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by

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PROPOSALS FOR AN INTEGRATED WIND TUNNEL-FLIGHT DYNAMICS SIMULATOR SYSTEM

by

L.J. Beecham,
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and
D.W. Partridge

SUMMARY

A design is considered in which the wind tunnel is an integral part of a system suitable for the simulation of the behaviour of aircraft and missiles in flight. The static aerodynamic loads on a wind tunnel model, mounted on a conventional quadrant support, are measured and combined with continuously computed gravitational, inertial and aerodynamic damping loads, the model orientation to the flight path being correctly maintained throughout.

The computer elements comprise a small analogue unit for the on-line correction of the wind tunnel data, and a D.D.A. unit consisting of CORSAIRs for the kinematic simulation and wind tunnel control.

Replaces R.A.E. Tech. Note No. Aero 2852 - A.R.C. 24681

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1 INTRODUCTION

In Ref.1 it was suggested that the separate roles of the wind tunnel and the computer could profitably be integrated to form a closed loop, flight dynamic simulator, the wind tunnel behaving as a function generator of the static aerodynamic forces and moments, and the disposition of the model to the airstream being continuously controlled by the computer. Such a system would have many advantages. In particular the maximum accuracy would be retained in the input signals representing the static aerodynamic terms, which tend to be dominant; also there would be no delay in the dynamic simulation, as in the present system, so that a rapid survey of the open loop behaviour under all operational conditions could be made as soon as a wind tunnel model was available.

The proposals outlined in Ref.1 were discussed at a meeting of the Guided Weapons Aerodynamics Committee on 23rd March, 1961, which approved the scheme in principle and recommended a detailed study.

The authors are grateful to Messrs. E.G.C. Burt and G. Herring, W.S. Brown and P.L. Owen, [illegible] Partridge and T.R.H. Sizer for the many helpful discussions which the present study has evoked, and for making available suitable facilities and equipment.

2 GENERAL APPROACH

The problem considered has been that of the controlled missile or aircraft with six degrees of freedom, and the determination of its motion relative to both flight path and space-fixed axes. Basically the tunnel model is to be used as a function generator of the static loads only, an extended time scale being used to ensure that the acceleration and rate terms are negligible. (It is proposed to limit the incidence operation rate so that a pitch oscillation of 25° amplitude would have a minimum period of approximately 20 seconds.) Because the aerodynamic damping terms are usually of secondary importance in the flight behaviour the assumption is made that the aerodynamic contribution from angular velocities may be regarded as linear with velocity, as in current practice, i.e. that the derivatives, M_q, $M_{\dot{\alpha}}$, etc are constant at a particular Mach number. Provision is made for these to be varied within the simulator. These would not be measured during the tests, but the angular velocities p,q,r, etc would be generated within the simulator, and scaled so that the contributions of qM_q, etc were correct at full scale. It is important to note that this method of simulation would not be applicable to flutter investigations where the reduced angular frequency is near unity. In this condition the period is the time taken for the air to travel a representative aircraft or missile length, and the effect of consequent phase changes along this length cannot be ignored.

The Eulerian equations of motion are solved to give, in the case of aircraft or missile dynamic stability tests, the components (u,v,w) of the velocity along the flight path, resolved along body axes. These are then used to generate the incidence and velocity vectors which are fed back to control the model attitude and tunnel operation. Due account is taken of the gravitational terms and those arising from the relative motions of the body, wind and earth axes. It should be noted that only the wind axes remain fixed relative to the wind tunnel.

In this way the motion relative to the flight path and to the earth in six degrees of freedom is simulated with a constrained model, and the time scale may be varied over a wide range.

The use of such a simulator is not restricted to this type of problem. It could also be applied, for example, to the relative motion between aircraft and a store during release, and this application is currently being studied. It would be particularly suitable for the solution of almost any motions involving continuously varying translatory aerodynamics which at present require a tedious step-by-step analysis.

The controlled missile problem has been considered under the following headings:-

(1) On-line correction of the wind tunnel data.

(2) Solution of the kinematic problems to relate the model attitude to the flight path and the transformation to space axes.

(3) Attitude control of the model in relation to the wind tunnel.

(4) Remote actuation of the model aerodynamic control surfaces.

It was thought impracticable, until handling experience has been gained, to lay down requirements for a number of tunnel installations of varying size and Mach number range. Instead it was decided to concentrate on the problems associated with the conversion of an intermediate size supersonic wind tunnel, the No.19 (18 in. x 18 in.) tunnel at Farnborough. However the application to any other test facility would affect only items (3) and (4) above, the desirability of having the main part of the simulator (i.e. that necessary for item (2)) transportable has been borne in mind.

3 ON-LINE DATA CORRECTION

It was considered desirable that this should be self-contained and distinct from the rest of the computer in order that it could be used for the more conventional type of tunnel test also.

The operations required are principally of the form

$$G = F(t) \sum_{1}^{n} a_i R_i$$

where R_i are balance readings of the forces and moments, temperatures and incidence.

a_i are calibration factors (usually small in comparison with the components in the same plane as G).

F(t) is a slowly varying function of time required in the simulation to represent the change of kinetic pressure ($\frac{1}{2}\rho V^2$) with missile altitude, deceleration, etc. For many initial applications it would be regarded as effectively constant.

In addition there may occasionally be cross-products, particularly involving axial force, of the form

$$\sum_i \sum_j a_{ij} R_i R_j .$$

The present data handling procedure is for the corrections to be applied at the time when the data are reduced to coefficient form in a general purpose digital machine subsequent to the tests. Apart from the interval between the tests and data reduction, the actual handling time per point is too long (1-5 seconds) on this type of machine for the present application.

It could be performed digitally on an incremental machine such as CORSAIR, but the operations involved are not particularly suited to this machine in which the basic operation is an integration. It is somewhat uneconomic, requiring the capacity of two 50-integrator CORSAIR's.

On the other hand the summing amplifiers which form the basis of pure analogue machines are admirably suited for this purpose. The corrections may be performed by the addition of signal voltages, suitably factored by potentiometers, using standard analogue techniques. A possible scheme is shown in Fig.1.

The scheme of Fig.1 does not include the cross-product interference terms $\sum_i \sum_j a_{ij} R_i R_j$. A layout which does so is shown in Fig.2, and this is seen to increase the size of the installation, probably unjustifiably. For example, in our experience only a few, if any, of such terms are present in any one balance, and their omission would influence only the axial force measurements. These however, are in any case unrepresentative of full scale conditions of skin friction and base pressure, so, as far as the simulator is concerned, the inclusion of these small corrections does not necessarily improve the solutions. On the other hand, for conventional static tunnel tests, since only axial force readings are affected, it would be a simple matter to apply these comparatively minor corrections subsequently on the occasions when they are required.

The function of the arrangement (Fig.1), working from left to right, is as follows:-

(1) The temperatures at up to three stations on the wind tunnel balance are registered on thermistor bridges. Zero-set potentiometers enable these to be referred to any datum, usually "wind-off" values or "no load, wind on" conditions, so that the voltage outputs $\pm R_{T_1}$, R_{T_2}, R_{T_3} represent temperature changes.

(2) The most appropriate of these are applied through coefficient setting potentiometers (k) to the inputs of summing amplifiers, one for each balance force or moment component. Zero-set potentiometers are again provided for reference setting. The output voltages, R_i, represent the balance readings corrected for temperature, and are available both positive and negative in relation to the reference voltage.

(3) These voltages, suitably factored by potentiometers to neutralise the interactions from the loads they represent, are added to the direct balance output in each channel, so that the voltage output, J_i from each summing amplifier is truly proportional to the force or moment represented.

(4) In the case of the axial force, X, J_x may be applied to give an output appropriate to free stream static pressure over the base, i.e. with no base drag contribution. Alternatively estimated corrections to base pressures, skin friction or thrust contributions may be introduced by

suitable inputs to the J_x amplifier, so that the output can be made representative of the axial force at full scale.

(5) Provision is made for the J_i output to be normalised with respect to the stagnation pressure, H_T, by a servo controlled, ganged potentiometer. The output from each channel is then proportional to the non-dimensional coefficient C_i. At a later stage, where the stream velocity may be varied during a test, the dependence of the kinetic pressure ($\frac{1}{2}\rho V^2$) on Mach number may be allowed for by adjustment of the "standard voltage" on this servo.

(6) The final bank of amplifiers and potentiometers is to enable the output voltages to be scaled consistently (volts per lb, or per lb ft) for input to the simulator.

(7) Provision of a digital voltmeter and selector switch enables the output of each amplifier to be sampled for calibration, interaction neutralisation, and correct functioning checks.

4 KINEMATICS

The solution of the equations of motion to obtain the orientation of the model to the free stream direction constituted the main exercise in Ref.1. The Euler angles θ,ϕ,ψ were obtained explicitly, but it has since been pointed out that the direction cosines, rather than the angles, are required, and this procedure avoids the singularities which would have been encountered in the original scheme at $\theta = \pi/2$.

