transducers can be satisfactorily used for rapid control of position over areas ranging from millimetres to many metres in size. It has also shown that trilateral coordinate measurement, realised in this case with wire transducers, can be used to control a cartesian manipulating system without the need of an on-line computer, provided input tape demanded positions were in trilateral form. The cost of the more complex digital to analogue converter is higher than a conventional system but the small increase is more than offset by the savings of the trilateral procedure. A complete system for machining areas up to tens of metres in range with jig-boring accuracy would cost little more than the control electronics alone of a large numerically controlled tool. Capital savings resulting from the use of frameless techniques could in many cases be as high as £200,000. With savings of this magnitude the use of an on-line digital computer for absolute conversion of trilateral lengths to cartesian form is easily justified as are auxiliary servos (8) to control the unwanted degrees of freedom.

5.2 Roundness measurement with a tensioned-wire transducer.

Circular surfaces are usually machined or measured by rotating the workpiece on a turntable. The alternative is to rotate the machining head, keeping the workpiece stationary. In both cases high frame stiffness is essential as dimension control relies on the frame members which are also part of the machining force-loop.

For small sizes adequate rigidity is relatively inexpensive to achieve, the only part needing careful attention being the bearing system upon which the worktable or work arm rotates. As dimension increases the frames become more difficult to stiffen. In the previous sub-section a method was described for positioning an object, regardless of size, without the need for a measurement framework of high precision. That application used the subdivisional type of wire transducer. This sub-section reports another frameless technique for the manufacture and inspection of large circular sections of workpieces. This application makes use of the deformation type of wire transducer.

A semi-finished, 2.3m diameter, taper bearing ring was kindly loaned by British Timken at the request of the writer. This was used to simulate a large circular spigot. This type of ring was chosen for this investigation as it was relatively easy to transport and was suitable in size for the available laboratory space. The method, however, appears suited for circular measurement of diameter to a hundred metres or more. Adjustable supports enabled the ring to be held plan and stress free.

A photograph of the complete equipment is given in figure 5.2.1. The central tripod carries a constant-force spring tensioning unit mounted on a freely rotating turntable. Attached to the transducer is an invar wire running to the electrically-driven carriage which moves the wire arround the ring. Closer detail of the central equipment is given in

Figure 5.2.1. General view of roundness measurement experiment.

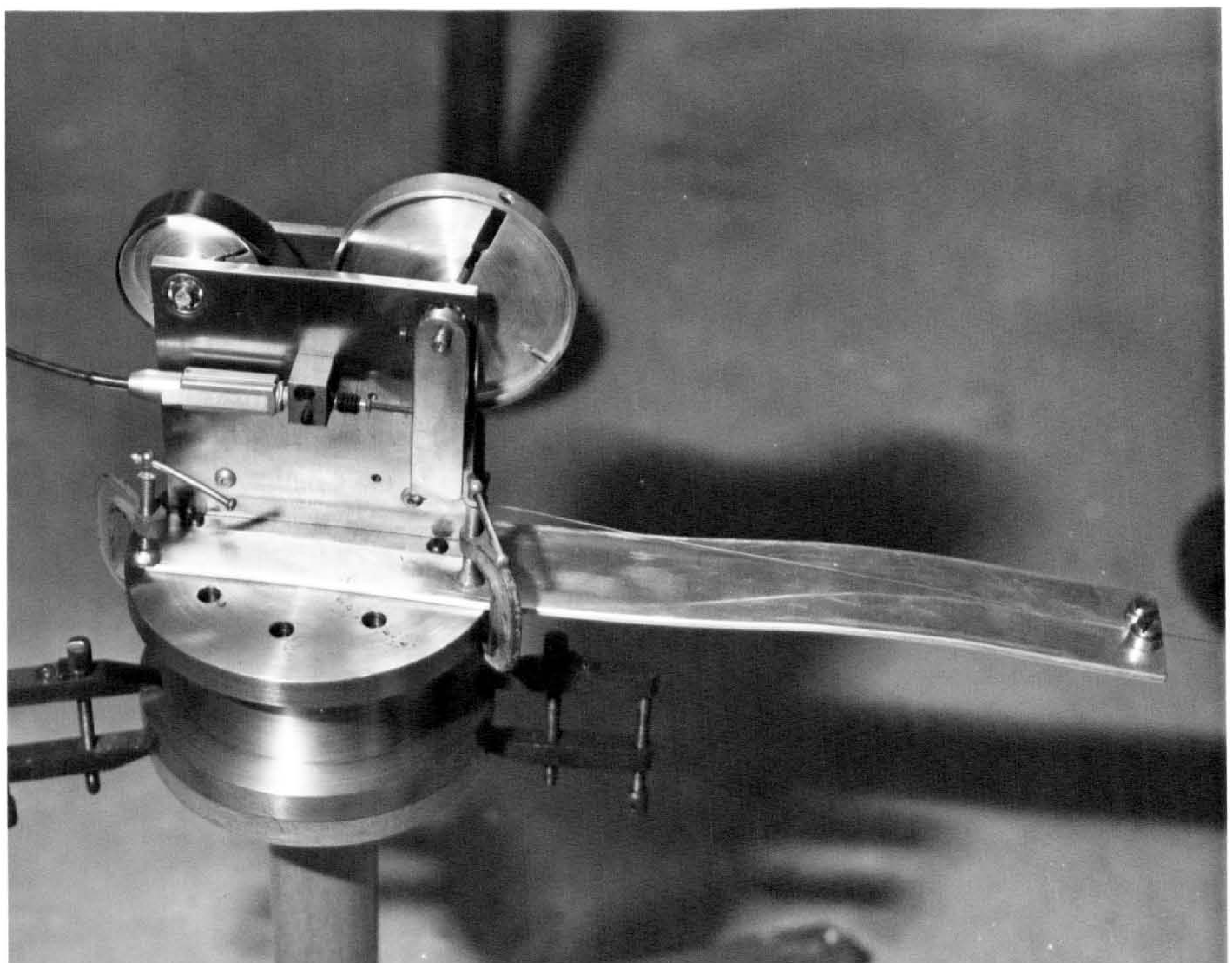

Figure. 5.2.2. Deformation transducer mounted on central turntable.

figure 5.2.2.

The wire is tensioned at 1kg being taken from the underside of the tensioning shaft to reduce eccentricity errors produced if the axis of rotation is not perpendicular to the plane of the ring. A Tesa electronic probe (GT10) measures the movement of the tensioning arm produced by changes in the radial length between the turntable and the inner surface of the ring. To reduce the sensitivity the probe is placed halfway along the arm.

The turntable is rotated by the follower arm which produces a moment overcoming the frictional forces of the turntable bearings. The length of the arm was chosen to ensure that the deflected wire length and the ideal straight lenght are within allowable tolerances.

Figure 5.2.3. shows the carriage in more detail. An electric motor drives the ball-bearing supported frame through a reduction gear-box to a steel drive wheel mounted on the output shaft. Absolute weights are used to force the wheel into contact with the ring. Coupled to the wheel shaft is a multi-turn potentiometer which provides a positional signal for recording purposes.

Horizontal stiffness was 20μm/kg for the central tripod but only 200μm/kg for the ring mounting arrangement. The ring will eventually be supported on concrete to obtain a more realistic simulation of a typical component.

Transducer precision was tested by deflecting the end of the follower arm about a millimetre and releasing it. Repeatability was found to bewell within 1μ m. Viscous damping was added between the turntable and the mount to condition the rotary oscillation of the measuring unit. Figure 5.2.4 (a) (b) show the improvement with the added damping. The natural frequency was about 5hz. Thw longitudinal resonant frequency

