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The New System for Controlling the Attitude and Motivator Deflections of a Model in the R.A.E. No. 19 Wind Tunnel

by

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THE NEW SYSTEM FOR CONTROLLING THE ATTITUDE AND MOTIVATOR DEFLECTIONS OF A MODEL IN THE R.A.E. NO.19 WIND TUNNEL

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SUMMARY

A new closed loop system is described which enables the incidence, roll and motivator (i.e. control surface) angles of a wind tunnel model to be controlled remotely, either by hand or by analogue voltages derived from, say, a computer.

Besides operating from direct (polar) demands, the system correctly positions the model if the demands are referred to Cartesian coordinates, and in this case compensation for sting bending can be made automatically.

The system is described in some detail and the results of dynamic performance measurements are given.

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* Replaces R.A.E. Technical Report 68015 - A.R.C. 30215.

CONTENTS

1 INTRODUCTION

In Ref.1 it was pointed out that in order to utilize the R.A.E. No.19 wind tunnel as an element of a flight dynamics simulator modifications would be necessary to the model attitude control system then existing. Greater rates of change of attitude were necessary and closed loop control was required in order that the computing elements of the simulator could command the model attitude. It was also necessary to provide means of varying model control surface angles to suit the demands of the computing elements.

The work required could be considered under the headings of mechanical engineering changes in the model support system, refinement in model design and servo-control systems development work. In the interests of economy of time and money the existing incidence quadrant was retained but the drive was changed from electro-mechanical to electro-hydraulic. An entirely new roll drive unit was made, also with electro-hydraulic drive.

The freedoms provided remained unchanged viz. incidence in the vertical plane of the tunnel, and roll, but the desired increased rates of change of angles were attained.

Accurate miniature oxide film potentiometers, of similar type to that described in Ref.2, and miniature electric motors developing relatively high torques enabled the model design problems to be solved, although each model design requires individual treatment.

The guiding philosophy for the servo control systems was that the tunnel and models were to be at least as convenient to use for conventional tests as previously and preferably more convenient. Thus alternative hand-set input demand controls have been provided for both model attitude and control surface servo systems.

Three modes of presentation of input demands are catered for by the model attitude system, distinguished by the titles 'polar mode', 'Cartesian mode' and 'trim boundary mode'. In the polar mode the quadrant incidence and roll angle demands are directly set, the latter being restricted to hand-set only, while the former may be either hand-set or in voltage analogue form. In the Cartesian mode the input demands are for $\bar{w}$ and $\bar{v}$ ($\sin \alpha$, $\sin \beta$ using sine definition of incidence), the velocity components along Oz and Oy Cartesian model axes normalised by the total velocity V. These demands may be either hand-set or in voltage analogue form. Since there are two combinations of total incidence and roll angle either of which would satisfy a demand for particular $\bar{w}$, $\bar{v}$, a switch has been provided, one position of which yields the solution involving a positive total incidence and the other that with negative incidence.

The trim boundary mode is especially tailored to the requirements of a system for the automatic generation of trim boundaries[3]. In this mode total incidence and rate of roll may be demanded either by hand-set or voltage analogue inputs, the values of $\bar{w}$ and $\bar{v}$ for the model being made available as output information.

It is necessary to limit model roll rotation to six revolutions, in order to avoid shearing the electrical leads to the model and balance, and so mechanical stops have been provided. In the Cartesian and trim boundary modes the roll rotation is prevented from approaching within a quarter of a revolution of these stops by the control system. At this point the system ceases to respond to input demands whilst one revolution of roll unwind is automatically executed, on completion of which the system resumes its normal function.

Adjustable stops have been provided to limit the usable range of total incidence to less than the maximum of ±25° normally available when test conditions so require. An automatic homing system has also been provided which rapidly returns the model to zero incidence in the event of an electrical power failure affecting the tunnel fan motor.

Provision has been made for simultaneous operation of up to four independent control surface servo systems in any one model. The input demands for particular control surface angles may be either hand-set or in voltage analogue form.

A detailed description of the system, together with some performance figures, follows in the body of the report.

2 THE MODEL ATTITUDE DRIVE UNITS

Hydraulic power for the attitude system is provided by a self-contained power pack comprising electric motor, hydraulic pump and accumulator together with automatic gear enabling accumulator pressure to be held within preset limits. In the present system the accumulator pressure is held between 1800 lb per sq inch and 2000 lb per sq inch and is reduced via a valve to about 200 lb per sq inch for the roll drive.

Control of the incidence jack and roll motor is normally by electrical torque motors operating single stage servo valves, but the incidence jack servo-valve may be by-passed and the jack controlled by a hand-valve if necessary. A hand pump is also provided to enable the incidence jack to be moved in the absence of pressure from the normal source. A layout of the hydraulic system is shown in Fig.1.

2.1 Incidence drive

The incidence quadrant is directly coupled to the piston of a long stroke operating jack, the cylinder being trunnion mounted on the tunnel working section structure. The servo-valve used has a maximum flow sufficient to give a rate of change of incidence of 8° per second. Indication of quadrant position is obtained from the potentiometer track recessed into the rear face of the quadrant. This track provides a voltage analogue of angle of total incidence, σ, linear to 1/20°. There is also a gear drive from the quadrant which is used to operate other position transducers, in particular a synchro transmitter which supplies the input to the tare correction unit[4], and another potentiometer and a commutator.

2.2 Roll drive

The roll mandrel is gear driven by a rotary hydraulic motor. The front of the mandrel incorporates a two inch diameter female taper to suit a standard model rear sting attachment. An electrical plug connector having forty conducting pins and two pressure tube joints is located at the base of the taper. The wires and pressure tubes pass through the mandrel and are fastened to the quadrant. To avoid damage through twisting as the mandrel and plug rotate, mechanical stops are incorporated which limit rotation to three revolutions in either direction from the mean position.

The number of revolutions allowed and a requirement for roll resolution to about 0.1° make for difficulty in finding a suitable position-indicating transducer. A compromise has been adopted by employing synchros geared so that one revolution corresponds to 90° roll rotation. There are then four positions per roll revolution which present the same output. To discriminate between these positions, and for other reasons discussed later, a potentiometer is also provided, geared so that full travel of the wiper occurs for the full six revolutions of roll. The effect of the gearing is to make electrical errors in the synchro of the order of ±1/10° contribute no more than ±1/40° to the roll angle error.

The roll servo valve is capable of passing sufficient flow to give a maximum rate of roll of about 60° per second.

2.3 Model control surface drive

If the correct force and moment measurements are to be obtained from the strain gauge balance associated with the model it is necessary that control surface operating torques are reacted through the balance. This need effectively rules out the use of hydraulic or pneumatic control actuation and drive is therefore provided by miniature electric motors. Those at present used are Siemens Halske type A41-P1, having a diameter of 0.59 inch and overall length of 0.85 inch. The procedure is then to trade speed for torque by a suitable combination of spur and worm gearing particular to the model in question. It sometimes proves convenient to concentrate the gearing and motors in one part of the model and to use push-pull rods to actuate levers attached to the control surface shafts. Wipers associated with oxide film potentiometers are also attached to the control surface shafts so that lost motion in the drive does not affect the accuracy of indication of control angles. A typical model arrangement having an internal six-component balance and two control surface servos is shown in the photograph, Fig.2.

3 THE CONTROL SYSTEM FOR MODEL ATTITUDE

3.1 Polar mode

In this mode the input demands are requests for particular values of total incidence, σ ("incidence magnitude"[6]) and roll angle, λ, ("incidence-plane angle"[6]). The incidence control system is then a straightforward position servo accepting inputs either in voltage analogue form directly or as derived from a hand-set potentiometer.

Stability of the servo system has been achieved by suitably shaping the frequency response by means of bridged-T filters[5].

An analogue of the total incidence and its sine (see 3.2) is available for display on a digital voltmeter or plotter. The scaling of the analogue voltage is chosen to conform with that of outputs in other modes.

The roll system is also a position servo system but since the position transducer is a synchro the circuitry is hybrid ac/dc. The input in this mode is hand-set only, by manual rotation of a synchro transmitter through gearing from a knob. Each rotation of this knob, against a scale divided into a hundred divisions, causes ten degrees change of roll angle. As each rotation of the knob is completed a numerical display, in the range 0 to 35, is changed by one digit in the appropriate sense. Thus a display of demand is directly given. No display of output is provided, other than a coarse one showing roll position relative to the end stops on a meter calibrated in $\frac{1}{4}$ revolutions.