The components of the gravitational force along missile axes are defined by the direction cosines n_1, n_2 and n_3, relating these axes to the z_o earth axis. Thus the equations of motion^2 are:-

$$\begin{aligned}
X + n_1\, mg &= m(\dot{u} + qw - rv) \quad (\equiv ma)\\
Y + n_2\, mg &= m(\dot{v} + ru - pw) \quad (\equiv mb)\\
Z + n_3\, mg &= m(\dot{w} + pv - qu) \quad (\equiv mc)\\
L &= A\dot{p} + qr\,(C-B)\\
M &= B\dot{q} + rp\,(A-C)\\
N &= C\dot{r} + pq\,(B-A)\\
\dot{n}_1 &= n_2 r - n_3 q\\
\dot{n}_2 &= n_3 p - n_1 r\\
\dot{n}_3 &= n_1 q - n_2 p
\end{aligned}$$

which we require to solve for u,v and w.

In the above

X,Y and Z	are aerodynamic forces
L,M,N	are aerodynamic moments
u,v and w	are components of the translational velocity resolved along the body principal axes, x,y,z
p,q and r	are components of the angular velocity relative to earth axes resolved about the body principal axes, x,y,z respectively
n_1, n_2, and n_3	are the direction cosines of the body axes x,y and z respectively to the vertical (earth z_o axis)
A,B and C	are the principal moments of inertia about x,y,z respectively
m	mass

In the above the aerodynamic forces have been regarded as due entirely to the model orientation to the wind, i.e. $Z = Z(u,v,w)$, etc - terms due to rates of change of body axes relative to wind or earth, e.g. $Z_{\dot{w}}$, Z_q, have been neglected although there is no inherent difficulty in their inclusion should the occasion demand. The appropriate rate terms are included in the moment equations, however, so that $M = M(u,v,w) + \dot{w}M_{\dot{w}} + qM_q$ etc.

By solving additionally for the remaining six direction cosines ($\ell_{1,2,3}$ and $m_{1,2,3}$) we may obtain the information necessary to specify the velocity and position of the missile represented by the tunnel model, in earth axes as well as relative to the flight path.

i.e. if x_o, y_o, z_o represent the displacements relative to earth axes, then

$$\begin{aligned} \ddot{x}_o &= \ell_1 a + \ell_2 b + \ell_3 c \\ -\ddot{y}_o &= m_1 a + m_2 b + m_3 c \\ -\ddot{z}_o &= n_1 a + n_2 b + n_3 c \end{aligned}$$

$$\begin{aligned} \dot{x}_o &= \int \ddot{x}_o dt \\ \dot{y}_o &= \int \ddot{y}_o dt \\ \dot{z}_o &= \int \ddot{z}_o dt \qquad \text{etc.} \end{aligned}$$

This increases considerably the scope of the original proposals for only a relatively modest increase in computer size, and the detailed proposals made here are for a machine of this capability.

Two types of differential analyser have been considered, viz. analogue (electronic, and electro-mechanical), and digital (D.D.A.).

4.1 Analogue differential analyser

4.1.1 Integrators and multipliers

A study of the specification of operational amplifiers used as electronic integrators has convinced us, and bench tests have confirmed, that over the long time scales envisaged, the drifts produced by grid current, etc, preclude them from consideration for the present application. Furthermore, the kinematic problem involves many multiplications of functional quantities which are not readily performed on electronic multipliers at this time scale.

The most suitable analogue equipment for combining these duties appears to be the servo-integrator/multiplier. This is effectively an electric motor with high quality tachometer feed-back, the output shaft of which is coupled to ganged potentiometers. Shaft rotation, proportional to the integral of the voltage input, moves the wipers over the potentiometer windings, which for integrator or multiplier purposes are supplied with constant or variable voltages respectively.

The only known commercial version has high gearing between the motor of the potentiometer (2650:1) which means that a cycle using the full range of the potentiometer would in this form, take 100 seconds, this is too long for the present application. A different gear ratio could be provided but the gearbox would need to be designed. The selection of this gear ratio is difficult at this stage since it effectively decides the time factor (real time:machine time) at which the computer is most accurate. This must be related to the range of problems likely to be encountered which is unknown since it is likely to be applied to both aircraft and missiles. The machine may be run more slowly only by reducing the amplitude scaling, i.e. the maximum applied voltage to the amplifier, with consequent loss in accuracy.

One further deficiency of these units is that there is no provision of a clutch between the tachometer and the potentiometer. As a consequence the motors must be at rest until the problem is started, with the resulting introduction of errors due to the different times taken to run up to the speeds determined by the initial condition settings (differences up to 200 milliseconds were measured).

A compact installation using these units is shown schematically in Fig.3, for the generation of the velocity components, u,v and w needed to define the model orientation to the wind. No system for the conversion into the necessary wind tunnel parameters is included (see section 5).

4.1.2 Amplifiers

In addition to those required for summing, amplifiers at unit gain are needed where the output of one potentiometer is applied to another, in order to prevent potentiometer loading, and also where a change of voltage sign is required. In all a total of 64 plus spares would be required for a pure analogue scheme such as that in Fig.3 - for simplicity the inverting and blocking amplifiers are not shown.

4.1.3 Initial condition setting

The 21 integrators in Fig.3 would require arrangements for initial condition setting, preferably by remote control since whole fields of investigation, e.g. inertia cross-coupling, are likely to be sensitive to initial values.

These could be set by utilising one potentiometer on each output shaft as a slave to set the shaft position. As already mentioned this would mean that the integrator inputs would not then be zero so that electromagnetic clutches between the tachometers and potentiometers are essential to prevent operation of the integrators prior to $t = 0$.

The initial conditions are in four groups:-

(1) The velocity components u,v,w. These are conveniently set by the selection of the tunnel free stream velocity, model incidence and incidence plane angle.

(2) The angular velocity components, p,q,r. These are required in all networks except the transformation to space axes.

(3) The direction cosines, which are likely to be defined by the Euler angles θ,ϕ and ψ.

(4) The initial linear velocities and displacements in space axes.

4.2 Digital differential analyser

There can be little doubt that the D.D.A. will ultimately replace the pure analogue computer for applications of the present type, particularly as development of the present proposals for application to larger facilities (e.g. the 8 ft × 8 ft supersonic tunnel at Bedford) is likely to lead to increasingly sophisticated requirements of homing accuracy, etc. There is much to be said, therefore, even if it were not at present inherently more accurate, for considering a D.D.A. approach from the outset for the immediate application.

Basically the D.D.A. is an incremental digital computer which functions by continually bringing up to date solutions already obtained instead of solving the equations in toto at each operation as in the general purpose type of digital machine. For this reason the iteration rate can be very high, which makes it a very suitable tool for dynamic problems, process control, etc.

Broadly there are two types of D.D.A. - those in which each integrator has its own arithmetic unit, and those with a single arithmetic unit which is time-shared between a number of integrators. The former have high iteration rates (25 Kc/s at least), but tend to be bulky and expensive. The latter are slower but more compact and relatively inexpensive. The most advanced of these sequential machines is CORSAIR[3], designed and developed in I.E.E. Department at R.A.E., and now being manufactured under license.

CORSAIR is a 50-integrator machine (Fig.4), all integrators being interrogated 500 times per second. The maximum register capacity is 14 binary digits corresponding to a least count of one part in 16,384.

By its nature, the D.D.A. is not subject to many of the drawbacks associated with the analogue equipment already described. The optimum time scale does not need to be settled in advance by choice of gearing; the accuracy will in general improve the longer the time scale chosen up to the point where the full register capacity is utilised. There is no electro-mechanical clutch requirement, and hence no difficulty in setting up initial conditions. There are no potentiometer loading problems, and the resolution, depending on the time scale, is inherently superior to potentiometer windings. Multiplication of functional quantities is readily achieved, since the basic operation of the machine is integration and $z = xy$ is programmed as

$$\Delta z = y \,.\, \Delta x + x \,.\, \Delta y$$

where

$$\Delta x, \Delta y \text{ are } \pm 1 \text{ or } 0 \,.$$

The D.D.A. schematic diagram of the proposed system is shown in Fig.5. Five stages are distinguished:-

<u>Stage 1</u> This is confined to 3-component measurements (X,Z,M) to define motion in the pitch plane (σ) only. Since there is no freedom in roll then both v and w become zero simultaneously, and hence both positive and negative values of σ are permissible.

<u>Stage 2</u> Single plane motion, but with σ constrained to be positive (or negative) only and therefore embodying the pulse frequency control technique (see para.5).

<u>Stage 3</u> Extension to 6-component measurements with on-line (analogue) data correction (section 3), roll actuation (λ), and rate limitation control.

<u>Stage 4</u> As for stage 3, but including information on velocity and position relative to earth-fixed axes. (This is the equivalent of the analogue scheme of Fig.3.)

<u>Stage 5</u> As for stage 4, but with provision for an autopilot loop from which model controls would be operated. No D.D.A. capacity can be specified at this stage.

The numbers of integrators required in each block at each stage are given in Table 1.

It should be noted that the movable model control facility could be utilised at all stages to study the open loop response to control application, and also possibly in a closed loop form for the study of autostabilisation behaviour. Integrator capacity for the generation of transfer functions would probably be available in stages 2 and 3.

The networks for stage 4 are shown in detail in Figs.6a to f. The reader is referred to the original paper on CORSAIR^3, for the detailed functioning, and to this and standard D.D.A. literature for the operational programming. It is sufficient here for the integrators to be regarded as independent components, represented symbolically by open-ended pentagons in Fig.6 et seq, in which input pulses enter on the left hand side, and output pulses leave on the right.

The number of pulses flowing into the lower of the two input channels is registered, positively or negatively. The output pulse rate is the rate at which pulses are applied to the upper input channel, factored by the integrator register capacity utilised at any instant. Thus, if the integrator is half full, the output pulse frequency is half that of the input. The maximum pulse frequency anywhere in the system is that of the iteration, viz. 500 per second. The circle in the nose of the integrator symbol indicates a reversal of sign of the output, a facility built into the machine.