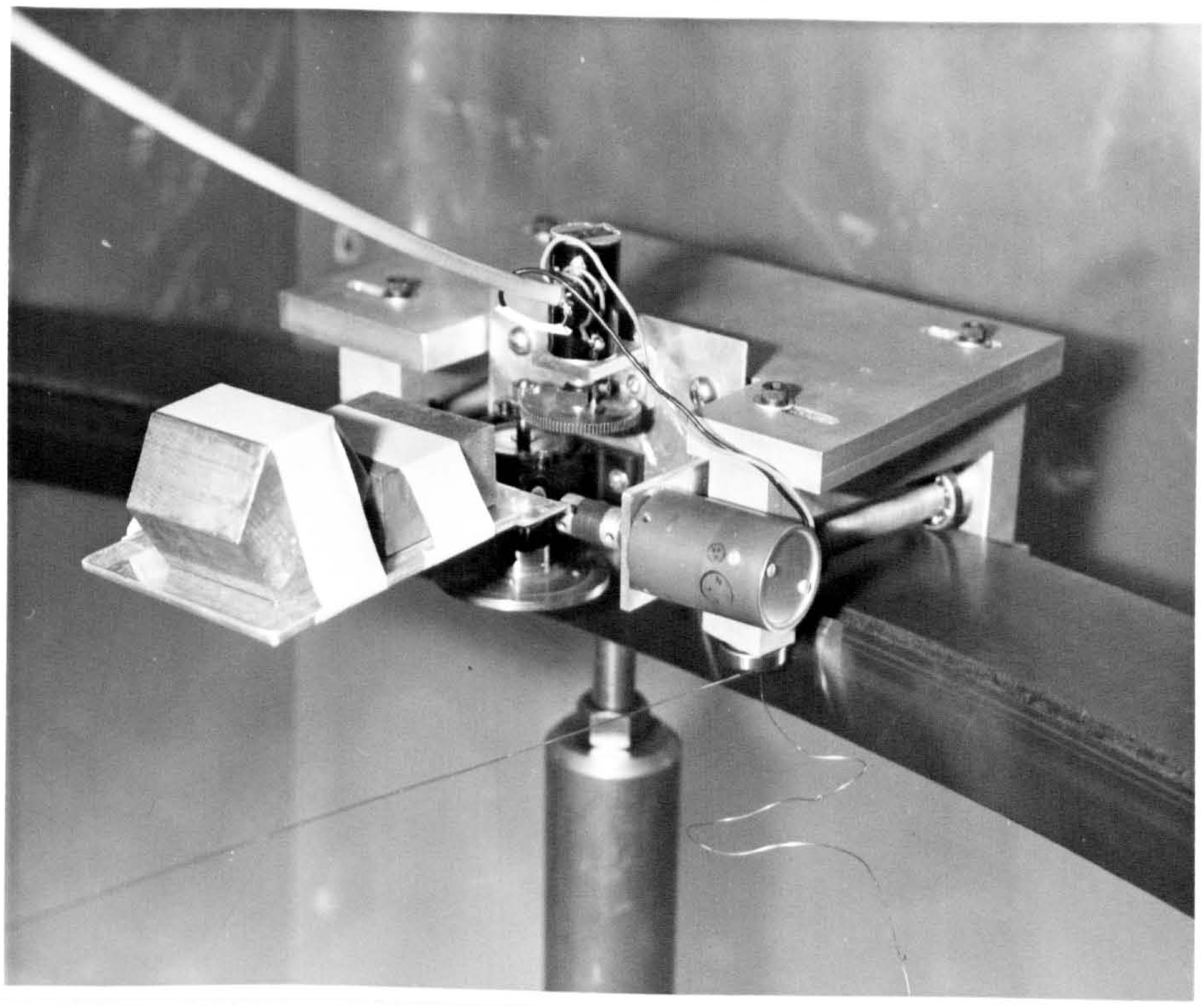

Figure 5.2.3. Electrically driven trolley for moving wire around ring.

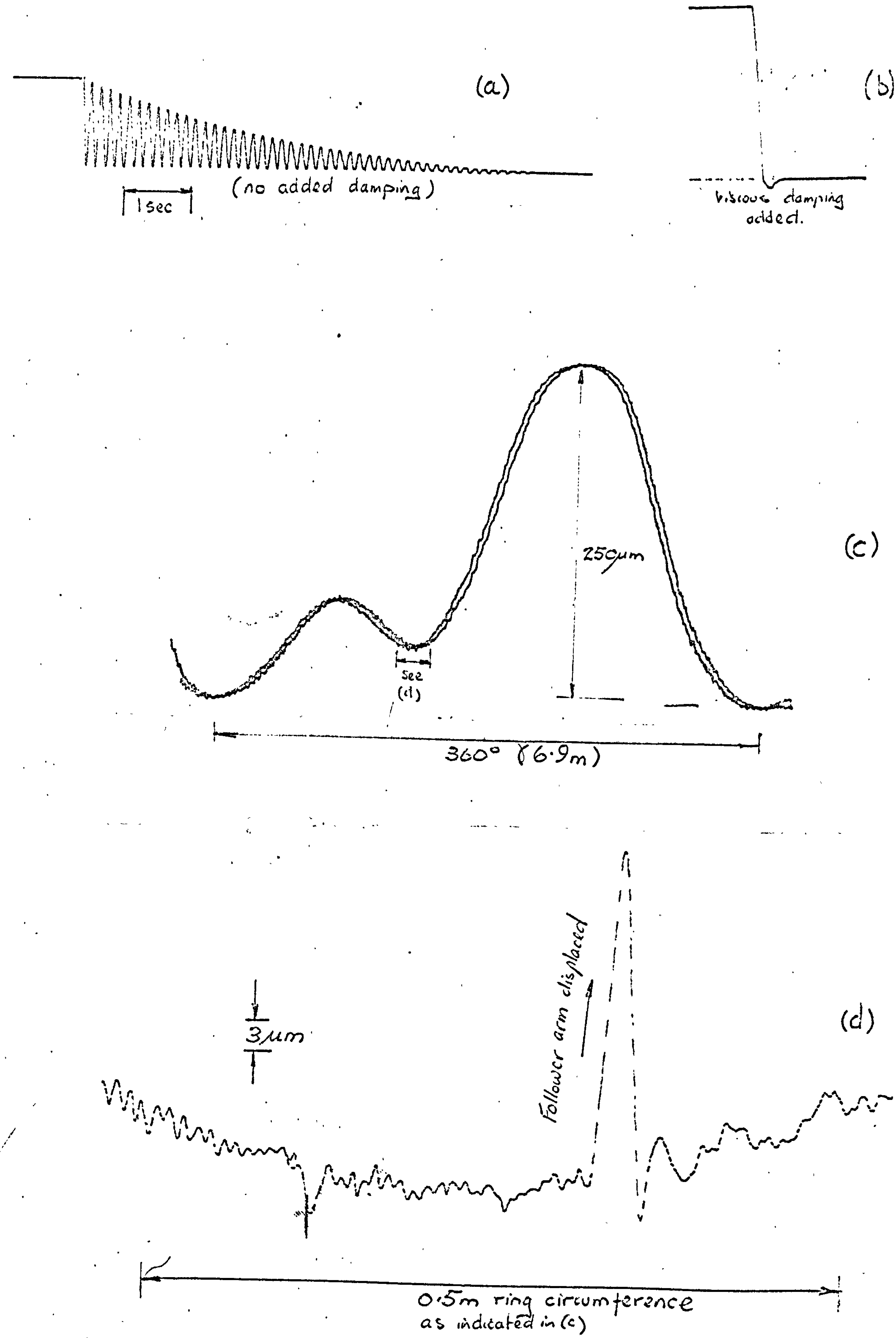

Figure 5.2.4. Recorded plots from roundness method.

of the transducer with the wire used was known to be well above 50hz. being a spring derived source of tension. Damping was found to be essential as non-uniform velocity of the carriage excited the following vibration mode.

Curve (c) is an actual plotted record of ring curvature. Two curves were taken in the same direction of movement and are seen to repeat within 3μm (radius is 0.9m.). Curves recorded for the opposite direction of movement were displaced at time as much as 9μm. This may have been due to the angular lag of the follower produced by the viscous damping force or may have been due to carriage positional variations upon the ring. Inferior open-loop speed control of the carriage prevented testing with traverse speeds below 3m/min which might have improved the repeatibity for the two directions of travel. The curve needs careful interpretation as cyclis sine errors are produced by the turntable not being central and by its axis not being perpendicular to the plane of the ring.

Curve (d) is a record takenover 0.5m of ring circumference with the radial dimensional sensitivity increased. Noise on the curve is of 2μm amplitude and was attributed to vibration of the ring on its supports and to follower transients. Electrical noise was less than 0.01μm in amplitude. During the traverse the follower was deflected to observe the response. This is indicated on the curve.

Due to the priority being given to the application discussed in the following sub-section, the work had not proceeded as far as was envisaged at the time of writing. However, a number of facets of this method have been demonstrated showing it to be practicable and capable of high precision. Having already shown that openloop measurement is possible it is self evident that a closed loop system could be constructed to automatically machine the spigot.

To reduce the setting up time needed to ensure that the turntable axis is correctly placed a second tensioned wire transducer could be used which is mounted above the one already installed . A perfect plane circle is defined when both wires retain fixed lengths with complete rotation.

Central control of the turntable is less important as this could be allowed for in a manner similar to that already used in solid frame roundness measuring machines.

It has also been shown that the error of the wire measuring system is unlikely to limit the methods performance for it is considerbly less than the error of the turntable bearing assembly and the runout of the bearing used to gauge the surface of the ring. These are fixed magnitude errors and are independent of the diameter being measured.

Measurement of absolute diameter has not been included as known methods, for instance, rolling contact wheels, stick micrometers and the Digiwire unit described in section 4, can adequately perform this function. The former method seems ideally suited to this application.

5.3 Seismic Strain Measurement with Tensioned Wires.

From the theoretical study of the detection limit of tensioned-wire deformation transducers it was realised that relative movements of 10^{-10} could be detected using a simple beam-balance tensioning a 10m length of wire. From experimental results obtained when testing the long term stability of the 12m measuring base it was established that creep and secular movements of the wire and measuring system were certainly less than 10^{-7} over a period of 500 hrs. These two considerations led to a further series of experiments in a location where temperature variation and background seismic noise were of lower magnitude.

A previous study of laser interferometer applications had shown that an experiment designed to measure earth strains was under construction by the Department of Geodesy and Geophysics of the University of Cambridge, using the N.P.L. developed interferometer. Dr. Davies, who heads the project, was contacted and it was learned that the tensioned wire extensometer might be a useful instrument for seismology if satisfactory performance resulted. A study was made of seismic-strain meters and a brief review is now given as background.

Seismology, the study of earth movements, has two main objectives, these being to collect data about earthquakes for predictive reasons and, secondly, the tremors caused by earthquakes and large explosions cause oscillations of the earth which enable knowledge of its structure to be investigated.