A difference in angular position relative to a datum between the input and feedback synchros results in an alternating voltage at the input of a phase sensitive discriminator the output of which is a direct voltage of sign appropriate to the difference in angular positions. This error voltage, suitably shaped by filtering and amplification causes the servo-valve to operate so as to remove the error.

The ambiguity in output indication due to the 4:1 gearing between synchro and roll mandrel suggests that when the system is first switched on any of four possible positions 90° apart may become the balanced position. However there is no confusion in practice, due to the coarse display. Once switched on, the tight error control prevents the system losing or gaining 90° steps.

In order to allow the alignment of a particular output angle with a particular input angle, i.e. to provide a datum shift, a differential synchro transmitter is interposed between input and feedback synchros. The rotational position of this transmitter may be varied finely by screwdriver adjustment of a geared shaft, and its location at the tunnel working section is convenient for adjustment while physically measuring the model roll angle during installation.

In the polar mode of operation the system is thus merely the closed-loop equivalent of that previously in use with this tunnel. It is the basis also of the other two modes of operation (3.2 and 3.3) but, in contrast to these, does not include provision for sting bending compensation.

3.2 Cartesian input mode

Cartesian incidence is specified by the normalised components of the reversed free-stream velocity, $|V|$. The velocity components along the body z and y axes are w and v respectively and the associated Cartesian incidence is then defined as $\bar{w}(\equiv w/|V|)$, $\bar{v}(\equiv v/|V|)$. This avoids any ambiguities associated with the choice of α or β - sine or tangent definition (Ref.6) - and is directly applicable to the dynamic simulation studies.

In this mode of operation compensation for sting bending is required, i.e.

$$\bar{w}_i = \bar{w} + \Delta\bar{w}$$

$$\bar{v}_i = \bar{v} + \Delta\bar{v}$$

where suffix i refers to demanded values and $\Delta\bar{w}$, $\Delta\bar{v}$ are differences arising from bending. By applying small angle approximations, these terms representing bending effects may be replaced by quantities which are readily available in analogue form from the on-line force and moment data computer described in Ref.4, (the analogous quantities are referred to as $\Delta\alpha$, $\Delta\beta$ in Ref.4). The error involved in the approximation rises with incidence from zero at zero incidence to ten percent of the sting bending angle at 25° incidence. Since the maximum sting bending angle is of the order of 1°, the error incurred by use of the approximation could be 1/10° in the worst case. The approximation is made for convenience, but could in principle be avoided at the cost of some additional circuitry should the need arise.

The problem is then to position the support system incidence σ and roll angle λ so as to achieve $\bar{w}$, $\bar{v}$ correct to within specified absolute limits. The problem is approached by developing 'driving functions' f_σ, f_λ for the σ and λ servos respectively so that in minimising these the errors in $\bar{w}$, $\bar{v}$ are also minimised.

From Fig.3:-

$$\begin{aligned} \bar{w} &= \sin\sigma\cos\lambda \\ \bar{v} &= \sin\sigma\sin\lambda \end{aligned} \qquad (1)$$

Whence

$$\begin{aligned} \delta\sigma &= (\delta\bar{w} \cos \lambda + \delta\bar{v} \sin \lambda)/\cos \sigma \\ \delta\lambda &= (\delta\bar{v} \cos \lambda - \delta\bar{w} \sin \lambda)/\sin \sigma \end{aligned} \quad . \qquad (2)$$

Let $\varepsilon\sigma$, $\varepsilon\lambda$ be errors in σ, λ such that they are positive if the instantaneous values of σ, λ are less than the notional demanded values (i.e. those corresponding to demanded $\bar{w}$, $\bar{v}$), and $\varepsilon\bar{w}$, $\varepsilon\bar{v}$ be the corresponding errors in $\bar{w}$, $\bar{v}$.

If the driving functions were formed by substituting these in equations (2) the resulting system would work for small errors, but it is apparent that at $\sigma = 0$ the $\delta\lambda$ term need not be small. Equations (1) show that the dependence of $\bar{w}$, $\bar{v}$ on λ falls with $\sin \sigma$, so that at $\sigma = 0$ the value of λ is immaterial. This suggests that a λ servo having a gain varying as $|\sin \sigma|$ would be appropriate. As the range of interest in σ is limited it may also be acceptable to allow the gain of the σ servo to vary as $\cos \sigma$. Then suitable driving functions could be:-

$$\begin{aligned} f_\sigma &= \varepsilon\bar{w} \cos \lambda + \varepsilon\bar{v} \sin \lambda \\ f_\lambda &= \varepsilon\bar{v} \cos \lambda - \varepsilon\bar{w} \sin \lambda \end{aligned} \quad . \qquad (3)$$

From equations (1) and the definitions of the error terms

$$\begin{aligned} \varepsilon\bar{w} &= \sin (\sigma + \varepsilon\sigma) \cos (\lambda + \varepsilon\lambda) - \sin \sigma \cos \lambda \\ \varepsilon\bar{v} &= \sin (\sigma + \varepsilon\sigma) \sin (\lambda + \varepsilon\lambda) - \sin \sigma \sin \lambda \end{aligned} \quad .$$

Combining these with equations (3) gives

$$f_\sigma = \sin (\sigma + \varepsilon\sigma) \cos \varepsilon\lambda - \sin \sigma \qquad (4a)$$

$$f_\lambda = \sin (\sigma + \varepsilon\sigma) \sin \varepsilon\lambda \quad . \qquad (4b)$$

But by the definition of $\varepsilon\sigma$, $(\sigma + \varepsilon\sigma)$ is the notional demanded incidence. Thus the roll servo driving function depends on the notional demanded incidence and is entirely independent of the incidence servo. At equilibrium $f_\lambda = 0$

and this is satisfied by $\varepsilon\lambda = 0$ or $\varepsilon\lambda = \pi$. If positive f_λ causes increasing λ then, for $(\sigma + \varepsilon\sigma)$ positive, $\sin \varepsilon\lambda$ is reduced for $-\pi/2 < \varepsilon\lambda < \pi/2$ and increased for $\pi/2 < \varepsilon\lambda < 3\pi/2$, and vice versa for $(\sigma + \varepsilon\sigma)$ negative. Thus for positive $(\sigma + \varepsilon\sigma)$ the stable solution is $\varepsilon\lambda = 0$ and for negative $(\sigma + \varepsilon\sigma)$, $\varepsilon\lambda = \pi$ is the stable position. If positive f_λ causes decreasing λ then the converse is true. Equation (4a) shows that $\varepsilon\lambda = 0$ enables the incidence servo to establish $\sigma + \varepsilon\sigma = \sigma$, if positive f_σ causes increasing σ, whereas $\varepsilon\lambda = \pi$ causes $-(\sigma + \varepsilon\sigma) = \sigma$ to be established. But from equations (1), as is well known, the solutions σ, λ and $-\sigma$, $\lambda + \pi$ are equivalent, so that the conversion is always performed correctly. Note that a particular polarity of f_λ always provides stable solutions with a particular polarity of σ, which can be reversed by reversing the polarity of f_λ. In the transient case where $\varepsilon\lambda = \pi/2$ the incidence servo initially tries to make $\sigma = 0$. In this case however the roll servo rotates towards $\varepsilon\lambda = 0$ or π accordingly as $(\sigma + \varepsilon\sigma)$ is positive or negative and hence begins to contribute to the rhs of equation (4a). Note that $\sigma + \varepsilon\sigma = 0$, i.e. a demand for the origin, effectively freezes the roll servo by making $f_\lambda = 0$.

In order to realise this system it is necessary to generate analogues of the driving functions. These contain analogues of $\varepsilon\bar{w}$, $\varepsilon\bar{v}$, and to form these it is first necessary to generate $\bar{w}$, $\bar{v}$ equivalent to the instantaneous values of σ, λ. The analogue of σ, obtained from the quadrant potentiometer, is applied to a diode function generator to produce the small term $-(\sigma - \sin\sigma)$, which has a maximum value of about 3% of σ at 25°. This term is then summed with σ to obtain $\sin\sigma$. Sin σ applied to an accurate sine/cosine potentiometer driven by the roll shaft then provides the analogues of $\sin\sigma\cos\lambda = \bar{w}$ and $\sin\sigma\sin\lambda = \bar{v}$. These analogues when summed with the demand analogues and the sting bending analogues, with due regard for signs, yield the analogues of $\varepsilon\bar{w}$, $\varepsilon\bar{v}$. The required driving voltages are then obtained by applying $\varepsilon\bar{w}$, $\varepsilon\bar{v}$ to two further sine/cosine potentiometers driven by the roll shaft, and appropriately summing the two pairs of voltages so derived. These latter potentiometers need not be very accurate, the effect of inaccuracies being to vary the servo gains. Because of the complementary nature of the error signal expressions a correct static balance is still achieved if for instance λ lies in the range -45° to +45° and $\cos\lambda$ is taken as unity and $\sin\lambda$ as zero in the error expressions.