In general the two inputs (shown, by convention incrementally) are functional quantities. However the integrator may be used to multiply by a constant factor simply by setting a constant register content; or for addition, in which case it is indicated by the infinity symbol in the integrator register. For special uses, e.g. as a digital servo (Fig.6d(i)), and as a limit switch (Fig.6e) the reader is referred to the standard literature.

It is preferable in the present problem for the input quantities (Figs.6a, b) to be X,Y, etc rather than the incremental quantities dX,dY, etc, and for these to be supplied directly to integrator y-registers. In this layout the highest order derivative in each force and moment equation is not available as an output quantity so that $\dot{u}, \dot{v}$ and $\dot{w}$ would not be directly available. However this does not prevent the inclusion of terms arising from their associated derivatives since, by definition[1], such derivatives have been assumed constant; and $\Delta \int \dot{w} M_{\dot{w}}\, dt$ may be written as $\Delta w\, M_{\dot{w}}$ for which $\dot{w}$ is not explicitly required. Since the quantities $\frac{d}{dt}\left(\frac{u}{V}\right), \frac{d}{dt}\left(\frac{v}{V}\right), \frac{d}{dt}\left(\frac{w}{V}\right)$ are likely to be required only as output quantities e.g. to a plotter, they may probably be generated to an adequate accuracy by differentiation (Fig.6d(i)).

From considerations of availability, ease of scaling, flexibility and accuracy (see section 7) the D.D.A. solution using synchronised CORSAIR units is clearly to be preferred for this aspect of the problem. On the strength of this superiority the solutions to other problems in the simulation have been considered only in terms of the D.D.A. (see section 5).

5 CONTROL OF THE WIND TUNNEL MODEL ORIENTATION TO WIND THE VECTOR

To close the simulator loop we require that the model shall be aligned with the air stream (i.e. the flight path) as defined by the component velocities u,v and w. Ideally this would be achieved with a Cartesian model support system in which v and w, (or, more correctly, v/V, w/V for variable speed) could be applied directly. In any future facility built exclusively for this type of simulator work provision of such a support system should be seriously considered. However for an existing facility such as the 18 in. x 18 in. tunnel proposed, the cost of the necessary modification was considered prohibitive.

In contrast to the idealised system in which the total incidence plane relative to the tunnel axes, is variable, the existing support system, in common with that in most supersonic tunnels, constrains the total incidence, σ, to a particular plane. The model may be rolled about its longitudinal (X) axis so that a reference plane, fixed in the model and containing the x-axis, makes an angle λ to the incidence plane.

The angles σ and λ are then related to $\frac{u}{V}, \frac{v}{V}$ and $\frac{w}{V}$ as follows:-

$$\sin \sigma = \pm \sqrt{\left(\frac{v}{V}\right)^2 + \left(\frac{w}{V}\right)^2} \equiv \pm \sqrt{\bar{v}^2 + \bar{w}^2}, \quad \text{say} \qquad (1)$$

$$\tan \lambda = \frac{v}{w} \equiv \frac{\bar{v}}{\bar{w}} . \qquad (2)$$

For conventional static wind tunnel tests both the positive and negative regimes of σ are used. But unless v and w are identically zero at some point in the motion we are simulating then the minimum incidence, σ_{min}, can never be zero and the problem is necessarily confined to either positive or negative regimes of σ. Because, unlike the flight or Cartesian support cases, the tunnel σ-plane is constrained, motions are possible which demand excessively high accelerations and velocities from the model support system.

This is best illustrated by a particular example. Consider an oscillation in pitch in the presence of some small, fixed sideslip angle, i.e. $\bar{v} = A/n$

$$\bar{v} = A/n$$

$$\bar{w} = A \sin \Omega t \ .$$

(A and n are constants).

Then

$$\sin \sigma_{max} = A \sqrt{\frac{1}{n^2} + 1}$$

$$\sin \sigma_{min} = A/n \quad ,$$

and normalising with respect to σ_{max} so that $\bar{\sigma} = \frac{\sin \sigma}{\sin \sigma_{max}}$, we have

$$\frac{\dot{\bar{\sigma}}}{\Omega} = \frac{1}{\bar{\sigma}} \sqrt{(1 - \bar{\sigma}^2)(\bar{\sigma}^2 - f^2)} \qquad (3)$$

$$\frac{\ddot{\bar{\sigma}}}{\Omega^2} = \frac{f^2}{\bar{\sigma}^3} - \bar{\sigma} \qquad (4)$$

and

$$\frac{\dot{\lambda}}{\Omega} = \frac{f\sqrt{1 - \bar{\sigma}^2}}{\bar{\sigma}^2} \qquad (5)$$

where

$$f = \frac{\sin \sigma_{min}}{\sin \sigma_{max}} \ .$$

From equation (4) above it will be seen that the acceleration at σ_{min} is 1/f times that at the peak ($\bar{\sigma} = 1$), a factor which could amount to 250 with the proposed system in which the discrimination in incidence is to be of the order of 0·1°. This is clearly undesirable since the time scaling of the simulation in the unconstrained case would be related to the accelerations at the peaks of the motion, the maximum permissible being that producing an angular acceleration of the model in pitch which the balance could just detect. A typical value is 8° per second^2. It will be noted that at small minimum incidences (i.e. $f << 1$) the roll rate ($\dot{\lambda}$) demand also increases as 1/f.

In principle it is possible to obviate these high demands near the origin by the provision of a cranked sting support with freedom to rotate relative to the tunnel axes, so that the resultant incidence plane is no longer constrained. Such a support is already in operation in the

18 in. × 18 in. tunnel, having been developed for use in tests in which constant wing incidence or sideslip is required to be maintained. However, its development for the present application although considered in detail, promised to be lengthy and mechanically unattractive, and the programming of the motions unduly complicated.

A more elegant solution involves the use of a variable time scale in which the problem is slowed down when the velocities and accelerations demanded from the model support are excessive*. The basic quantum of the D.D.A. is the input pulse, and the simulation will reach exactly the same stage for a given number of pulses, irrespective of the rate at which they have been supplied. Hence we may slow up the simulation to any degree we like by suitable control of the input pulse frequency without affecting the accuracy. This is quite distinct from the usual time scaling by control of the register capacities with a fixed input pulse frequency.

Using the foregoing example, and locally extending the time scale by a factor r at a particular point, then, since $\frac{d^2\bar{\sigma}}{dt^2}$ in real time is reduced by $\frac{1}{r^2}$, a suitable relationship is $\frac{1}{r} = \sqrt{\bar{\sigma}}$. By this means the accelerations at maximum and minimum incidences are made equal (equation (4)). The period (in real time) is given by $T = 4\int_f^1 r \times \frac{d\bar{\sigma}}{\dot{\bar{\sigma}}}$, which, taking the worst case (i.e. f = 0) becomes

$$T = \frac{4}{\Omega}\int_0^1 \frac{d\bar{\sigma}}{\sqrt{\bar{\sigma}(1-\bar{\sigma}^2)}}$$

$$= \frac{4\sqrt{2}}{\Omega} K\left(\frac{1}{\sqrt{2}}\right) \qquad (6)$$

where K is the complete elliptic integral of the first kind.

This is 1·66 times the period for a fixed pulse frequency, and the factor is surprisingly small.

The roll rate limitation, $\dot{\lambda}$, can be met by another method of pulse frequency control in which the maximum pulse rate is scaled to correspond to the limiting value of $\dot{\lambda}$. If a higher rate is demanded then pulses accumulate and ultimately switch off the problem pulse supply until the accumulation has dropped to a predetermined level (Fig.6e) (the pulse supply to the digital servo loops and hard adders is not controlled). The high stop-start iteration rate produces an effectively smooth control. Both the $\ddot{\bar{\sigma}}$ and $\dot{\lambda}$ controls

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*The requirements of only the digital (D.D.A.) system to achieve this are considered here since the superiority of the D.D.A. technique for the major part of the simulator, viz. that dealing with the kinematic problem, has been established in the preceding section.

operate independently, the pulse frequency at any time being dictated by the more stringent requirement. It is, of course, quite straightforward to control $\dot{\sigma}$ in a similar manner to $\dot{\lambda}$, but this is likely to be rendered unnecessary by the control of $\ddot{\bar{\sigma}}$.

Other functional relationships between the pulse frequency and the incidence, $\bar{\sigma}$, may be found to be acceptable in practice, (and more readily generated than $\sqrt{\bar{\sigma}}$) since the minimum incidence is not identically zero but the discrimination, viz. 0·1°. In Fig.6d(ii), for example, the pulse frequency varies linearly with σ ($dF(\sigma)$ = constant × $d\sigma$), and Figs.8a to c show typical records obtained with the minimum incidence limited to 0·1°. The overall extension is a combination of both the $\dot{\lambda}$ and $\ddot{\sigma}$ frequency control networks.

To achieve the necessary fine servo control of the model support, and the increased angular velocities, the existing electric motor drives for σ and λ need replacement by hydraulic systems (see Fig.9). The working rates have been chosen to be as high as possible without producing model accelerations or aerodynamic damping loads detectable by the balance, and within the capacity of small and readily available hydraulic components.