Two basic forms of instrument are used. The first, and most general, is the inertial device in which a suspended mass moves relative to the earth during relatively rapid earthmovements. These are basically simple and generally inexpensive but they respond only to movements over periods of seconds, are responsive to tilt variations, and cannot detect changing strain conditions in the earth. Records from these, however, enable the origin of the earthquakes to be established and also yield timing information about the resultant wave propogation.

The second type of instrument that has been adopted (but on a lesser basis due to their high cost and lengthly time required to bring them into service) is the extensometer or strain-seismometer by which changes in the earth length of typically 10m intervals or more are monitored. Movements exist continuously due to microseisms and solid tides of the earth's crust produced by the gravitational pull of the moon and sun varying the shape of the earth. Tidal magnitudes have typically 1 to 5 10^{-8} relative amplitudes with a 12 hour period. Strain meters have long period performance with stabilities of 10^{-7} or better per annum and resolve movements of 10^{-10} or smaller. With strain meters the installation location largely determines the performance which depends upon the microseism level, barometer pressure stability and temperature stability.

The first high-gain strain meter installation was due to Benioff who built a fused-quartz instrument from which similar instruments now bear his name. This instrument, built about 1930 (32), consisted of two large diameter steel tube piers cemented into bedrock. A quartz tube, about 50mm diameter and cemented together from sections to obtain 20m length, was supported horizontally with wire slings. One end of the tube was fastened to the pier and the gap at the other end was monitored with an electrical output, velocity transducer.

More recent installations of this form have been reported by Benioff in 1959 (33). Major et alia in 1964 (34) and by Blayney and Gilman in 1965 (35). Major also reported a vertical model in the paper. Blayney and Gilman claim 'portability' as they have used flexure pivot supports for the quartz standard instead of slings from above. Lengths up to 200 feet have been built (34) and readout is now generally as displacement using differential capacitor transducers or interferometer techniques. The instruments are typically located in horizontal tunnels or mines placed well down in the ground, to obtain good temperature stability (0.01°C is desirable) and to avoid surface effects such as ground heating and man-made vibrations.

Other mechanical methods have been reported. Sassa et alia (36) constructed a method in which a geodetic surveying invar wire of 1.65mm diameter was hung between two horizontal supports, 25m apart. A 350gm weight was supported in the centre and its vertical movements recorded. In this method the reference position is the bedrock in the centre of the span. For accurate results no bending of the rock can be tolerated. This method is similar to the sag wire used to check geodetic comparator length stability in which case no central weight is used. It does have the advantage of cheapness and simplicity of installation.

With the development of the coherent laser source the current trent is to use long-length interferometers for strain measurements. The long arm path is usually enclosed or evacuated to eliminate barometer and temperature effects (37-40). It is still necessary to have a deep installation, however, if local surface effects are to be eliminated. Advantages claimed for the interferometer are that very long paths (up to a kilometre is (40) realistic) can be used and better long term stability is possible.

Bender reviewed the use of lasers for this application in 1967 (18) where he also reports the intended construction of longer length Benioff instruments. The cost and lack of portability factors of laser methods would appear to offer no advantages over Benioff gauges.

This brief review shows that a cheap and rapidly commissioned method has yet to be realised. The tensioned wire method may be the answer, for the performance, described below, seems comparable with Benioff instruments . The device can be installed in a matter of hours (as only two end fastenings are needed), can be temperature compensated by using dual wires having different temperature coefficient of expansions, requires bore-hole tube magnitudes instead of tunnels in the earth's crust, and is low in cost as large colume production equipment has been used where possible. One advantage, realised and now being studied by R. Bilham of the Department of Geodesy at Cambridge University, is that bore-holes, which are numerous, can be used if remote controlled expanding clamps can be developed.

The remainder of this section describes the equipments made in the Cambridge University seismic station at Queensbury in Yorkshire. A disused railway tunnel about 3.0km long has been rented. The ends have been walled in and in the tunnel centre a 100m length is enclosed with draught screens across the tunnel. The entrance to the tunnel is shown in Figure 5.3.1. It is about 12m wide and 10m high in the centre. Overburden is said to about 100m at the central working location. The vertical walls are of stone construction with bricks used for the upper vaulting. In the past few months a 55m interferometer, running entirely in vacuum

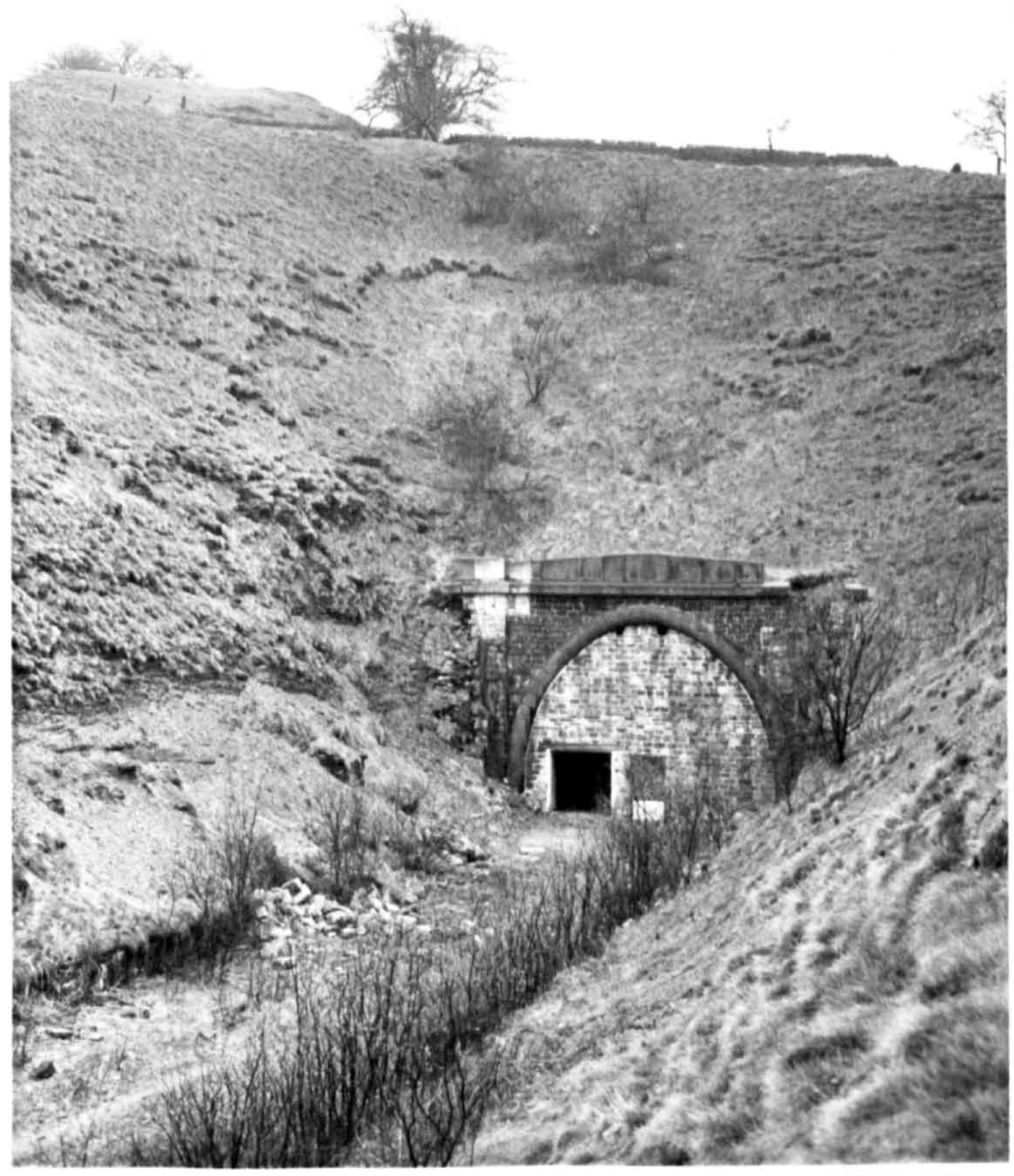

Figure 5.3.1. Entrance to tunnel at Queensbury, Yorkshire.