It is convenient, for mechanical reasons, to mount the sine/cosine potentiometers on a shaft which adopts the attitude required of the roll mandrel in the tunnel. The roll mandrel is made to follow by the roll servo system as in the polar mode, with the difference that the input is provided by a synchro driven by the dummy roll shaft instead of by a hand-set synchro. Since the gain of the dummy roll servo varies as $\sin \sigma$ it is beneficial to provide similarly varying damping using tacho-feed-back attenuated by a potentiometer driven by the incidence gear-box. It is also necessary to ensure that the dummy roll servo has a maximum rate matched to that of the tunnel roll servo. The rate is thus limited by use of the excess tacho-generator output passed by zener diodes arranged to conduct when the desired rate is exceeded.

Voltage analogues of input demand to this system are supplied either by external sources or by two hand-set potentiometers, the one used for $\bar{w}_i$ being also that used for σ demands in the polar mode. A sign switch is provided which inverts the polarity of f_λ, thus the operator may select solutions with either positive σ or negative σ.

Clearly varying $\bar{w}$ while keeping $\bar{v}$ constant involves the model rolling and changing incidence simultaneously. The changes of roll angle involved increase as smaller values of $\bar{v}$ are considered and the rate required at minimum σ rises until in the extreme case of $\bar{v}$ = zero, 180° of roll should occur instantaneously coincident with $\bar{w}$ passing through zero. In order to avoid the dynamic errors which would arise from this effect the flight dynamics simulator employs a variable time scale, the extension of which is incidence dependent. However, if it is known in advance that constant roll angle is a solution to a particular proposed motion, e.g. tests with $\bar{v} = 0$, it is advantageous to suppress the roll at the origin by switching off the dummy roll motor. The correct roll angle is first set by demanding the maximum values of incidence occurring in the motion in question. In these circumstances sting bending compensation in the incidence plane is still applied in the correct sense. This procedure is particularly useful during balance calibration.

3.3 Trim boundary mode

In this mode the input demands are for values of total incidence σ and rate of roll $\dot{\lambda}$ but values of $\bar{w}$ and $\bar{v}$ appropriate to the model are required for display.

The incidence servo is then controlled precisely as in the polar mode (section 3.1) but use is made of the dummy roll servo to compute $\bar{w}$ and $\bar{v}$ as in the Cartesian mode, except that values of $f\sigma$ and $f\lambda$ which it also computes are no longer relevant and are not used. The dummy roll shaft is instead driven as a speed controlled system, using the tacho-generator output as the feed-back of shaft speed which is balanced against the voltage analogue of rate demand. This latter is applied either via the hand-set potentiometer used to give $\bar{v}$ demand in the Cartesian mode or from external sources.

As in the Cartesian mode the tunnel roll servo input is from the synchro transmitter driven by the dummy roll shaft.

3.4 Automatic roll unwind

In the Cartesian and trim boundary modes the roll rotation is prevented from approaching within 1/4 revolution of the end stops. The voltage output of the coarse potentiometer fitted to the roll drive unit is compared with preset values by four voltage comparators. The presets are set up to correspond with the outputs at the desired limits. As soon as the potentiometer output moves outside a limit the appropriate comparator output changes sign and actuates, via logic blocks, a relay which switches out the driving signal to the dummy roll servo and supplies a signal which causes this servo to move at a controlled speed in the unwind sense. At the same time the logic makes a second comparator circuit, which is set to reverse its output when the potentiometer voltage corresponds to one revolution less than the limit. Upon reversal of this output the relay is released and the system rebalances at one revolution less. A similar system limits rotation in the opposite sense. Warning lights on the control panel indicate when the unwind process is taking place. The large error signal present in the dummy roll servo when this takes place is used to stop computation in the simulator, thus facilitating simulations involving continuous roll in one direction.

3.5 Automatic homing system

In the event of failure of the electrical power supply to the tunnel motor it is necessary for the protection of models that they be returned to zero incidence before being traversed by the tunnel shock wave system. The time available varies with the stagnation pressure but is never less than four seconds which is sufficient for automatic operation of the homing system even if the model is at maximum incidence when failure occurs.

In order to operate the No.19 tunnel it had been a prerequisite that a voltage supplied by an accumulator be switched on. Automatic homing is now provided by arranging that this voltage, when switched on, actuates relays which interrupt the input to the incidence servo valve and substitute voltages derived from the same accumulator source and of such a sign as to restore the quadrant to zero incidence. The sign of voltage applied is determined by a commutator driven by the quadrant gear box. When there is a voltage across the tunnel motor further relays override this arrangement and the system functions normally. Should the accumulator voltage when switched on be below rated value, or should the commutator contact fail, other relays cause the safety system to be switched out and a demand for zero incidence to be substituted for the input demand in the normal servo system. The system is thus fail-safe. It requires at least two failures, each individually rare, to coincide in time for the model to be rendered vulnerable.

This system automatically protects the model in the urgent case of electrical power failure to the tunnel. In the event of hydraulic or system failures there is no immediate urgency and the hand control valves and pump can be used to restore the model to zero incidence prior to stopping the tunnel unless the failure is in an essential pipe-line. In this case the possibility of repair before stopping the tunnel exists since all such pipes are external to the tunnel.

A simplified diagram showing the most important aspects of the complete attitude control system is shown in Fig.4.

4 THE CONTROL SYSTEM FOR MODEL CONTROL SURFACES

Provision is made for the operation of up to four independent motivators (e.g. control surface panels). In each case the analogue input demand is a voltage supplied either from external sources or from the appropriate hand-set potentiometer. By means of a differential dc amplifier the input is compared with the analogue of control position derived from the appropriate oxide film potentiometer in the model and the amplifier output is used to drive the miniature electric motor actuating the control surface. A potentiometer which gives some input attenuation, for scaling purposes, is provided together with another to effect a small datum shift, this arrangement being repeated for each channel. The transistorised amplifier used in each channel consists of a voltage amplifier and a power amplifier. Servo stabilisation is by a feed-back sensitive to the motor back emf and is adjustable to meet the needs of particular servos by a control which simultaneously reduces gain and adds acceleration dependent feed-back. The system at present successfully operates two models in which the control surfaces are driven by the same type of motor but via widely different gearing to provide 10 oz-in torque in one case and 4.7 lb-in in the other.

5 ACCURACY

The static accuracy of attitude setting depends on the law accuracy of the position measuring transducers and upon the resolution of the control systems. The most important dynamic errors are those associated with rate of change of attitude. Unless a system embodies feed-forward of integral of error, which the present one does not, there is an error which is directly proportional to rate. If these dynamic errors are reasonably small whilst maintaining an adequate rate of response the resulting static resolution will be very high. It has been demonstrated that the static resolution achieved contributes negligible static error to the attitude control system.

5.1 Attitude system, polar mode

The incidence transducer is a potentiometer which has been calibrated against an accurate inclinometer and shown to indicate incidence correctly to within ±1/20°. The power supplies to this potentiometer cannot contribute any error when incidence is hand-set, since the same supplies then energise the input demand, but for external inputs drift in the power supply voltages could generate errors. Those used have a stabilisation ratio of 1000:1 and temperature coefficient less than 0.02% per °C. The load applied to them is constant but in any case their output resistance is less than 0.02 ohm. The static accuracy is then ±0.05° ±0.01° per °C change from datum.

Dynamic errors in incidence are shown in Fig.5 where error is plotted versus incidence for various frequencies of sinusoidal input. Extrapolation to zero frequency indicates the negligible static resolution error.

The static accuracy of the roll system depends upon the electrical errors of the input and feed-back synchros. These are specified within six minutes of arc in each case, and since there is four-to-one gearing (anti-backlash) between the synchros and roll demand and feed-back the static errors, which are independent of the power supply, are within ±0.05°.