They are however dictated largely by the problem accuracy required. The representation has been taken throughout as 1 part in 1000 so that there must be a flow of 1000 positive and negative pulses into and out of a representative integrator register. The maximum rate at which these can be supplied is the full CORSAIR machine rate of 500 per second, so that the minimum period is 4π seconds. The maximum angular frequency, Ω, is therefore 0·5 radians/second for 0·1% representation.

A S.H.M. oscillation in pitch of 25° amplitude at this frequency produces a maximum angular velocity and acceleration of 0·2 radians/second and 0·1 radians/second^2 respectively. On a typical model for the 18 in. × 18 in. tunnel, say 12 in. long, weighing 10 lb, with its centre of gravity 4 inches from the centre of rotation these correspond to a reduced angular velocity in pitch ($\dot{\sigma}\ell/V$) of about $1\text{-}2 \times 10^{-4}$, an inertial force of 0·003 lb, and an inertial torque of 0·08 lb inches. The first two would usually have negligible effect on the balance readings. The last would be 0·1% of a moment balance designed for a maximum load of 80 lb inches, which is fairly typical. For sensitive balances, however, this might need watching.

The hydraulic jack dimensions and the capacity of the R.A.E. type hydraulic pump set (Fig.9) are such that the minimum period of a 25° amplitude oscillation is 20 seconds (c.f. the 4π second above). It should be noted that the maximum angular velocity of the support quadrant is fixed by the maximum piston velocity, so that if a lower accuracy of representation than 0·1% could be tolerated then for smaller amplitude motions the period could be reduced proportionately. The peak acceleration would however be increased inversely in this case.

6 INPUT AND OUTPUT REQUIREMENTS

The combination of analogue and digital equipment within the same system requires that certain parameters, in particular those operating error servos shall be convertible from one system into the other. In the currently proposed system the model balance servo, the on-line data correction and the graph plotters are analogue devices, whilst the main body of the simulator is digital.

The requirement is for the wind velocity and the orientation of the wind tunnel model to it to be continuously controlled from the simulator, and the form of the analogue/digital and digital/analogue conversion required will depend upon the manner in which this control is exercised. For example, the component velocities u,v and w could be made available as voltages and used to generate σ,λ and V in a purely analogue manner as in Ref.1, or by use of special law potentiometers. The incidence jack, roll motor and nozzle throat, which are position servos, would then be driven directly by the error voltage. On the other hand these tunnel parameters may be digitised, incrementally or integrally, and supplied to the CORSAIR units, the error sensing being achieved within the simulator by digital servo techniques. In this case the demand σ,λ and V would be generated, together with the errors, in digital form, the errors being then converted to analogue to drive the incidence, roll and nozzle servos appropriately. This method is attractive inasmuch as the highest accuracy is retained, but it requires integrator capacity which could not be met without an additional 50-integrator unit (stage 4).

To enable the wind tunnel to be operable for conventional testing without the simulator equipment it is proposed to instal pulse driven Pullin incremental motors with synchronous link units for external servo control of the model support, etc. The quantities σ,λ and V will be generated within the simulator when present (Fig.6(ii)), or selected manually through a small pulse generator for conventional testing. The remaining output quantities (Fig.5) will be handled by electronic digital-to-analogue converters.

With this system, then, σ,λ and V are not required as CORSAIR input quantities which may then be confined to the six-static force and moments measured on the model, available as voltages directly from the Elliott self-balancing bridges in the early stages and later from the on-line correction network. One suitable sequential analogue/digital converter, (VOSCO 1) has been developed by Weapons Department, R.A.E., with a sampling rate of 6000, 13 binary digit numbers per second. A contract for a lower accuracy unit (10 binary digits) consistent with the 0·1% used herein is being considered.

It is highly desirable that at the output of the CORSAIR's the parameters relating to the motion relative to both earth and space axes shall be available in analogue form for graph plotter presentation. The standard 50-integrator CORSAIR includes a digital-to-analogue converter and plotter which can be used to present any variable from one bank of ten integrators against one from any other bank. A greater flexibility is required for the present application. To make full use of the on-line data reduction facility for routine tunnel tests six small X-Y plotters such as the Bryan (Cat.No.1806) are required. From the three CORSAIR units envisaged for stage 4, therefore, we need to be able to select simultaneously up to six pairs of parameters relevant to the dynamic behaviour, viz. angular and linear velocities, displacements, incidences, real and problem times, (Fig.5). Patchboard selection of these would be a necessary feature. (Forces and moments will be directly available as analogue quantities for plotting.)

7 ACCURACY OF SIMULATION

Because of the uncertainty of the form of errors, i.e. biased or random, and the multiplicity of interacting loops within the simulator it has been virtually impossible to assess the absolute accuracy of either existing simulators, such as TRIDAC, or the schemes considered herein, in any consistent manner. Instead a limited comparison over the portion of the problem considered most sensitive to error, viz. the axes transformations and direction cosine generation, has been made, and it is hoped that this will be indicative of the relative performances on the rest of the problem.

This exercise was necessarily confined to the D.D.A. scheme since the analogue units were not available, and was carried out on the existing CORSAIR. The check was that for dynamic accuracy used on TRIDAC (Ref.4), viz. a double axes-transformation with a comparison of input and output information. The tests were not identical inasmuch as those on CORSAIR were associated with angular velocities p,q and r around 25 radians/minute compared with 100 radians/minute on TRIDAC. However, reducing the angular velocities on the latter would not have improved the accuracy, so that comparison of the results at 25 radians/minute is valid.

For given values of p,q and r the direction cosines and their derivatives were evaluated from the differential relationships of section 4. A second transformation was then made, viz.

$$p' \;=\; n_3\dot{n}_2 + m_3\dot{m}_2 + \ell_3\dot{\ell}_2 \quad , \qquad \text{etc}$$

and the difference between $\int p\,dt$ and $\int p'\,dt$ recorded.

After 16 cycles for which the maximum TRIDAC error was quoted[4] as 2·5%, the error with CORSAIR was 0·5% but increasing slowly.

To investigate this further a more stringent test was applied[5] to determine the maximum error in any individual direction cosine (as opposed to that in the resolute) during an axis transformation. The error after 100 cycles was found to be proportional to the number of axis rotations, the maximum being 0·08% per cycle, or, again comparing after 16 cycles, 1·3%.

There are thus good grounds for supposing that the accuracy obtainable with the proposed D.D.A. scheme on the extended time scale will be at least comparable with that from existing analogue simulators, and is likely to be considerably better.

8 REMOTE ACTUATION OF MODEL CONTROL SURFACES

It is highly desirable in utilising the full potential of the proposed simulator that the control settings should be continuously variable during any test. This will enable autopilot loops to be included, if and when required.

The requirement is for a motorised unit complete with control setting indicator, miniaturised sufficiently so that four units may be incorporated into a model suitable for an 18 in. x 18 in. supersonic tunnel. The proposed design is shown in Fig.10. The units, each containing motor (9/16 in. diameter), potentiometer to indicate setting, 60 to 1 reduction gear and provision for taking up backlash, are self contained, and four can be accommodated within a model 1½ in. diameter.

These have been designed to give a maximum rate of change of control setting of 15°/second (on the extended wind tunnel time scale) over a range of ±30°.

A prototype of the unit in Fig.10 has been built by 45 Department, R.A.E., and a suitable potentiometer developed and installed by G.V. Planer Ltd. This potentiometer has an overall track length of 0·25 in. the track being an oxide film deposited on a glass backing[6]. Good linear characteristics have been obtained (Fig.11), and the unit is currently being tested for accuracy of response and output torque.

The assembly of four control units complete with a strain gauge sting balance is intended to form the rear end of a generalised Cartesian missile model. Wing, fin, forebody and nose geometry may be varied as required, and Fig.12 shows a typical application. This model is now being manufactured at R.A.E.

Fig.13 shows a possible twist-and-steer arrangement in which the wing settings are independently controlled. A six-component internal strain gauge balance is included. A model on these lines will shortly be in manufacture.

9 IMPLEMENTATION

In the light of these studies the following is in hand:-

(1) The initial installation is to be in the R.A.E. 18 in. × 18 in. supersonic wind tunnel at Farnborough suitably modified to provide for hydraulic servo-controlled actuation of the model support and to include a simplified form of continuous Mach number control.

(2) A contract has been placed for an analogue on-line data correction system suitable for the elimination of linear interaction terms (Fig.1), and complete with digital voltmeter and selector switch to all amplifier outputs.

(3) A contract has been placed for the supply and maintenance of three CORSAIR D.D.A. installation complete with

(i) time shared analogue/digital convertor,

(ii) parallel operation digital/analogue convertors,

(iii) six X-Y plotters,

(iv) provision for the patchboard selection of up to six pairs of output variables simultaneously.

(4) Provision has been made for the coupling with this system of a proportion of the integrators of any additional CORSAIR units should there be a future requirement to extend the scope of the proposed system.

ACKNOWLEDGEMENTS

Acknowledgements are due to B.E. Pecover, R. Purkiss and B. Stokes for their contribution to the on-line data corrector specification and the development of the control actuator unit.