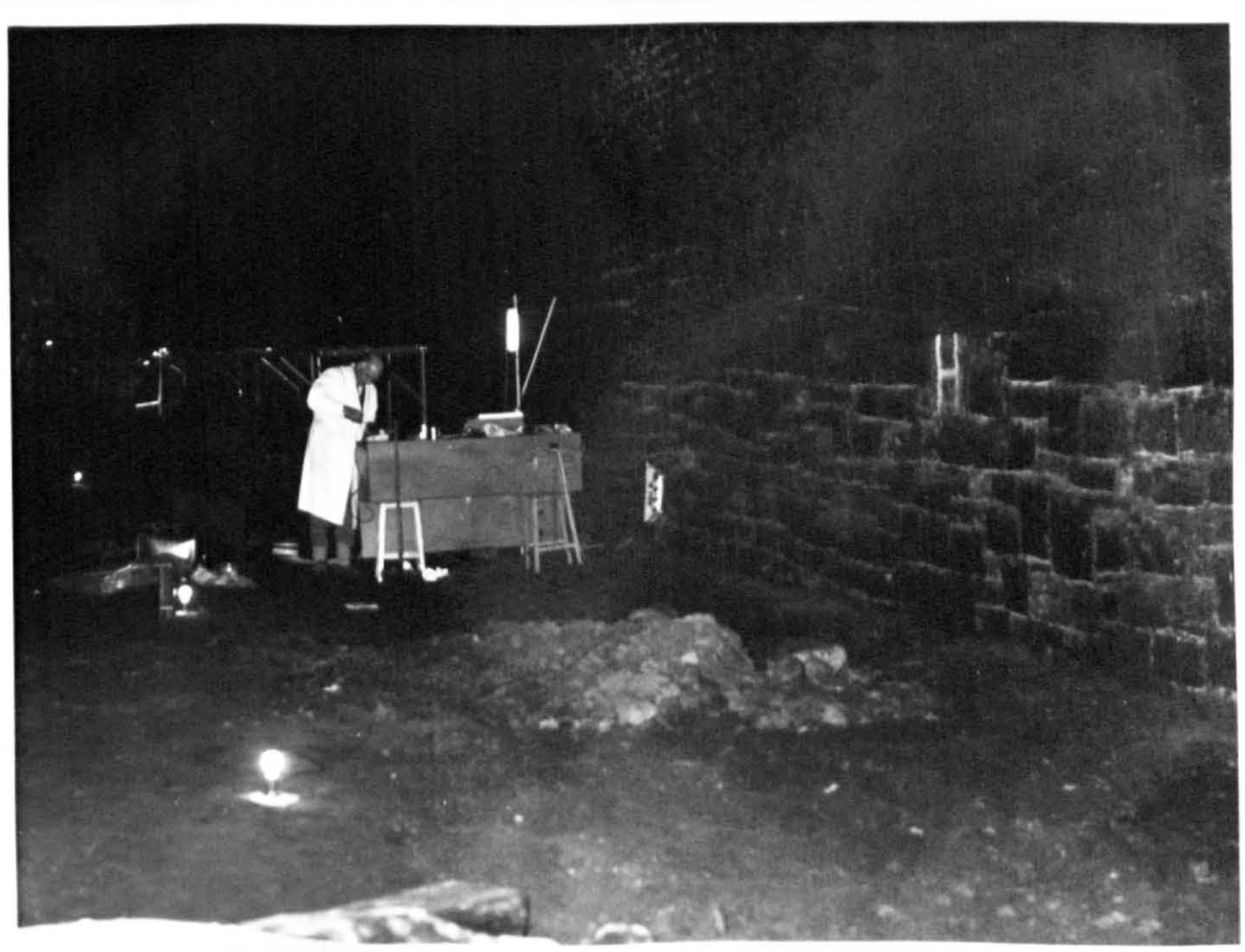

Figure 5.3.2. Interior view of tunnel experiment location.

retained in an aluminium tube, has been installed by the Department of Geodesy staff. As temperature does not critically affect their apparatus no serious temperature measurements had been made. The interferometer had not been operated satisfactorily to give useful strain records at the time of writing. Permission was given by Dr. Davies for a wire instrument to be installed at the end of their interferometer, as shown in Figure 5.3.2.

As much was unknown it was decided to modify the simplified balances, made for creep testing (Figure 4.4) instead of building improved designs. From experience gained on the measuring base, clamped, i.e. stressed joints, in a measuring system had not been found to be a source of instability. It was, therefore, decided to mount the balances on the stone wall using expanding 5/16in. diameter, bolts. Previous workers have structural cement or adhesives and required long period to stabilise. Three balances were mounted on a normalised steel plate as shown in Figure 5.3.3. A three point support is used and there is about 20mm clearance from the wall at the rear. In this figure the lower balance only is set up with a 0.9mm diameter invar wire. The other balances were subsequently used for a 0.38mm invar wire in the centre and a carbon-fibre 'roving' cord at the top. A similar plate is used at the other end to hold the wire ends. No covers were used during experiments but these would be advantageous. The linear differential voltage transformer probe heads (Tesa GT 10) have ball bearing ends contacting the balance arms and measure in-line with the wire axis to reduce bearing errors. High sensitivity (1μm f.s.d. - GH 22) electronic units were used for these experiments.

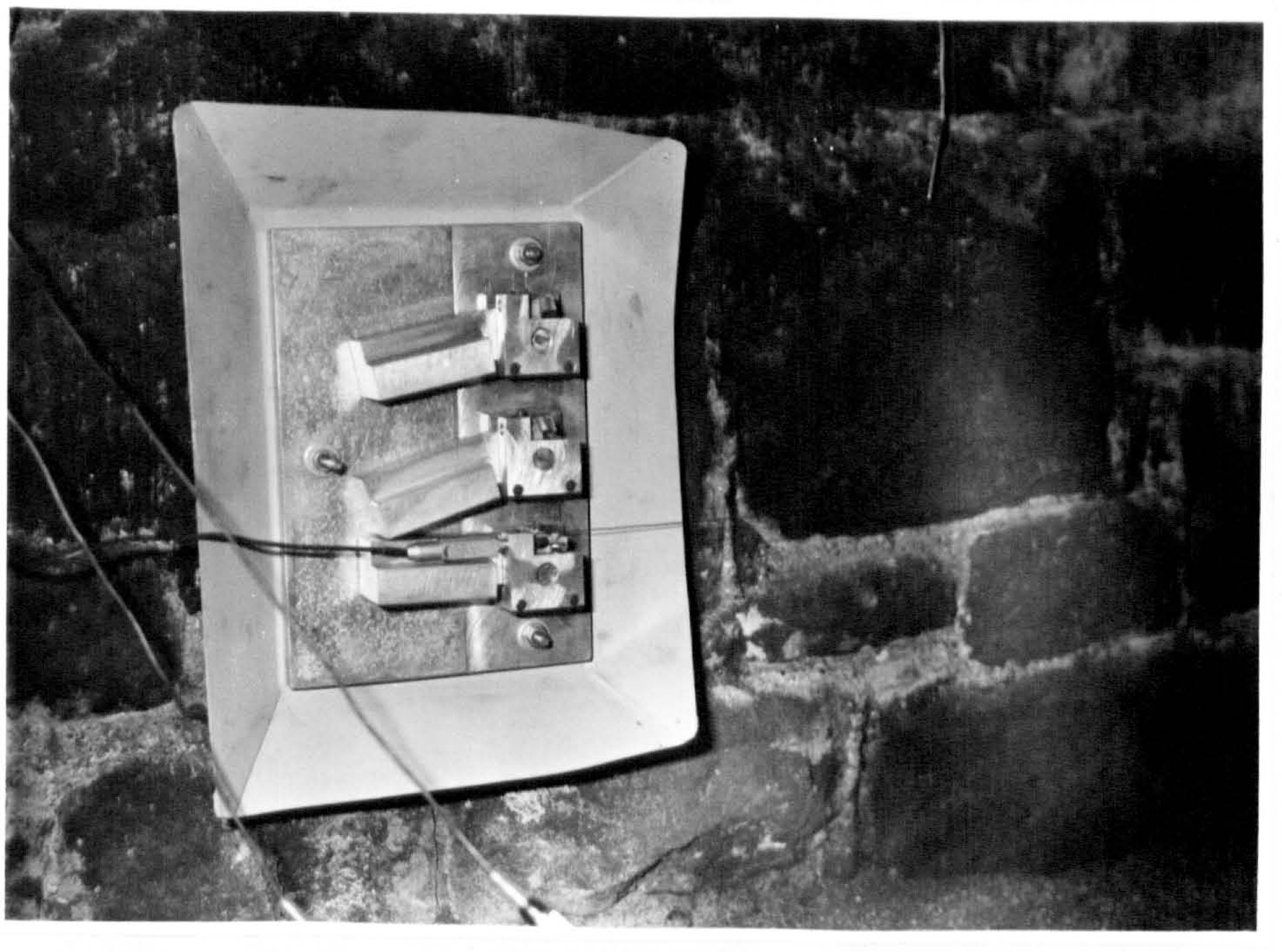

Figure 5.3.3. Modified balances mounted on tunnel wall.