Dynamic errors in roll angle are shown in Fig.6 where error is plotted against $\sin \lambda$ at various steady rates of roll. As before extrapolation to zero rate indicates the very small static resolution error.

5.2 Attitude system, Cartesian mode

In this mode additional sources of error are the sine/cosine potentiometer mounted on the dummy roll shaft, which is used to compute the output values of $\bar{w}$ and $\bar{v}$, the sine function generator which computes sin σ from the incidence potentiometer output, and the resolution of the dummy roll shaft control system.

The law accuracy of the sine/cosine potentiometer is specified as within ±0.05%. The importance of accuracy in this potentiometer increases with incidence and at maximum incidence it can contribute the equivalent of 0.025° static error, which on the most pessimistic assumption could be additive to that arising in the polar mode.

The sine function generator is required to make a correction which increases with incidence to a maximum of 3.14% at 25°. This correction has been set up using five segments to represent the difference between linear and sine law over the range in question and is considered to contribute negligible error.

Since the output motion in this mode is not a simple function of the input, it is difficult to devise meaningful dynamic tests. However, the dummy roll servo has been tested by supplying sinusoidal demands for $\bar{w}$ and $\bar{v}$ phased 90° apart. The resulting motion is a rate of roll at constant incidence. The error in $\bar{v}$ is plotted versus $\bar{w}$ for various frequencies in Fig.7. A typical accuracy to within ±0.05° is obtained.

5.3 Attitude system, trim boundary mode

In this mode the errors are similar to those in the Cartesian mode except that the response of the dummy roll servo is no longer a factor since this shaft is directly driven and its positional variation constitutes input data.

5.4 Control surface servos

Static accuracy is dependent upon the law accuracy of the feed-back potentiometers, stability of potentiometer power supplies when the system is supplied with externally generated input demands, and resolution of the control system. The power supplies for the potentiometers are the same as those used by the model attitude system (see section 5.1) and are separate from those supplying the variable loads of the servo motors. Potentiometer law accuracy as high as ±0.15% is obtainable in most cases. Static error due to gearing backlash is eliminated by mounting the potentiometer wiper directly onto the control surface shaft.

Fig.8 shows the calibration of a typical potentiometer providing 0.1° accuracy in a range of 50°.

The system resolution and dynamic response depends on the mechanical design chosen for a particular model.

In Figs.9 and 10 input is plotted against output for sinusoidal demands of varying period using the two widely different systems already referred to in section 4.

6 FUTURE DEVELOPMENT

Future development of the attitude system will be aimed at reducing dynamic lags. As it stands the system has proved satisfactory for flight dynamics simulation, although the highest rates originally envisaged in the simulator application cannot at present be employed without detracting from accuracy. The system meets the needs of the automatic trim boundary generation equipment and for conventional wind tunnel use eliminates the need for cross plotting and interpolation of results to obtain, for example, data at varying pitch but constant yaw inclination. This represents a very considerable saving in time and an improvement in accuracy for the determination of such data.

It may become feasible to carry out the operations of error signal processing, which at present employ the dummy roll shaft, directly on the tunnel roll mandrel. Elimination of the extra servo would certainly be expected to give a small improvement in accuracy but care will be necessary to avoid losing the operational flexibility of the present arrangement.

Acknowledgements

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SYMBOLS

O, x, y, z	right angle axis system fixed in model
$\bar{w}$	velocity component along Oz axis normalised wrt total velocity
$\bar{v}$	velocity component along Oy axis normalised wrt total velocity
$\|V\|$	reversed free stream velocity
σ	total incidence
λ	roll angle
$\Delta\bar{w}$	increment in $\bar{w}$ due to sting bending
$\Delta\bar{v}$	increment in $\bar{v}$ due to sting bending
ε	error in quantity indicated by suffix

REFERENCES

No.	Author	Title, etc.
1	L. J. Beecham W. L. Walters D. W. Partridge	Proposals for an integrated wind tunnel flight dynamics simulator system. A.R.C. Current Paper 789 (1962)
2	E. F. Price	Design and testing of twisted bourdon tube potentiometer type pressure transducers. R.A.E. Tech. Note T.D.57 (1961)
3	B. E. Pecover	The automatic generation of boundaries of trimmed flight, using a wind tunnel and model. R.A.E. Tech. Report to be published
4	B. E. Pecover	An analogue computer for on-line correction of wind-tunnel force and moment data. A.R.C. Current Paper 946 (1966)
5	N. G. Meadows	Bridged-T compensating networks. Industrial Electronics June and July 1965
6	H. R. Hopkin	A scheme of notation and nomenclature for aircraft dynamics and associated aerodynamics. Part 2 - Basic notation and nomenclature (Section 6.2) R.A.E. Tech. Report 66200 (1966)