LIST OF SYMBOLS

A,B,C	are the principal moments of inertia about the body x,y,z axes respectively
a,b,c	linear accelerations along instantaneously fixed x,y,z axes respectively
f	$\frac{\sin \sigma_{min}}{\sin \sigma_{max}}$
m	mass
L,M,N	aerodynamic moments about x,y,z axes respectively
ℓ,m,n	direction cosines
p,q,r	are components of the angular velocity relative to earth axes resolved about the body axes x,y,z

LIST OF SYMBOLS (Cont'd)

q_M	kinetic pressure, $\frac{1}{2}\rho V^2$
T	period
t	variable machine time scale
t*	fixed machine time scale
u,v,w	are components of the translational velocity resolved along the body axes, x,y,z
V	velocity $\equiv (u^2 + v^2 + w^2)^{\frac{1}{2}}$
x,y,z	body fixed axes - also displacements
λ	incidence plane angle (i.e. angle between the body x-z plane and that containing the body x-axis and flight path)
ρ	air density
σ	incidences (i.e. angle between body x-axis and flight path)
$\bar{\sigma}$	$\sin \sigma \div \sin \sigma_{max}$
Ω	angular frequency

Suffices

o	relative to earth-fixed axes
1,2,3	relative to body x,y,z axes respectively

Superscripts

-	normalised with respect to V
.	differentiation with respect to real time

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TABLE 1

CORSAIR integrator utilisation in the various stages

Block	Stage 1	Stage 2	Stage 3	Stage 4
Forces	9	9	16	19
Moments	4	4	18	21+
Direction cosines	2	2	6	27
Normalised velocities and accelerations	21	21	28	28
Setting angles and P.F.C. functions	5	*19 (6)	21	21
Pulse frequency control	-	* 9 (3)	9	9
Transformation from body to earth axes	-	-	-	24
Total	41	64 (45)	98	149

* Allows for fixed error in $\bar{v}$ of 0·1°. This check the functioning of pulse frequency control by λ. Figures in brackets relate to requirement for control by σ only.

\+ Includes provision for regeneration of p dt, q dt and r dt, since number of outputs from any one integrator is limited to 8.

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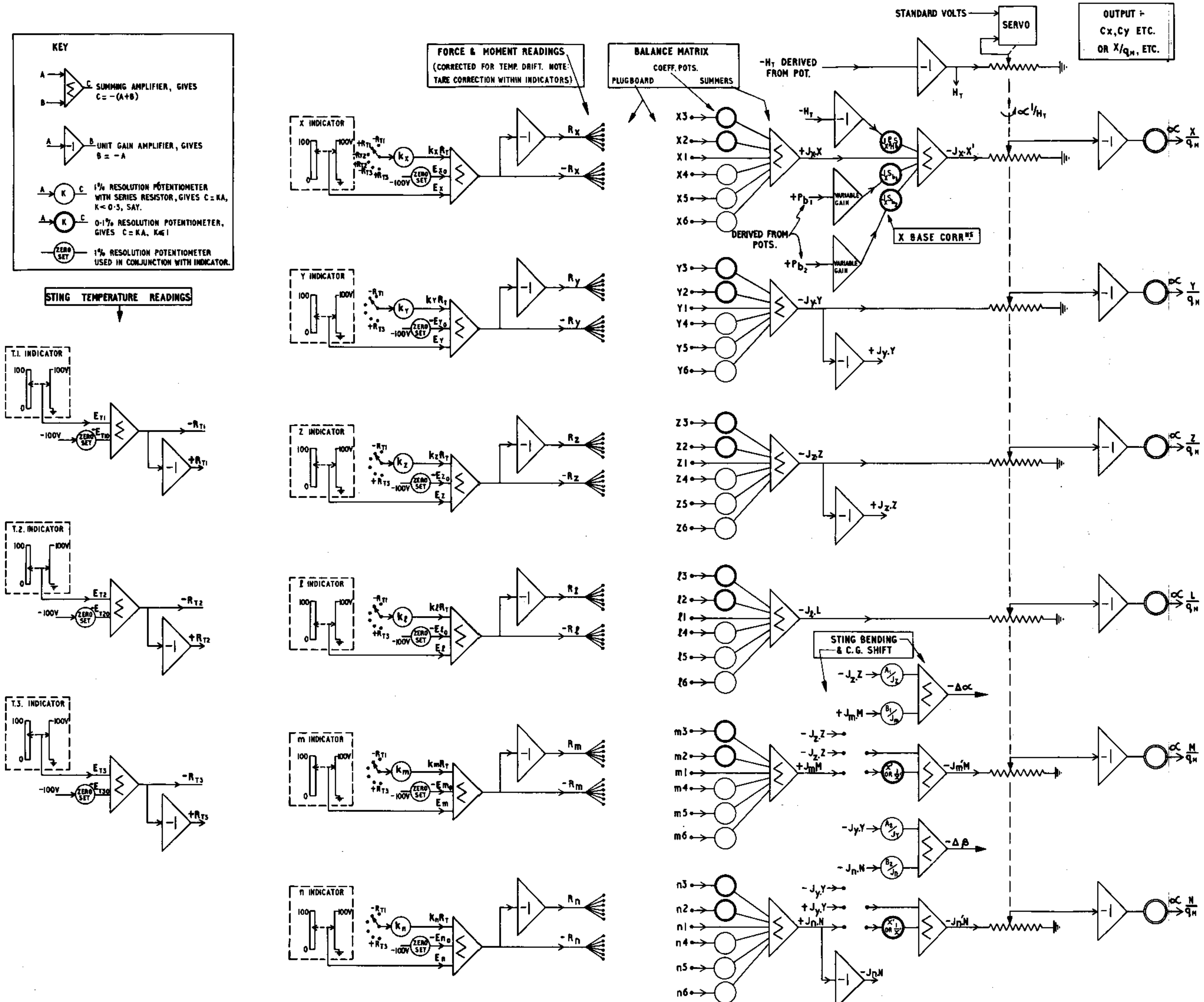


FIG. 1. ANALOGUE ON-LINE DATA CORRECTION NETWORK FOR LINEAR INTERACTION TERMS.

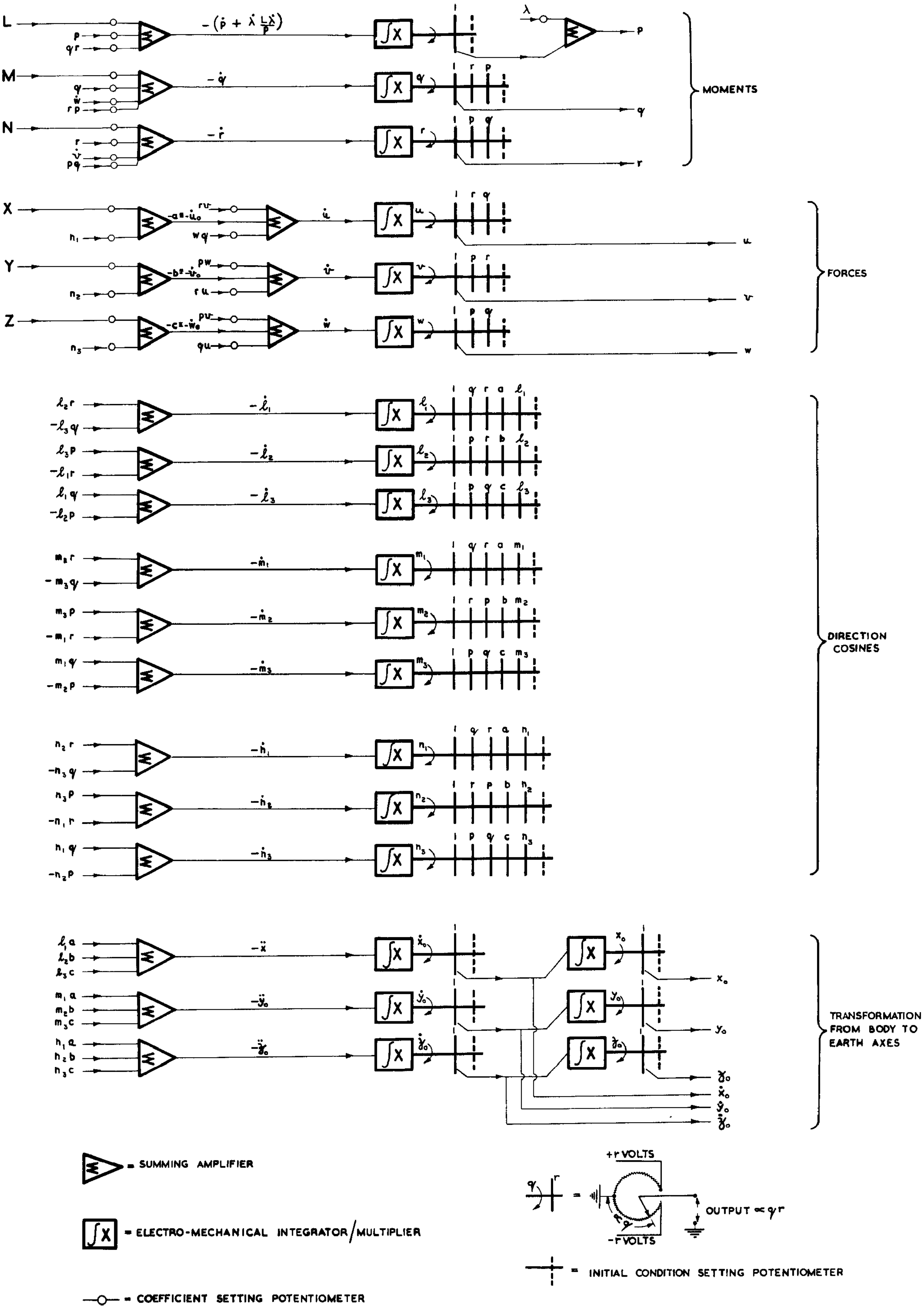


FIG.3. SCHEMATIC DIAGRAM OF ELECTRO-MECHANICAL ANALOGUE SIMULATOR.