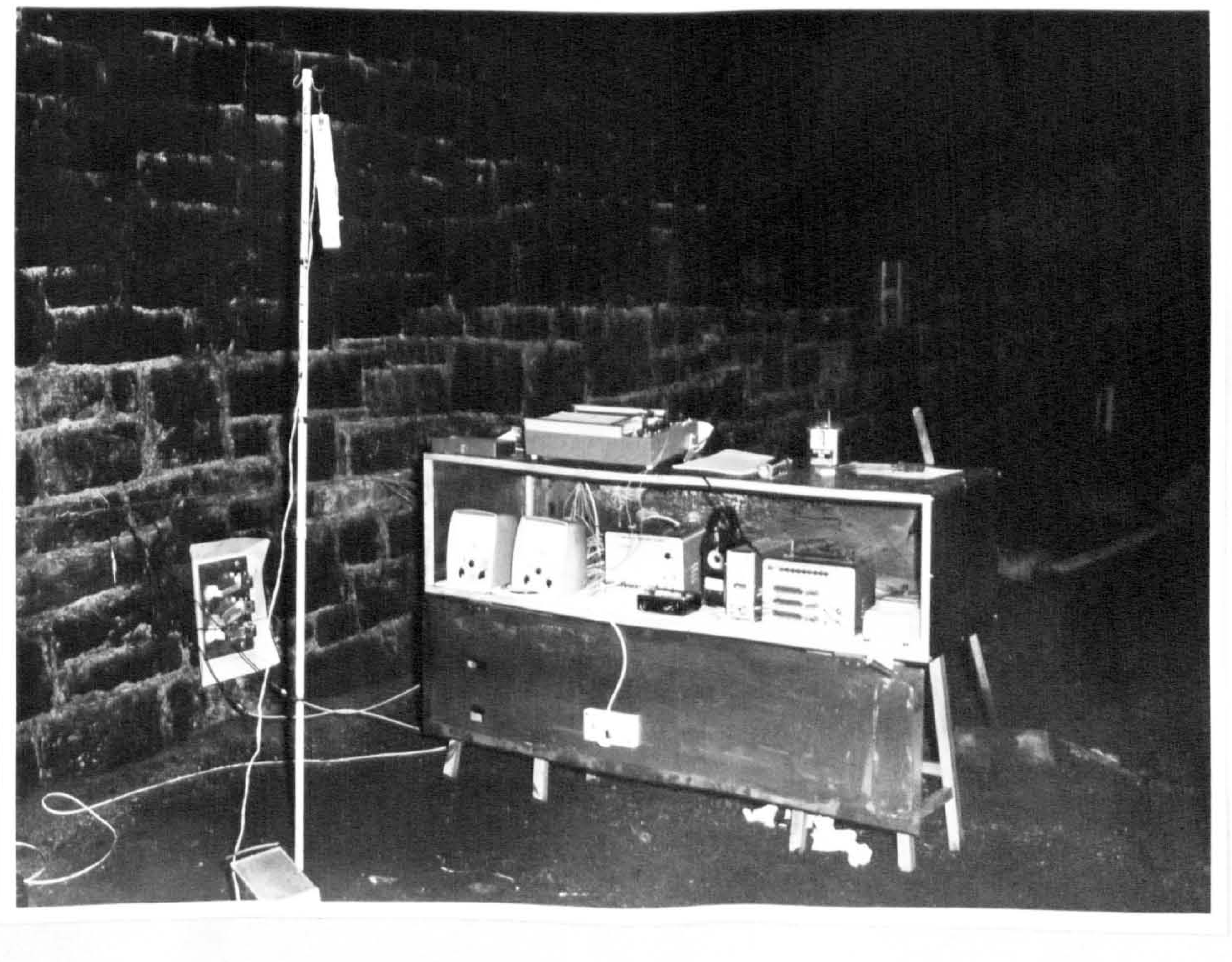

Figure 5.3.4. General view of experimental extensometer equipment.

Quoted stability corresponds to no greater than 10^{-9} relative length change in 6 months. Nine thermistor probes were used to record mean temperature along the 10m span. The equipment used to continuously record data is given in Figure 5.3.4. An x-y plotter was used to record the balance movements over periods of several minutes enabling rapid assessment of secular drift and creep rates.as the sensitivity of the plotting machine was some 10^3 greater than the chopper bar instrument used for long term recording, The equipment took 2 hours to install and was placed in operation on 30th April 1969.

The initial drift rate was about 10^{-8}/hr. which enabled a tidal curve to be obtained during the first 12 hours of operation. Movement was indicated as base lengthening, presumably due to small movements of the bolted plates as tests with the same batch of invar wire had shown immediate 10^{-8} stability over several weeks was normally obtained.

Tests were made of the system resolution and short-term repeatability using the graph plotter. Figure 5.3.5 is a copy of a plot obtained in which several factors were established. The recorded noise level was found to be equivalent to a relative strain of 5 10^{-11} or less and it was established that this was similar in magnitude to a clamped gauge head electrical output, indicating then seismic noise is probably 10^{-12} or less. The support plate was deflected inward and outward by hand to check the repeatability. Stiction of about 5 10^{-10} is evident. However, movements induced by heating the wire with a bare hand shows no stiction. It would appear that for very small movements the pivots move as a solid elastic mount and begin to roll as the magnitude increases giving a stiction effect. It is clear, however, that for such exacting

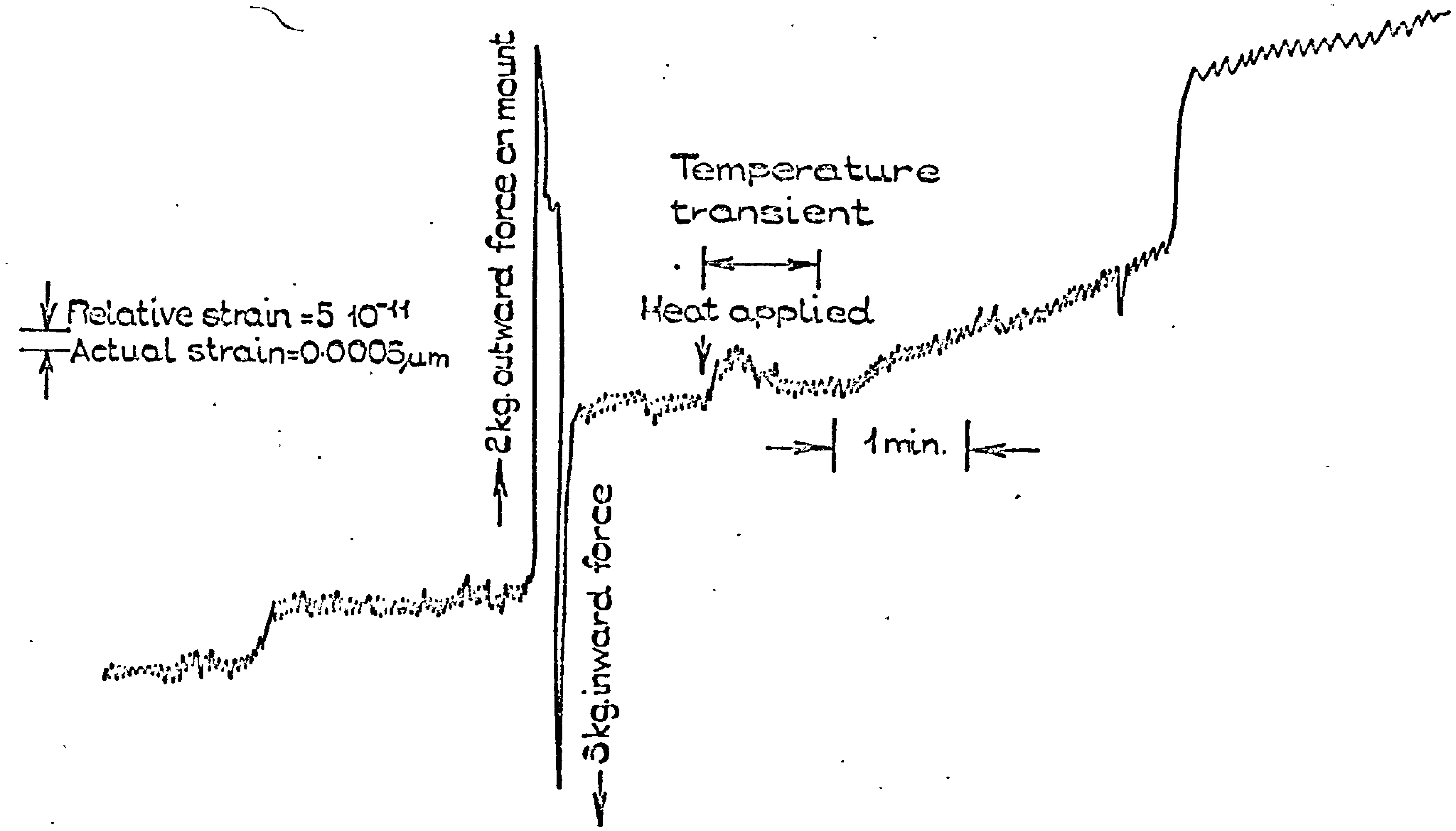

Fig. 5.3.5. High gain, short period, tests of beam balance in quiet environment

application flexure pivots appear more reliable and precise. (A flexure pivot balance is under construction). This curve also enables the mounting plate stiffness to be estimated as 100kg/μm showing that releasing a wire in other units has negligible effect. A longer term test was then made to ascertain long term drift rate. As the station was unmanned the sensitivity was set low to avoid losing the record. The results showed, in fact, that maximum sensitivity could have been used as it was found that apparent lengthening of the wall was no greater than 10^{-8} over the 150 hour test. Both invar wires were stable to this value but the carbon fibre continued to extent at 10^{-8}/hr.

A 36 hour test was then made using maximum sensitivity (100mm of chart per μm of wire movement) available from the recorder. The results of this test have been summarised in Figure 5.3.6.