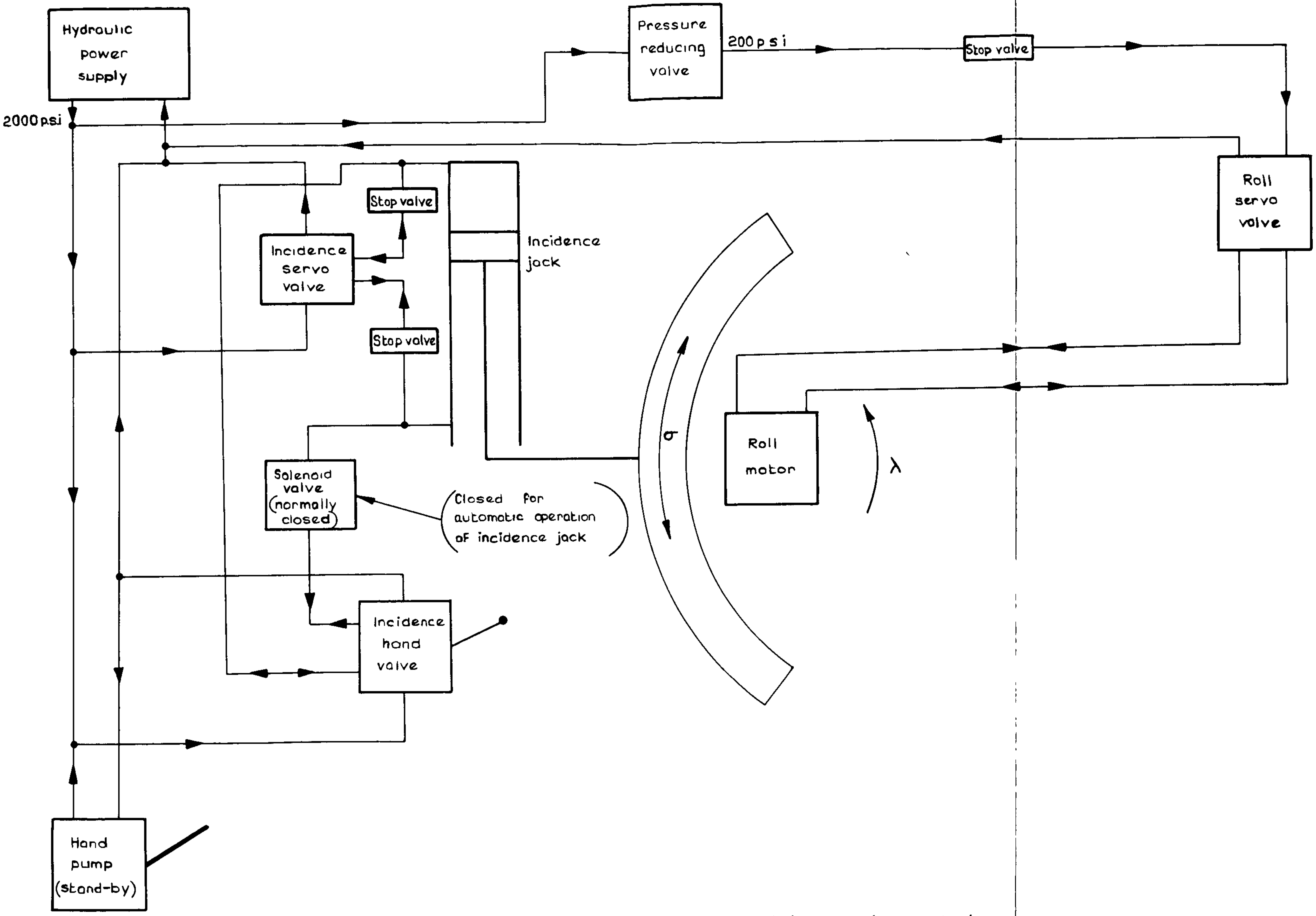


Fig. I Diagram of hydraulic system, model attitude control

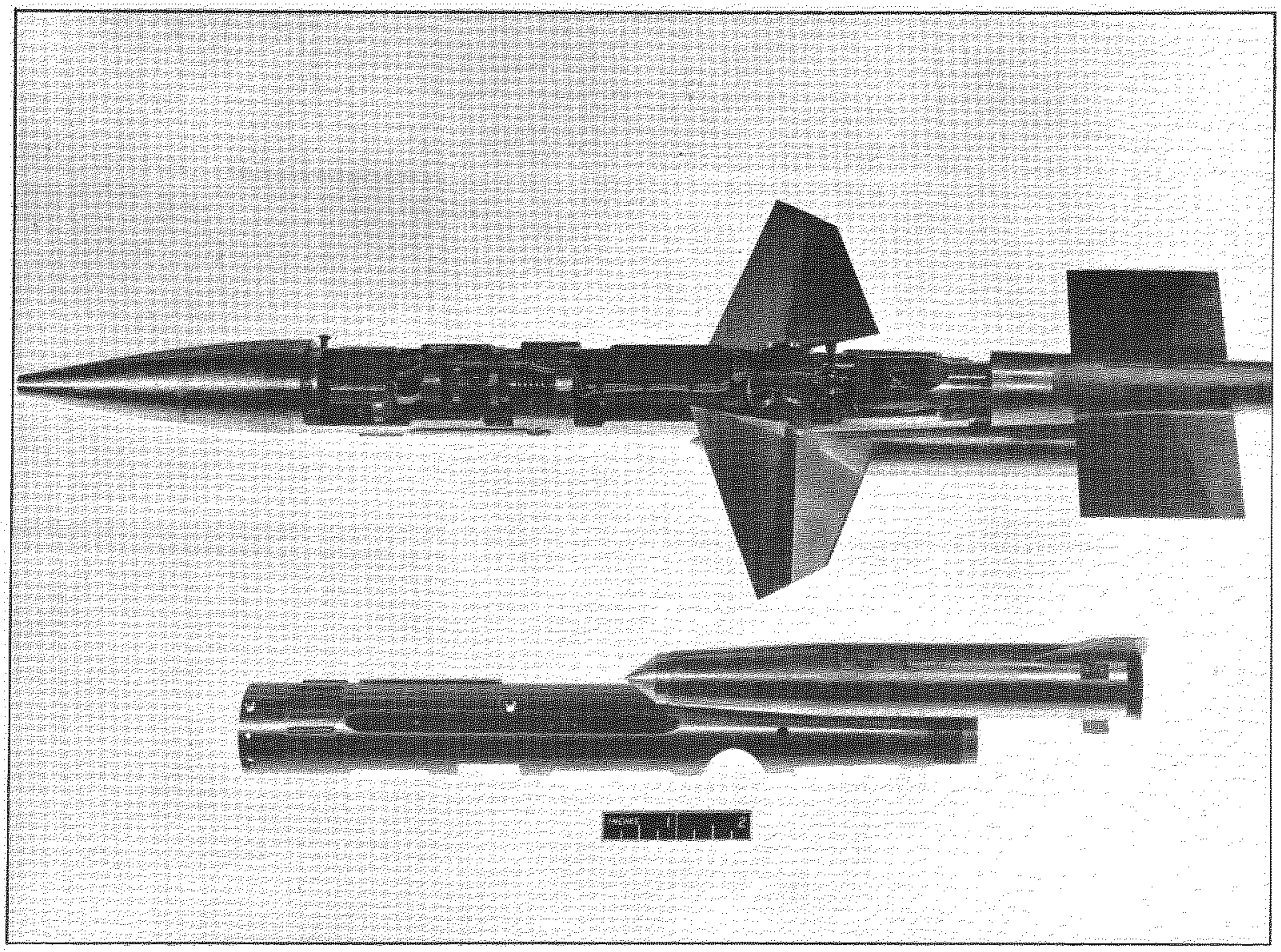
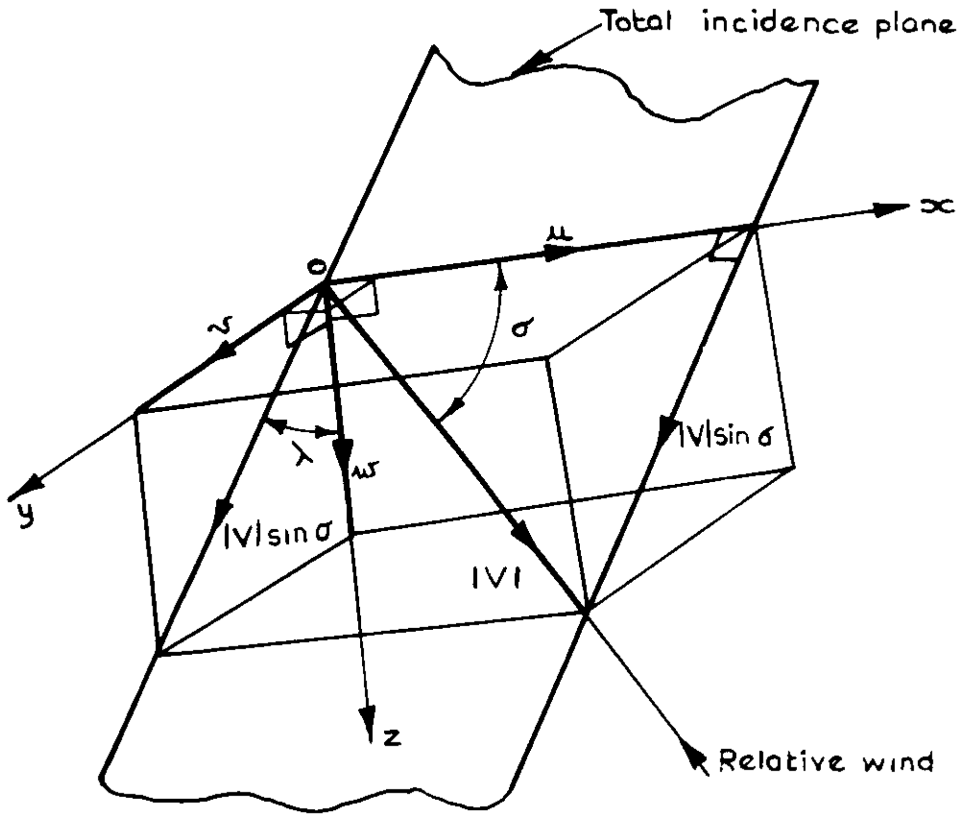