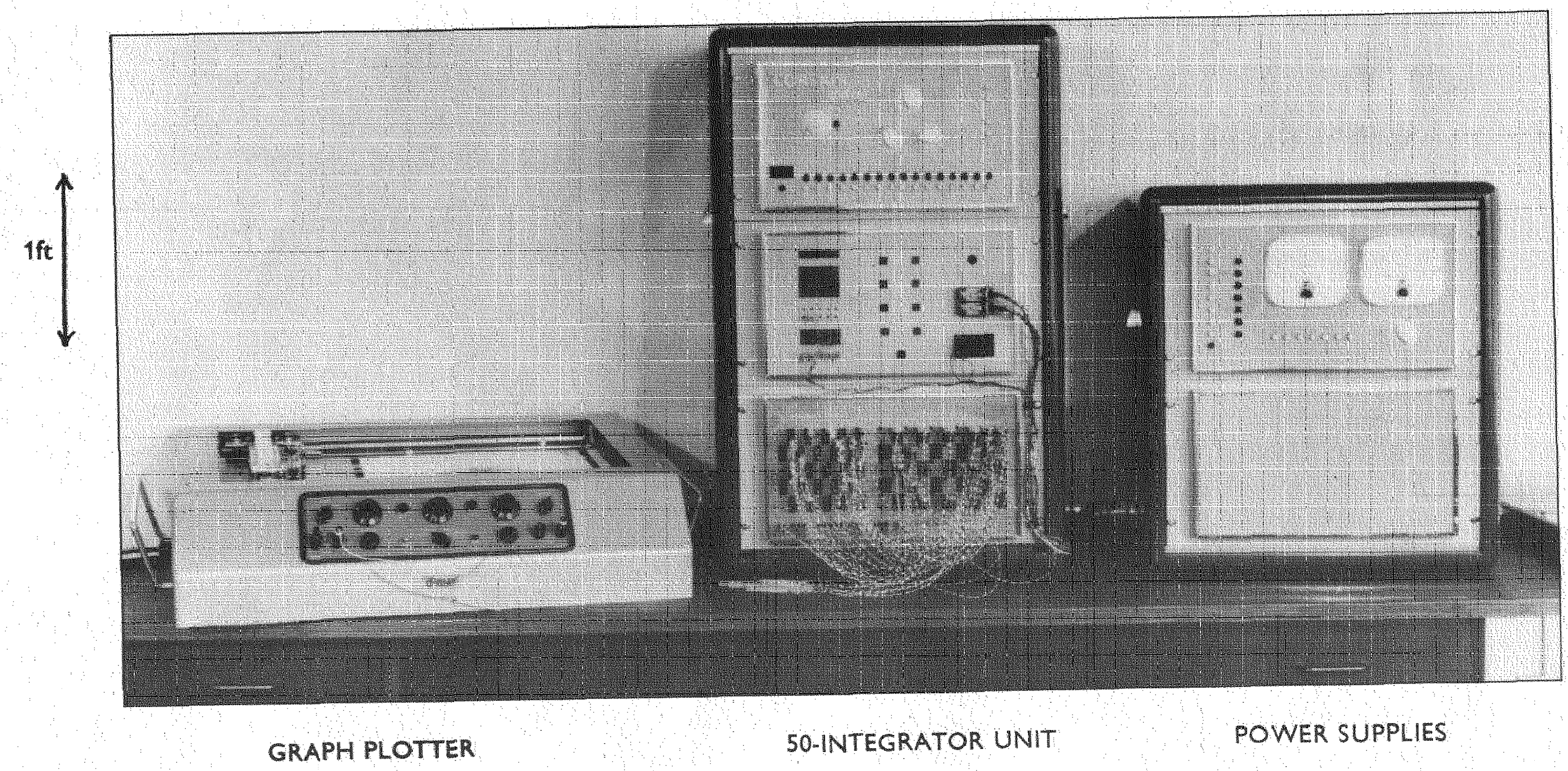


FIG.4. A 50 - INTEGRATOR **CORSAIR** INSTALLATION

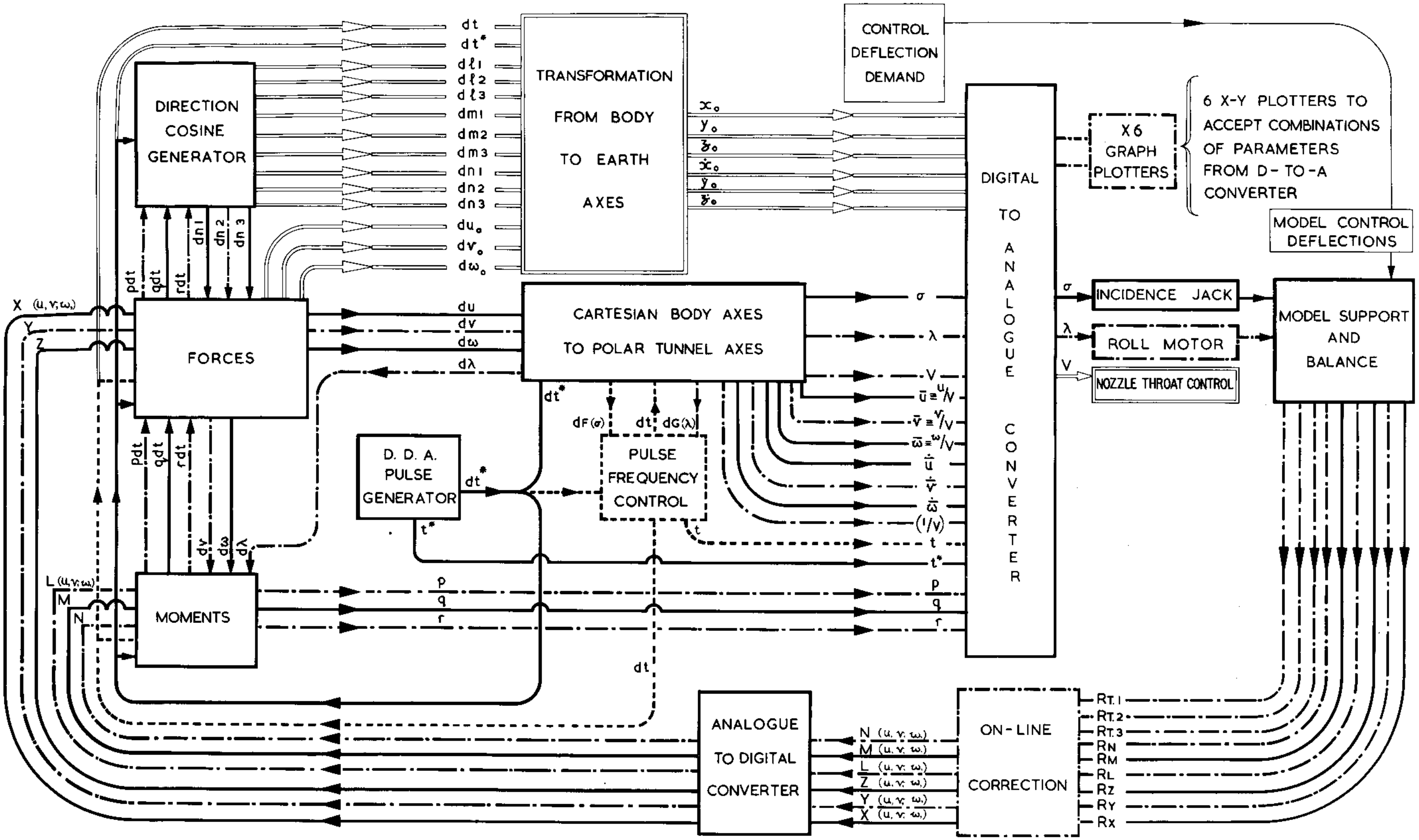
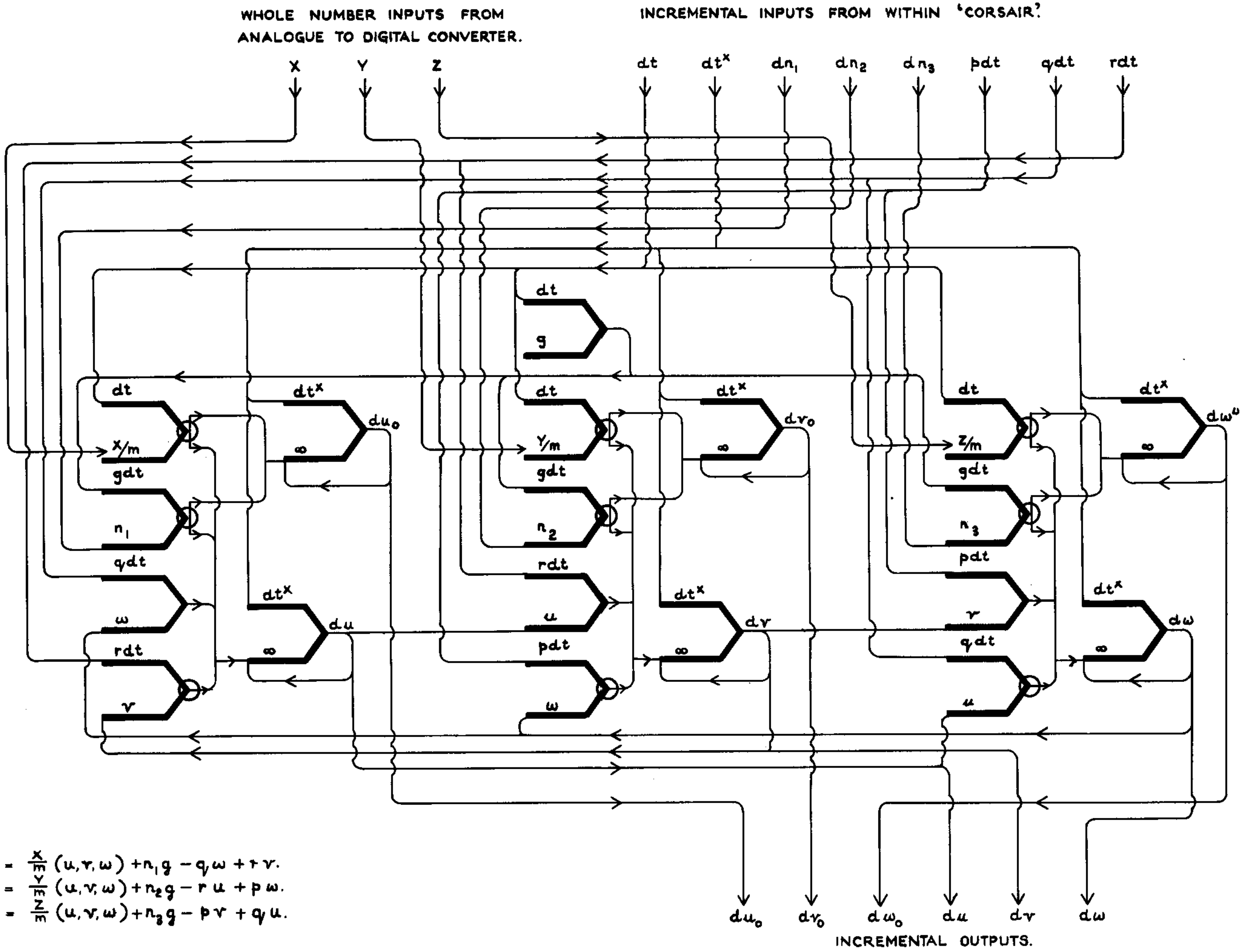