Curve (a) is for the larger invar wire and was only valid during the last 12 hours as it was found the balance was initially binding upon the gauge head. Once set correctly it did support the results obtained from the 0.38mm wire given in (b). These clearly show cyclic variations of 12 hour period, presumably solid tides of the earth having magnitude of 1.2 10^{-8}, agreeing with the amplitude of the record published by Benioff (33) but smaller than the 5 10^{-8} usually quoted. The stone wall may not be transmitting the full elastic movement of the rock. Secular drift of the measurement is difficult to assess from such a short record, but is certainly within a few parts in 10^{-8}. Curve (c) is the temperature record showing variation of about $\pm$.02°C with an apparent rise in mean of 0.01°C. The previous 5 day tests,

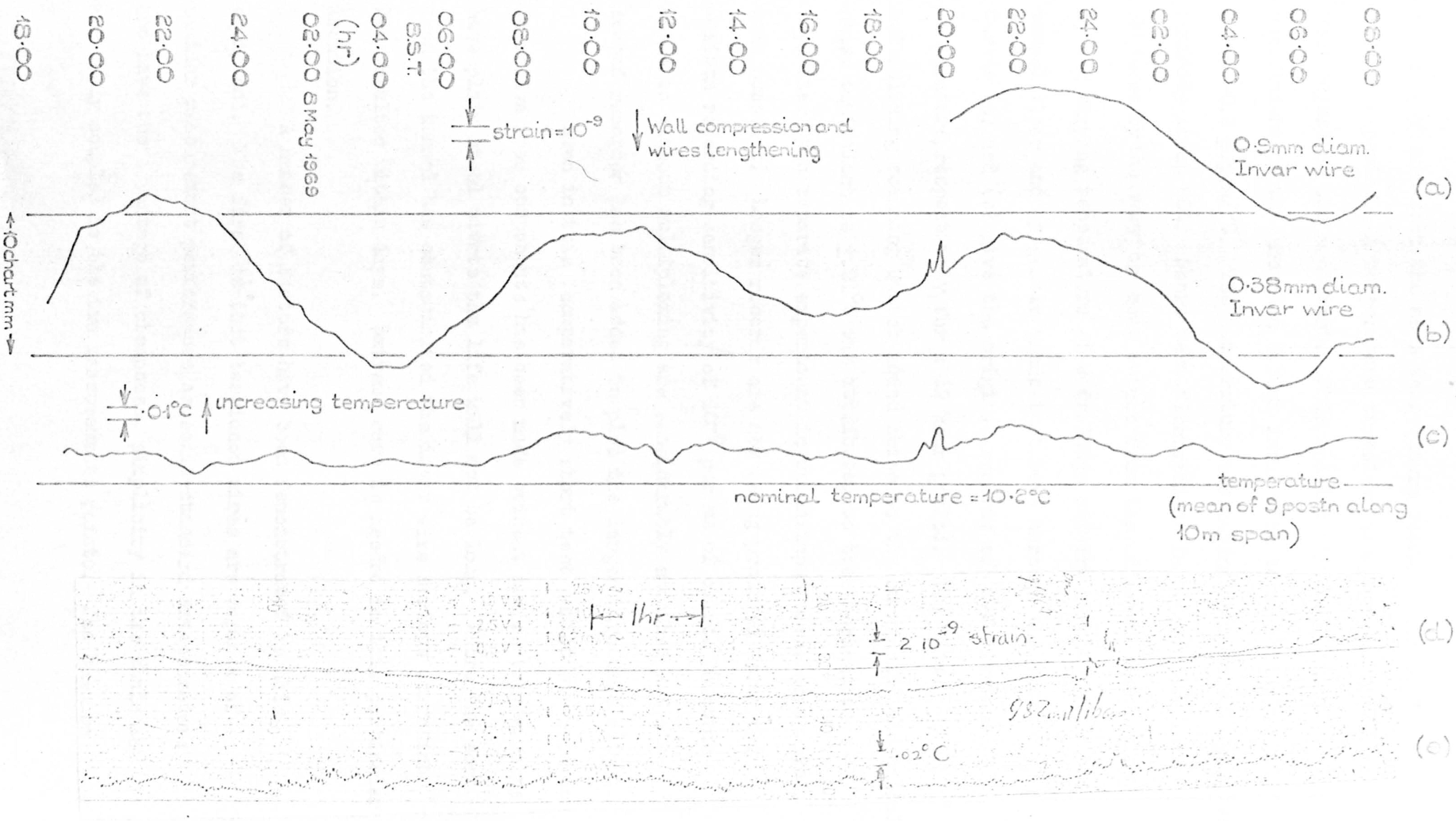

Fig. 5.3.6. 36 hr. duration record of strain and temperature obtained 100hrs after installation

however, showed that the mean temperature remained within $\pm .02^{\circ}C$ over that period. A temperature transient was produced at 22.00 hour when adjusting the equipment. This enabled the temperature coefficient of the annealed 0.38mm invar wire to be estimated at about ∓ 0.2 p.p.m/$^{\circ}$C. The temperature was nominally $10^{\circ}C$ and relative humidity about 80%. Short term fluctuations in temperature were produced by the varying heat output from the adjacent vacuum pump, by the varying temperature of a drainage culvert running under the tunnel floor and by gentle winds that move through the tunnel. Curves (d) and (e) give the original records of .38mm wire and temperature, respectively, for a 12 hour period. The time-multiplexing scanning switch added noise to the curves and electrical noise equivalent to $\pm .01^{\circ}C$ was attributed to the thermometer amplifier by a separate experiment in which input conditions were held constant. Longer records are now being produced using the maximum recording sensitivity of 10^{-9} per mm of chart. Records obtained without multiplexing are considerably smoother and a second recorder has been added to plot the larger wire unit output.

Even in this comparatively short test period the need for corrosive free components has been made evident and as the balances have plain steel pivots the life will not be long. Where the soot from the tunnel has contaminated the invar wire serious corrosion has resulted within days. Extreme care is needed in this particular location.

A number of factors have been demonstrated by this equipment. The first is that tensioned wires are capable of similar measurement performance as solid-standard extensometers and have the advantage of cheapness, simplicity in the whole and are only coupled to the two measurements points. The balance design can be improved by using more suitable pivots, such as flexure strips. By the use of a larger radius arm and larger span lengths (100m is practicable) sensitivities can be further increased if needed. The system cost is probably less than inertial seismometers but the need for a good location remains. It has been demonstrated that stressed joints in the rock (not previously used in this field) for mounting locations allow the system to be installed in hours and be useable almost immediately at tidal sensitivities. Long term performance of the gauging system is assured by using an established equipment. The tests were still not able, as yet, to show that the invar wires used have any greater than 10^{-8} relative creep and as the wall itself may be changing length (or the rock beneath) it is unlikely that creep will be measurable. Kiln-fired brick walls are known to increase in length at about 4 parts per million per annum (41).

This method has some disadvantages. The most serious may be that violent movements, such as those caused near the epicentre of an earthquake, will produce large tension transients in the wire due to the high inertia of absolute balances (Section 4). This will probably give rise to shift in strain due to mechanical hysteresis making measurement of residual strains uncertain. This may be reduced by using large wires at low tensions, using low hysteresis wires (if suitable materials exist) and probably by the use of spring balances if their stability is adequate. Temperature effects may be reduced by compensation with special compounded wires or parallel units (Section 4). Barometric pressure variations also effect the equipment. Benioff (33) has shown that this error depends upon the bulk modubus so pressure error magnitudes should be comparable with solid quartz tubes.

Gravitational changes are also important as these change the catenary shape and the balance weight. The former is independent of gravity with absolute balances for the sag error term is proportional to the tension/weight per unit length ratio. Gravitational changes, however, will alter the tension. Typical records obtained from other sources showed that daily variations in the gravitational constant are about 0.1 milligal. i.e. g varies 10^{-7}. As the elastic extension of a wire is typically 10^{-3} of the length or less, the total length change will be about 10^{-10} which is almost negligible.

Further experiments will be carried out in this location until the writers grant expires. Results will be published when longer-period stabilities have been proven and results can be correlated with the interferometer. The design of flexure strip supported balances will be investigated after consultation with Professor R.V. Jones of Aberdeen University, who is a recognised authority on fine mechanisms.

6. CONCLUSIONS

1. During the past two years further research by the writer at the University of Warwick has been concerned with large-scale metrology as a discipline, with particular use of a new class of dimensional transducers using a tensioned wire or cord to convert length movements into electrical signals.

2. Extensive study of published literature (Section) on suitable techniques and current practice has been made, showing that improvement is needed and that economic returns are possible in numerous applications. Review papers on decametre range transducers and position-sensitive photocells have been published.

3. In order to test the longer-length devices a 12m length controlled base has been constructed (Section 3) which has a long term stability of better than 0.2 p.p.m. This exercise showed that relatively simple and cheap control is possible with <u>internal</u> temperature control techniques and that this method could well be applied to precision measuring machines and machine tools and possibly to geodetic comparators. Testing the length stability of this base led to the development of deformation type of wire transducers.

4. The theory, practice and performance of the past few years experience with continuous subdivision wire transducers and deformation wire transducers has been given in Section 4 where it was shown that continuous lengths from millmetres to decametres can be measured with up to 1 p.p.m. s.d. error. It was also shown that relative defomation of 10^{-10} or smaller could be detected given a suitable environment. Linearised and improved response

continuous devices have been built. Improvements to current survey tape practice have been suggested and the possibility of a mechanical, digital readout, length sub-standard is suggested.

5. The first major application of continuous wire transducers was to control position using trilateral measurements rather than the cartesian co-ordinates usually used in engineering. A fast response tooling manipulator has been designed and built and controlled in position by two 12m continuous wire transducers.

A special technique for satisfactorily reducing the trilateration interaction has been demonstrated showing that a cartesian tool can be positioned without the need for an on-line computer. This equipment was demonstrated at the 1968 Physics Exhibition. It seems capable of positioning within 10 x 15m area to within 10 p.p.m. error.

6. The use of a deformation transducer for roundness measurement of a large base or spigot has been demonstrated showing that repeatability of 10 p.p.m. is easily achieved with simple equipment. This experiment was still under investigation at the time of compilation and results are limited.

7. Earth solid-tidal strains of 10^{-8} relative magnitude, have been measured with a tensioned invar wire showing that a cheap and rapidly commissioned method is feasible for seismic measurement. Improved balances would be preferred for this application as the steel ball bearings used are liable to corrosion.