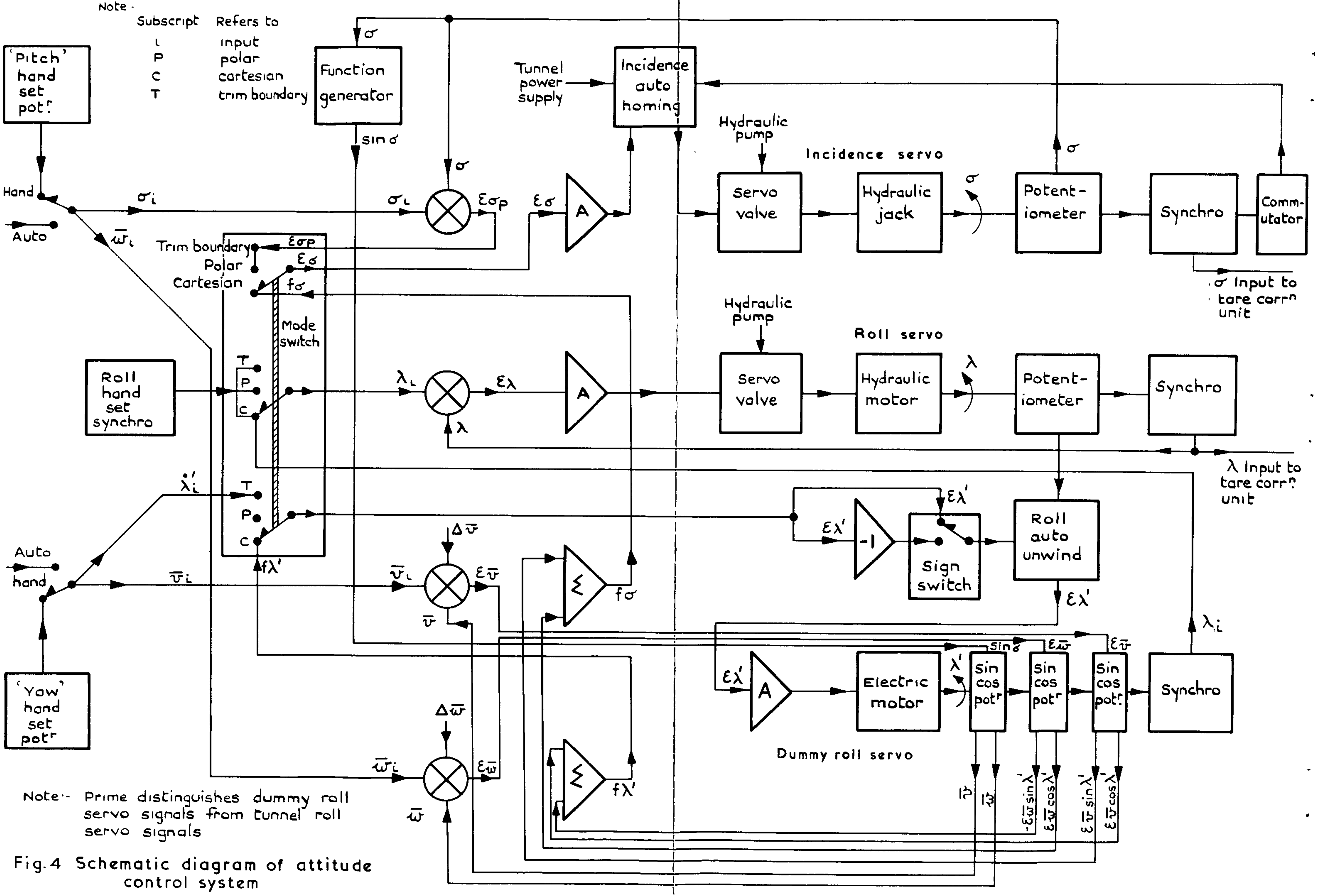
Fig.2. Model with panel position servos and internal six component balance



$$\frac{w}{|V|} \equiv \bar{w} = \sin\sigma \cos\lambda$$

$$\frac{v}{|V|} \equiv \bar{v} = \sin\sigma \sin\lambda$$

Fig. 3 Diagram showing angles of incidence



Note:- Prime distinguishes dummy roll servo signals from tunnel roll servo signals