FIG.5. SCHEMATIC DIAGRAM OF WIND TUNNEL FLIGHT DYNAMICS SIMULATOR

━━ STAGE 1. 1 CORSAIR
┅┅ STAGE 2. 1 OR 2 CORSAIRS
─·─ STAGE 3. 2 CORSAIRS
═══ STAGE 4. 3 CORSAIRS
─── STAGE 5.



$$\dot{u} = \frac{X}{m}(u,v,w) + n_1 g - q w + r v.$$
$$\dot{v} = \frac{Y}{m}(u,v,w) + n_2 g - r u + p w.$$
$$\dot{w} = \frac{Z}{m}(u,v,w) + n_3 g - p v + q u.$$

FIG. 6. INTEGRATOR NETWORKS FOR STAGE 4.
(a) FORCE BLOCK.

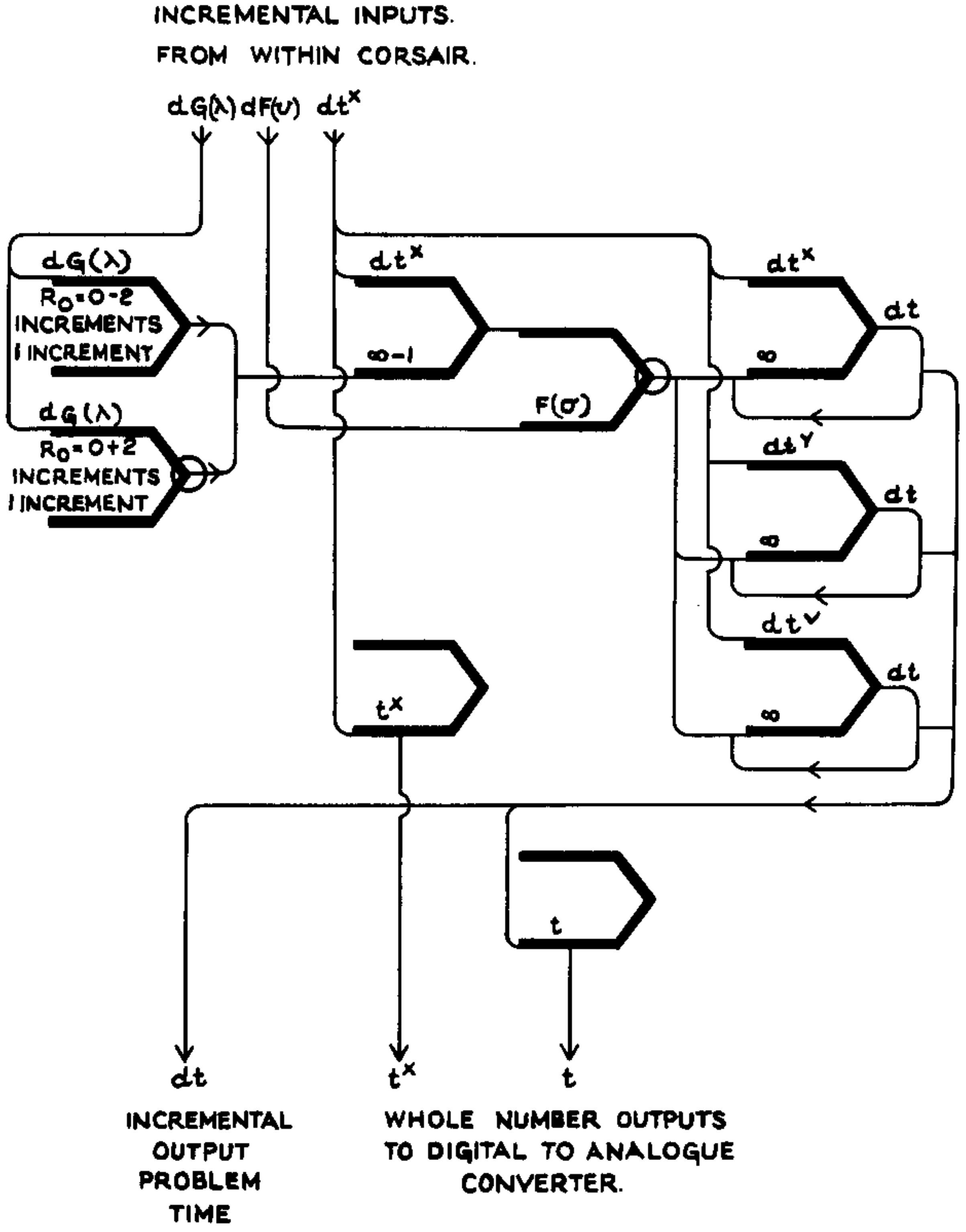
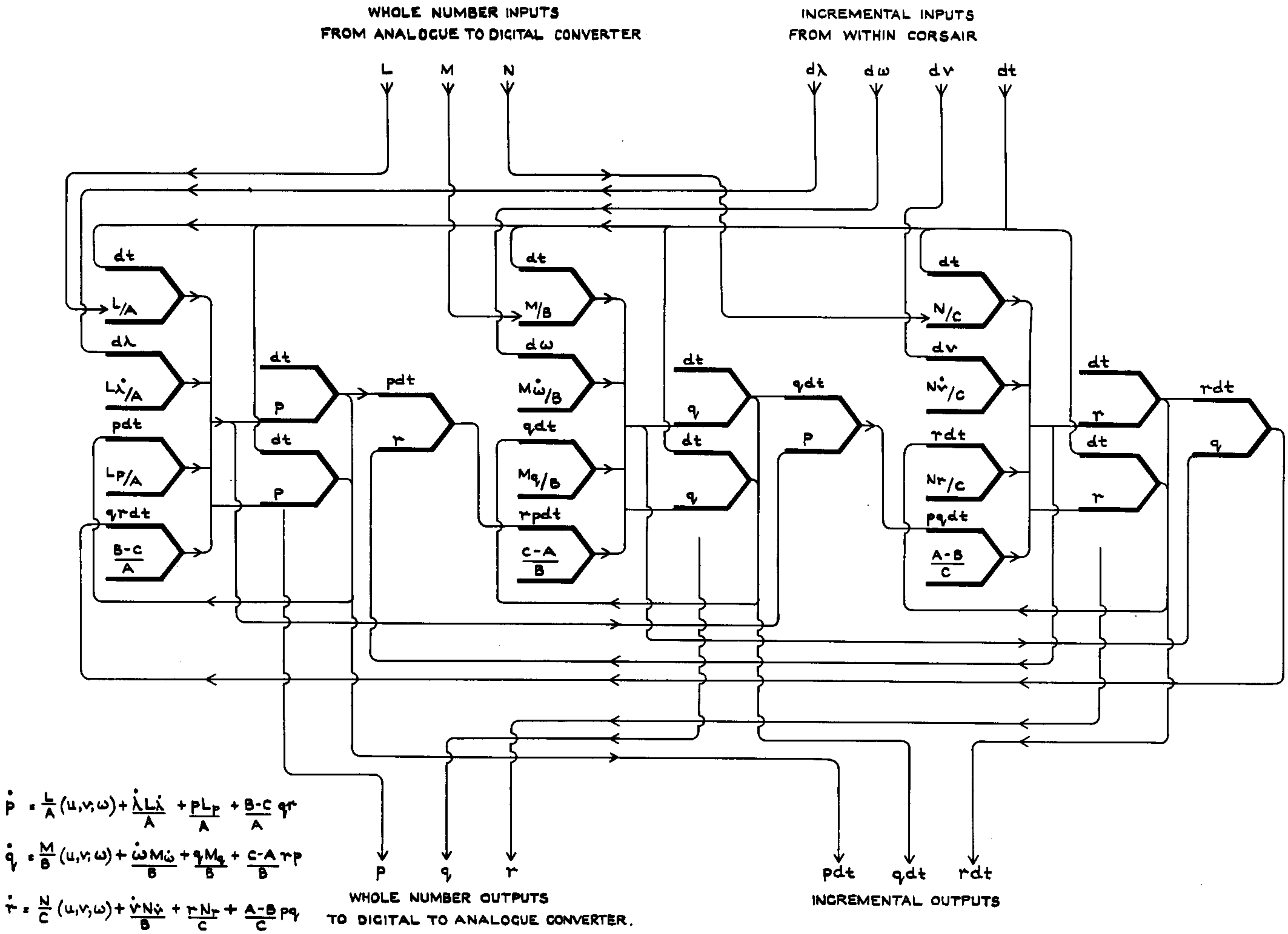