8. A large number of visitors interested in large-scale metrology have been entertained and a number of solutions have been suggested to several industrial problems. Interest in the manufacture of the wire units has been shown which will eventually assist others who have expressed the desire to purchase ready-made equipment.

7. APPENDICES

7.1 Temperature Measurement and Recording Relevant to the Research.

For large scale dimensional measurements temperature distribution is most important as it cannot be assumed that sufficient thermal conductivity exists to equalise the distribution as is generally the case in normal metrology.

A market survey of electronic thermometers resulted in the selection of thermistor methods. These have the advantage of having impedances of about 3Kohm which enables long leads and normal switching equipment to be used. The basic unit purchased was that of Grant Instruments of Toft Cambridge with a $\pm$ 5°C, about 20°C range and a $\pm$25°C, about 20°C range. Provision to manually connect to remote probes is available. A recorder output was made available. From the two years experience with this equipment it has been found that measurement stability is well within the 0.1°C claimed, it being, in fact, closer to 0.02°C over periods of days. This unit can be seen in Figure 7.1.1. in the left hand front corner.

Mean temperature could be found by averaging the individual readings of a number of probes but this is tedious. The average can be produced directly by series-parallel connecting 4 or 9 probes to gain the same effective resistance. (2492Ω at 20°C, 3986Ω at 10°C).

Provided the individual values vary no more than 5°C from each other this would produce the average accurate to within 0.1°C. A switching unit was built enabling probes to be individually adjusted (100Ω linear resistors in series with each probe)

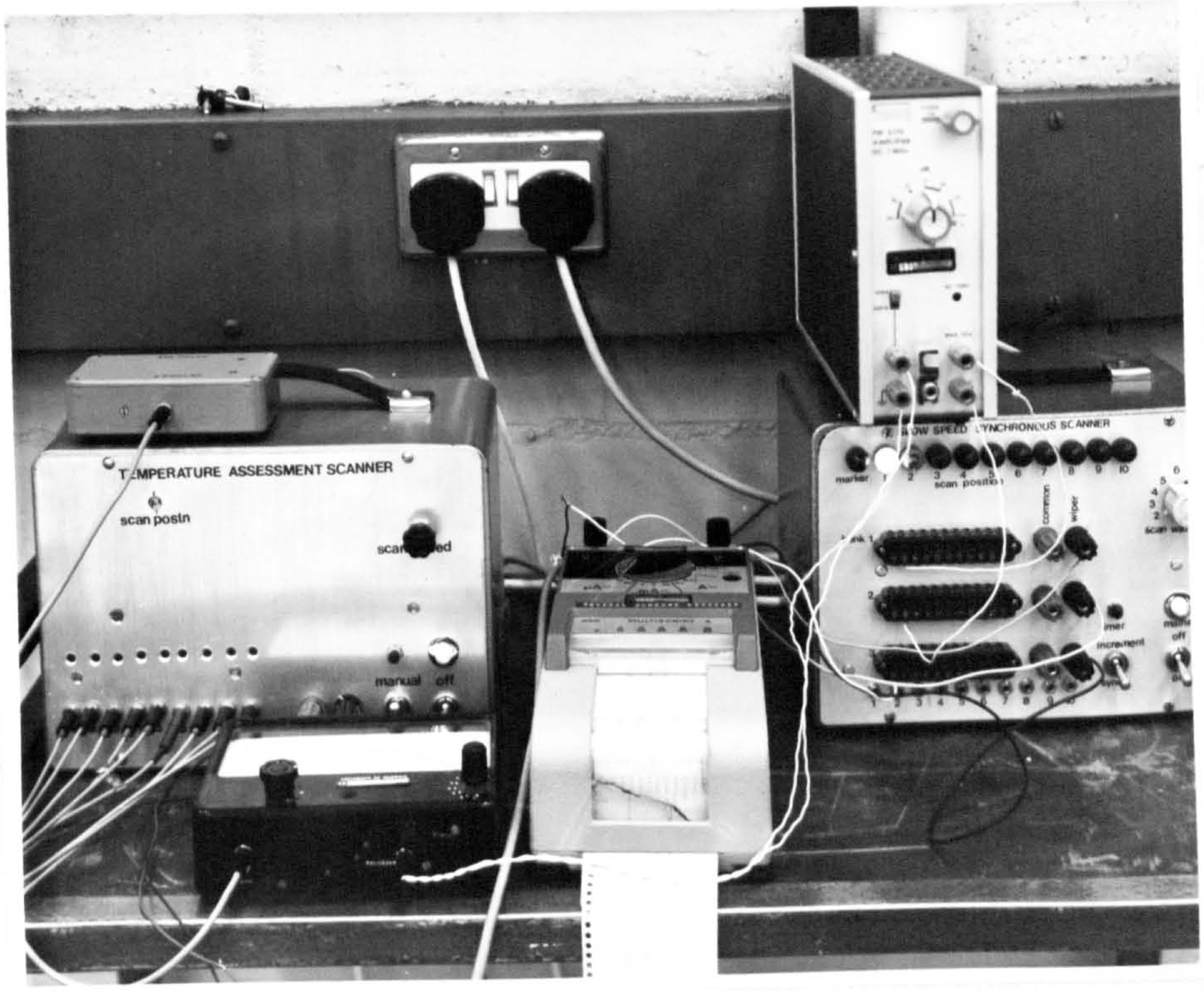

Figure 7.1.1. Temperature measurement and recording equipment.

to the same absolute value in sequence and enabling each to be tested for extreme divergence. A separate position interconnected the nine probes to give average output. This unit is on the left hand side of Figure 7.1.1. Provision to continuously and automatically scan through individual and average connected circuit positions was included to enable rapid discovery of variance, a procedure not entirely satisfactory due to the transients produced by the switching action.

As the required resolution grew finer with project refinement, a d.c. amplifier was used to increase the output from the electronic bridge network associated with the thermometer. Continuous records were made with a chopper bar recorder (Multiscript, Model 3, Smiths Industries).The recorder and amplifier can be seen in Figure 7.1.1. Temperature sensitivity on the recorder was about 0.01°C/mm. The long term stability of the amplifier and thermometer was tested by replacing the thermistor with a low temperature coefficient resistor held at constant temperature. This test showed that amplifier drift gave indicated errors of ±.01°C over periods of days.

In most cases it was necessary to record temperature and dimension simultaneously. A time multiplexing scanner unit was built to sequentially switch the thermometer and dimensional probe outputs to the common recorder, or alternatively to connect various thermistor probes to the bridge as needed. This unit, shown in the figure has a uniselector pulsed with a synchronous motor driven, microswitch. A choice of 30 second or 60 second step rate was provided. Manual increment allows a separate signal to be selected for setting up purposes.

This equipment, designed originally for laboratory use with the unmodified thermometer and probes, was pressed into service in the seismic extensometer application. Signal levels of 500μv were involved and switching performance was not satisfactory. In this application the thermometer centre-reading value of 20°C was unsuited and an external resistance was added in parallel with the average-connected probes to obtain a 10°C mean value. This did not seriously affect the gain as the resistance changes are proportional to absolute zero temperature.

APPENDIX 7.2

INERTIA OF THE CONSTANT TORQUE SPRING MOTOR

The constant-torque, reverse wound, spring motor is represented in thé figure. The spring strip is prestressed to have a natural radius of curvature just less than the storage bush which runs freely.

The inertia of this assembly, as seen at the output shaft, consists of contributions from the output bush, guiding cheeks (if used) and the spring material on the output bush at a given position of the output shaft plus a similar contribution of the storage part of the motor. The two sections are effectively geared by the action radii of the two spring-coils.

By careful design the inertia of the bushes and cheeks can be made considerably smaller than that of the spring coils. The inertia can, therefore, be taken as two cylinders of variable thickness which are coupled by their outside radii. The inertia is

$$Im = \frac{\pi}{2} b\rho \left\{ \left[(r_3 + n_o t)^4 - r_3{}^4\right] + \left(\frac{r_3 + n_o t}{r_2 + n_s t}\right)^2 \left[(r_2 + n_s t)^4 - r_2{}^4\right] \right\} \quad ..(1)$$