Fig. 4 Schematic diagram of attitude control system

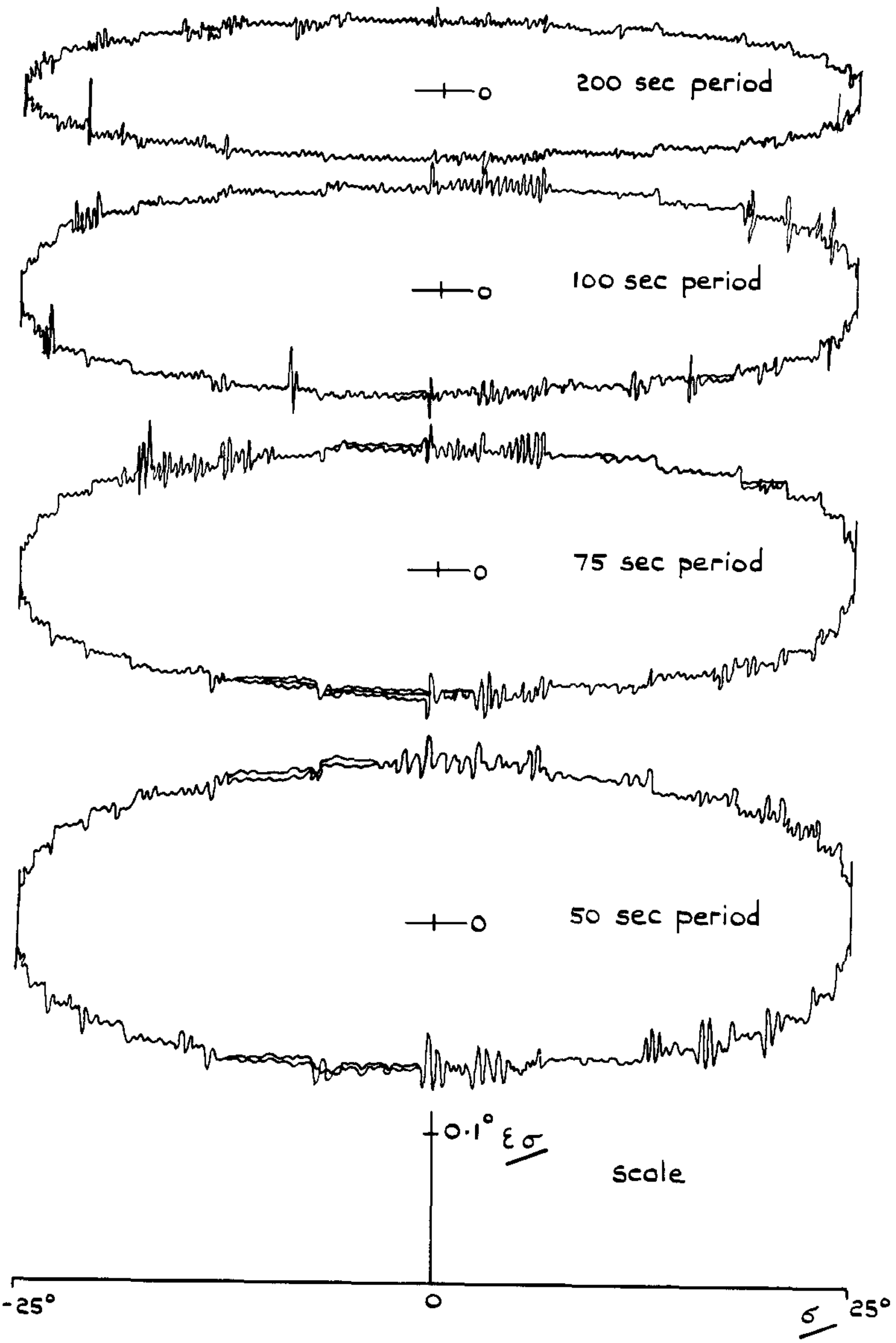


Fig. 5 Incidence errors when following sinusoidal demands of varying frequency

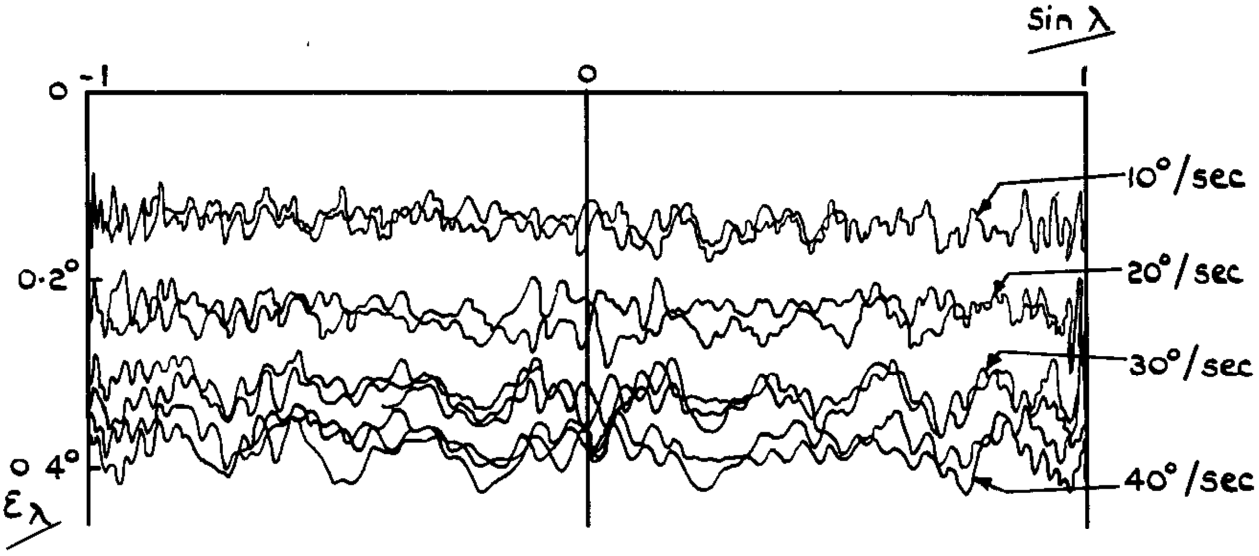
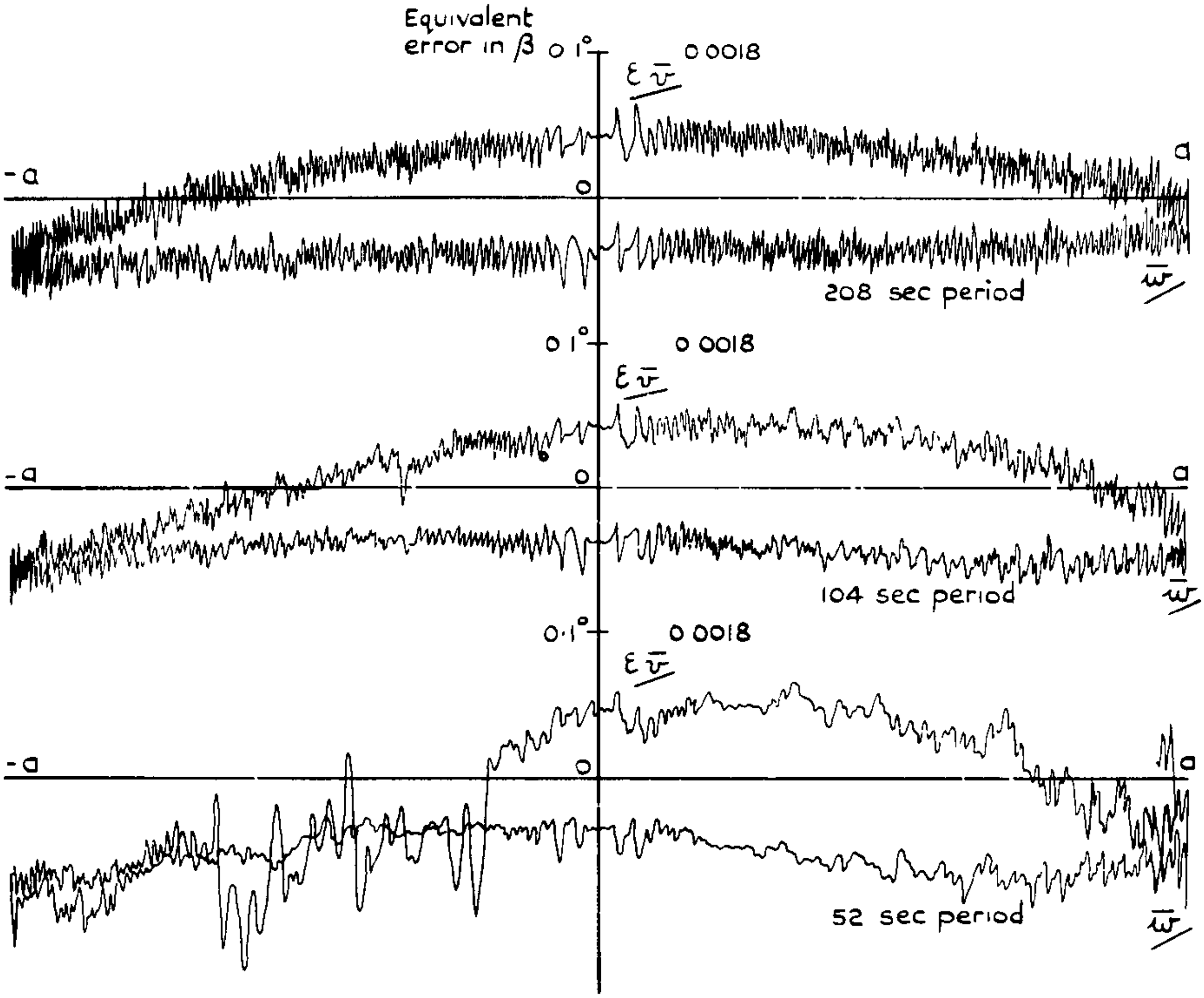


Fig. 6 Roll errors when following various demand rates



Note - Input demands were $\bar{w} = a \cos nt$
$\bar{v} = a \sin nt$

Ensuing motion is steady rate of roll at const incidence, $\sin^{-1} a$

Error in v or w should be independent of 'a', although this is taken for granted here and an arbitrary value used ($\simeq 0{\cdot}3$)

Fig.7 Errors in $\bar{v}$ following inputs calling for various steady rates from the dummy roll servo

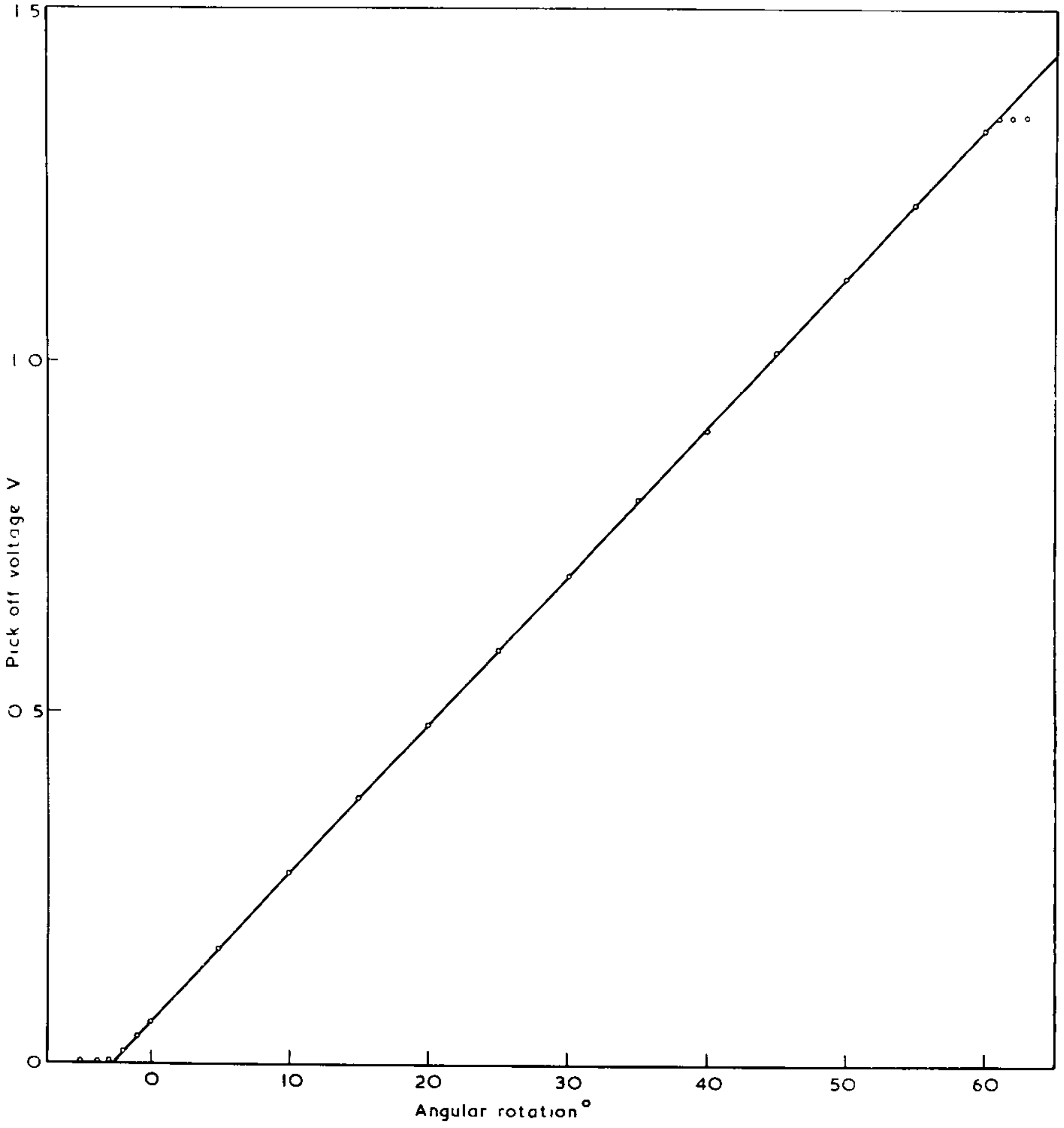


Fig. 8 Calibration of typical oxide film potentiometer for control surface position indication