The length of spring on the output bush l_o at any number of output turns is given by

$$l_o = \int_o^{2\pi n_o} \left(r_3 + \frac{t\theta}{2}\right) d\theta \qquad (\theta \text{ the shaft rotation}) \quad ...$$

$$= \pi n_o (2r_3 + n_o t) \qquad ...(2)$$

By similar reasoning the length of spring on the storage bush, l_s, is

$$l_s = \pi n_s (2r_2 + n_s t) \qquad ...(3)$$

The total spring length is

$$L_o = \pi N_o (2r_3 + N_o t) \qquad ...(4)$$

Where N_o is the total output turns specified. At any position

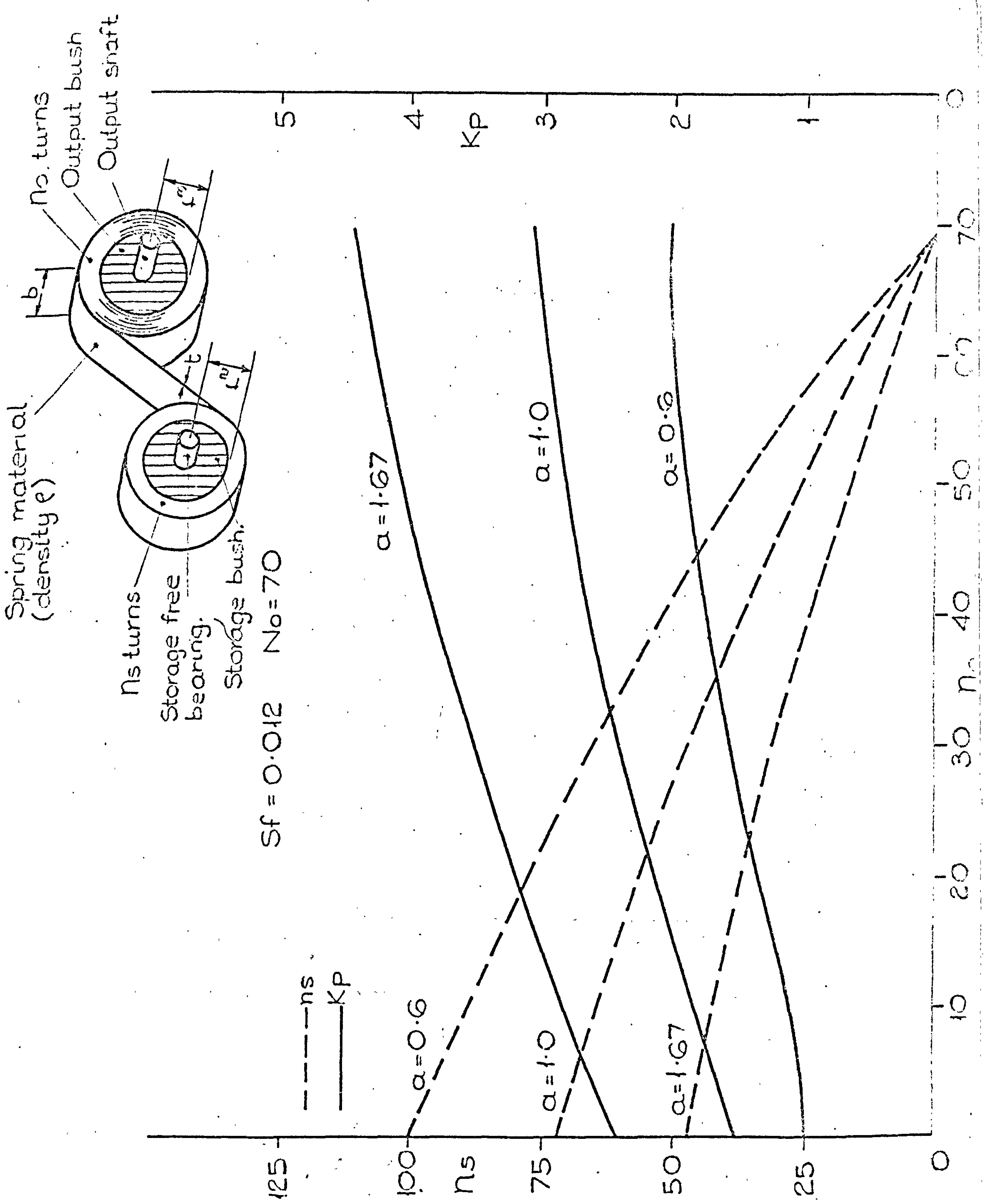

Figure 7.2.1. Variation of inertia of constant torque spring motor.

$l_o + l_s = L_o$ (the connection ends and inter spool distances neglected)

giving from equation (2), (3) and (4)

$$n_s^2 + (\frac{2r_2}{t})\, n_s + (n_o^2 + \frac{2r_3 n_o}{t} - \frac{2r_3 N_o}{t} + N_o^2) = 0 \qquad \ldots.(5)$$

for which the positive root is valid giving

$$n_s = \frac{-r_2}{t} + \sqrt{\frac{r_2^2}{t} - n_o^2 + N_o^2 + \frac{2r_3}{t} N_o - n_o} \qquad \ldots.(6)$$

The r_2, r_3 and t, are related by the stress factor, Sf, which depends on chosen fatigue life. Votta states this to be

$$\frac{Sf}{t} = (\frac{1}{r_2} + \frac{1}{r_3}) \qquad \ldots.(7)$$

provided $r_2 \approx r_n$ the natural curvature radius of the preformed spring. It is convenient to eliminate r_2 and t from equations (1) and (6).

Substitute $r_2 = ar_3$ and equation (7) to obtain

$$I = \frac{\pi}{2} b\delta r_3^4 \left\{ \left[1 + Sfn_o \frac{a}{1+a}\right]^4 - 1 + \left(\frac{1 + Sfn_o\frac{a}{1+a}}{1 + Sfn_s\frac{a}{1+a}}\right)^2 \left[\left(a + Sfn_s\frac{a}{1+a}\right)^4 - a^4\right]\right\}$$

$$= \frac{\pi}{2} b\delta r_3^4 . K_p$$

where K_p is the position dependent bracketed term. Similarly for n_s

$$n_s = -\frac{1 + a}{Sf} + \sqrt{\left(\frac{1 + a}{Sf}\right)^2 - n_o + N_o^2 + \frac{2}{Sf}\frac{1 + a}{a}(N_o - n_o)}$$

Commercial springs are normally made with a = 0.6 to obtain economic use of material. K_p is plotted in the figure along with corresponding values of n_s for a range of 'a' values in a 70 turn motor with stress factor of .012 (infinite life for stainless steel spring strip). The plots indicate that the inertia for large turn motors has a maximum when the output bush contains all the spring material ($n_o = N_o$) and that the inertia varies some 30% with position. For assessment purposes therefore, the inertia of the spring motor may be approximated as a cylinder of material on the output bush giving

$$I = \frac{\pi}{2} b\delta \left[(r_3 + N_o t)^4 - r_3^4\right].$$

Material	Modulus of Elasticity ($kg\ mm^{-2}$)	Tensile Strength ($kg\ mm^{-2}$)	Coeff. of Linear Exp. ($10^{-6}/^{o}C$)	Thermoelastic coeff. ($10^{-6}/^{o}C$)	Hysteresis (%)	Specific Gravity
Stainless steel	20300	105	12	-250	1.0	7.8
Phospher Bronze	10500	21	10	-360	-	8.8
Ni Span C902	19600	32	6	- 50	0.02	8.0
Invar	159000	52	-0.5 - 2	-500	0.5	8.1
Carbon Fibres H.M.	38500	280	-0.6	-	0.1?	2.0
Fused Silica	8000	-	0.2 - 0.5	-	-	2.7

Appendix 7.3 Selected materials data relevant to tensioned- wire devices.

7.4 Published Papers Arising from Ph.D. Thesis.

A number of papers have been submitted for publication on the work of this thesis. Of these, the following have already been published.

(a) "Linear and angular tranducers for positional control in the decametre range". Proceedings of the Institute of Electrical Engineers, London.

(b) "Position-sensitive photocells and their application to static and dynamic dimensional metrology". OpticaActa of International Journal Series.

(c) "A length stabilised 12m measuring base". Journal of Scientific instruments of the Institute of Physics.

(d) "Long-length precision transducers for industrial ranges". Conference proceedings of Industrial Measurements Techniques for on-line computers Conference.

Papers submitted attime ofcompilation are:-

(e) "Theory and design of tensioned-wire dimensional measuring instruments". Submitted to the Institute of Measurement and Control, London.

(f) "Numerically-controlled position using trilateral co-ordinate measurement". Submitted for the 1968 Machine Tool Design and Research (M.T.D.R.) Conference.

It is proposed to publish details of the seismic application reported in Section 5.3 when further results have been obtained.

The yet unpublished papers have not been repeated here as they are virtually identical with the relevant portions of the text of the thesis. Those which have appeared in print now follow.

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7.5 Submitted Work not Performed at Warwick University.

After the completion of the Masters degree research and submission, a short project was made as the necessary equipment was available to verify a principle of angle measurement (7). This work was published in the Journal of Scientific Instruments and a reprint is included. It was not submitted for the Masters Degree and is, therefore, eligible for inclusion in this submission.

7.6 Presented Papers, Exhibits and Press Accounts.

Presented Papers.

At the request of the Institute of Electrical Engineers a short paper was delivered to the "Industrial measurements for on-line computers" conference held in June 1968. The paper on decametre range transducers was read at Savoy Place on 17th December 1968.

Exhibits and Press Accounts.

In November 1968 it was decided that the trilateral control system discussed in Section 5.1. would be one of two exhibits by the School of Engineering Science at the 1969 Physics Exhibition. A photograph of the exhibit, Figure 7.6.1., is given with the Handbook entry. This resulted in a short description in the "Engineering" journal which is also included.

As the project conclusions became more evident a brief account has been sent to about forty establishments, half in industrial and the remainder in government groups. Two engineering magazines responded. "Metal Working Production", published a full page account and "The Engineer" are to compile an article based on a visit made by one of the Editorial Staff to the University. The former is included.

The 12m Digiwire units were demonstrated to the Production Engineering Research Association staff at Melton Mowbray and a number of enquiries have been received by their reference to the work.

The National Research Development Corporation have taken patents on the wire transducers and on the trilateral control method. These are:-

1. U.K. patent application No. 19578/67
   "Measurement of long distances".

2. U.K. patent application No. 26183/63, "Method and apparatus for accurate inspection and automatic machining using the component as a base".

Interest has already been shown in manufacture and application of tensioned-wire methods.

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