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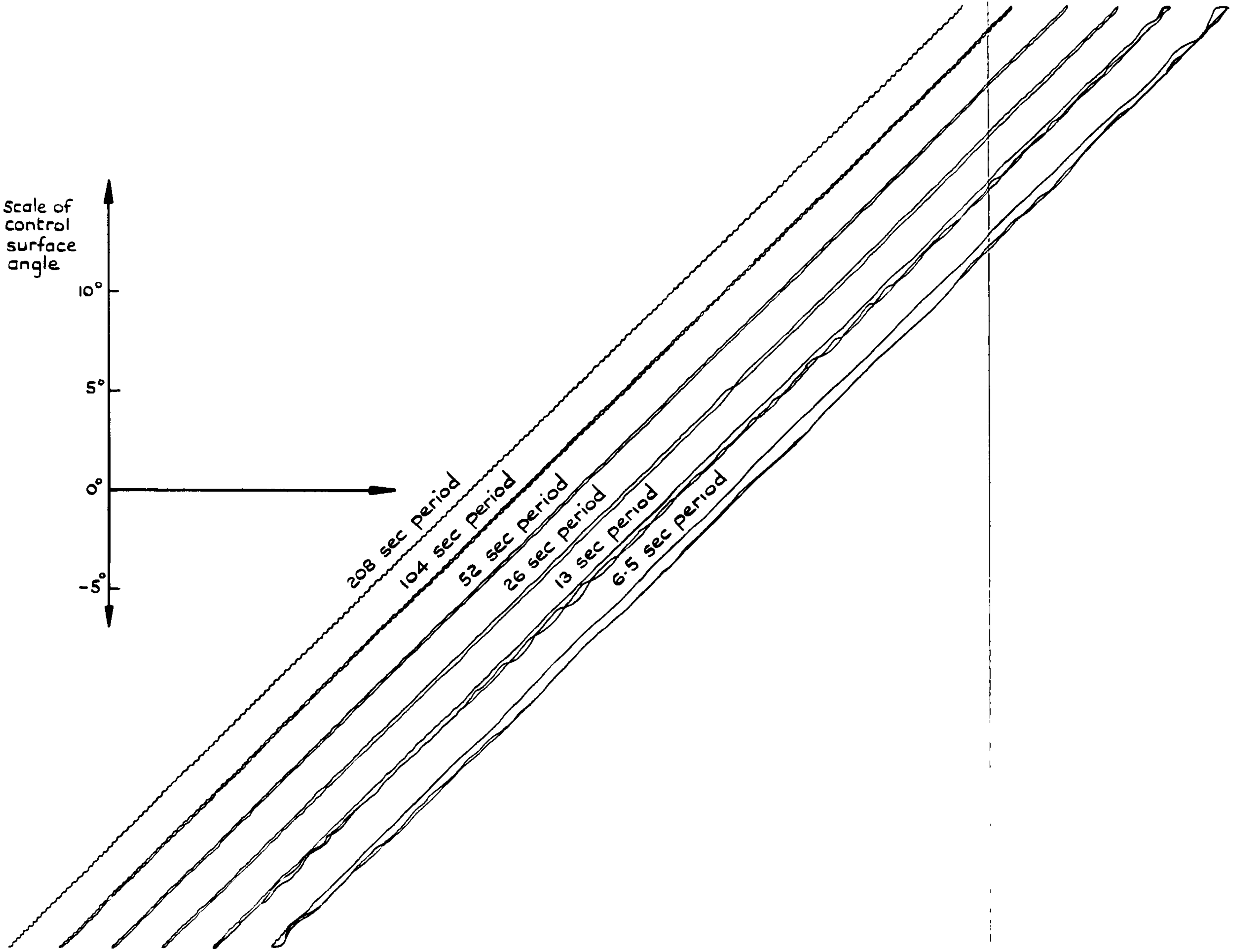

Fig.9 Typical response of low geared control surface servo output versus input for sinusoidal inputs of various frequency

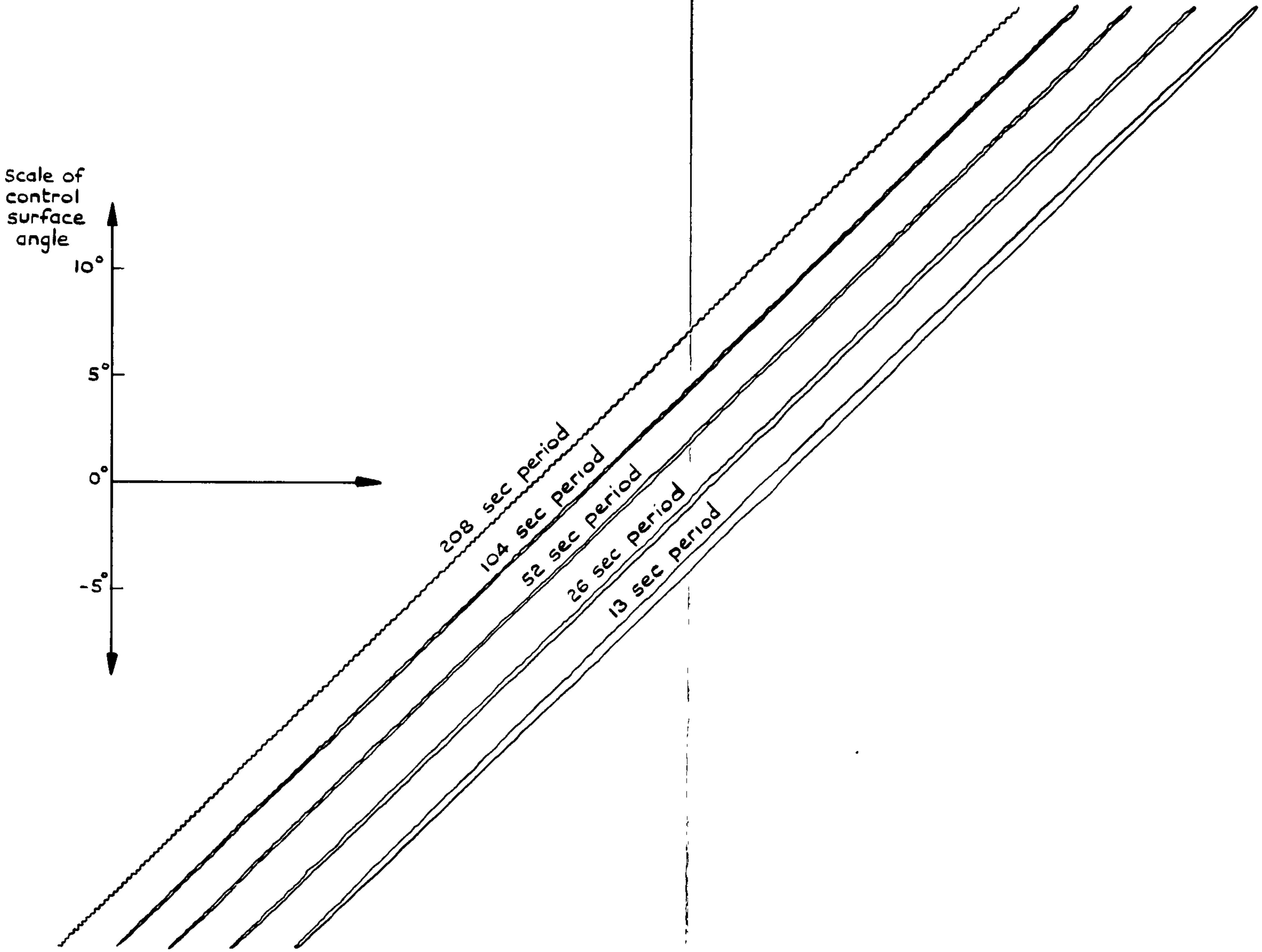

Fig. 10 Typical response of high geared control surface servo output versus input for sinusoidal inputs of various frequency

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A new closed loop system is described which enables the incidence, roll and motivator (i.e. control surface) angles of a wind tunnel model to be controlled remotely, either by hand or by analogue voltages derived from, say, a computer.

Besides operating from direct (polar) demands, the system correctly positions the model if the demands are referred to Cartesian coordinates, and in this case compensation for sting bending can be made automatically.

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