FIG 6 (CONTD.) (e) PULSE FREQUENCY CONTROL.



$$\dot{p} = \frac{L}{A}(u,v,\omega) + \frac{\dot{\lambda} L_{\dot{\lambda}}}{A} + \frac{p L_p}{A} + \frac{B-C}{A} qr$$

$$\dot{q} = \frac{M}{B}(u,v,\omega) + \frac{\dot{\omega} M_{\dot{\omega}}}{B} + \frac{q M_q}{B} + \frac{C-A}{B} rp$$

$$\dot{r} = \frac{N}{C}(u,v,\omega) + \frac{\dot{v} N_{\dot{v}}}{B} + \frac{r N_r}{C} + \frac{A-B}{C} pq$$

(b) MOMENT BLOCK.

FIG. 6. (CONTD)

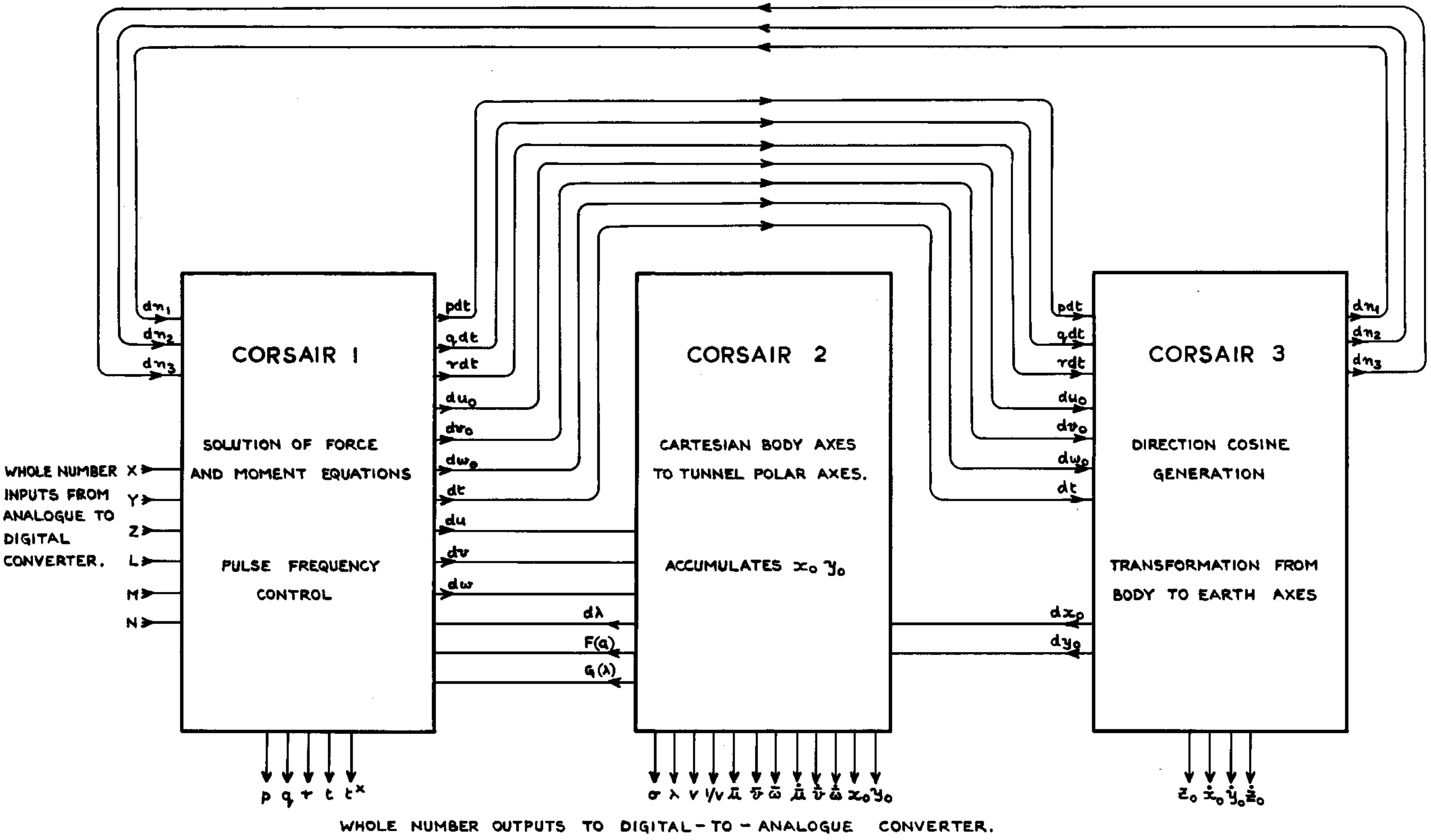
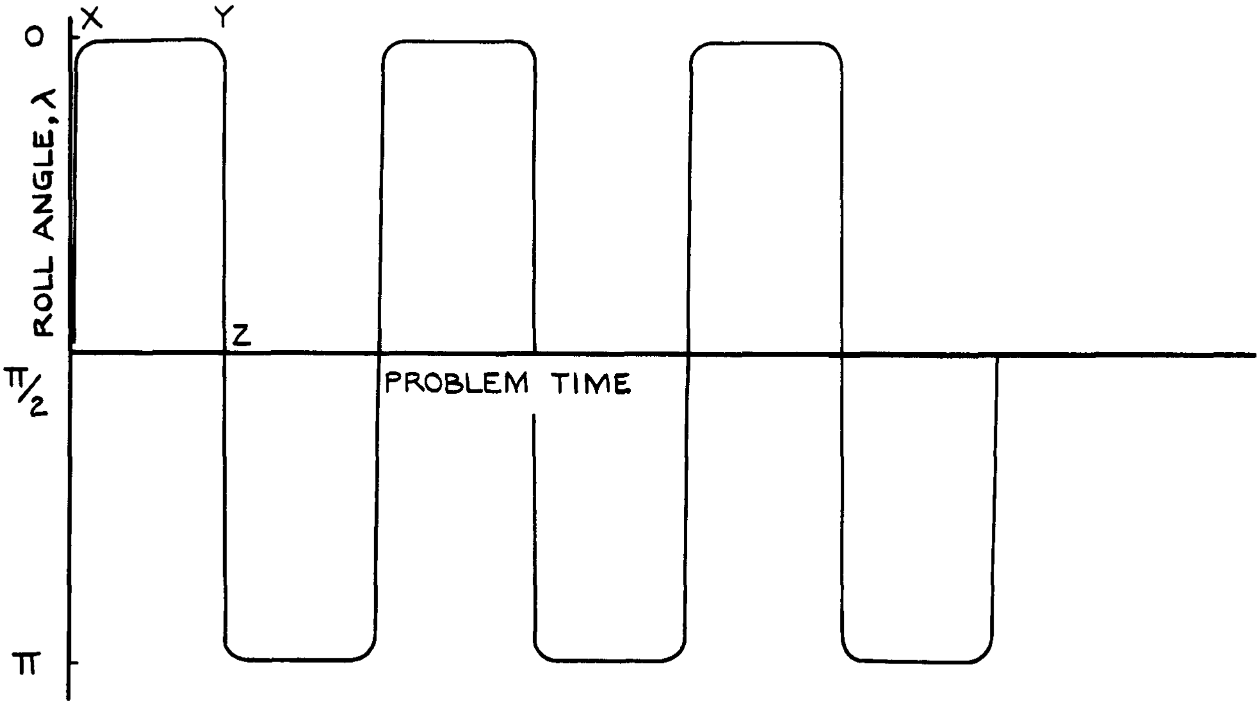


FIG. 7. FLOW DIAGRAM FOR STAGE 4.



$\bar{\upsilon} = 0{\cdot}00175\ (\equiv 0{\cdot}1°)$

$\bar{\omega} = 0{\cdot}5 \sin 0{\cdot}488t$

$\tan \lambda = \frac{\bar{\upsilon}}{\bar{\omega}}$

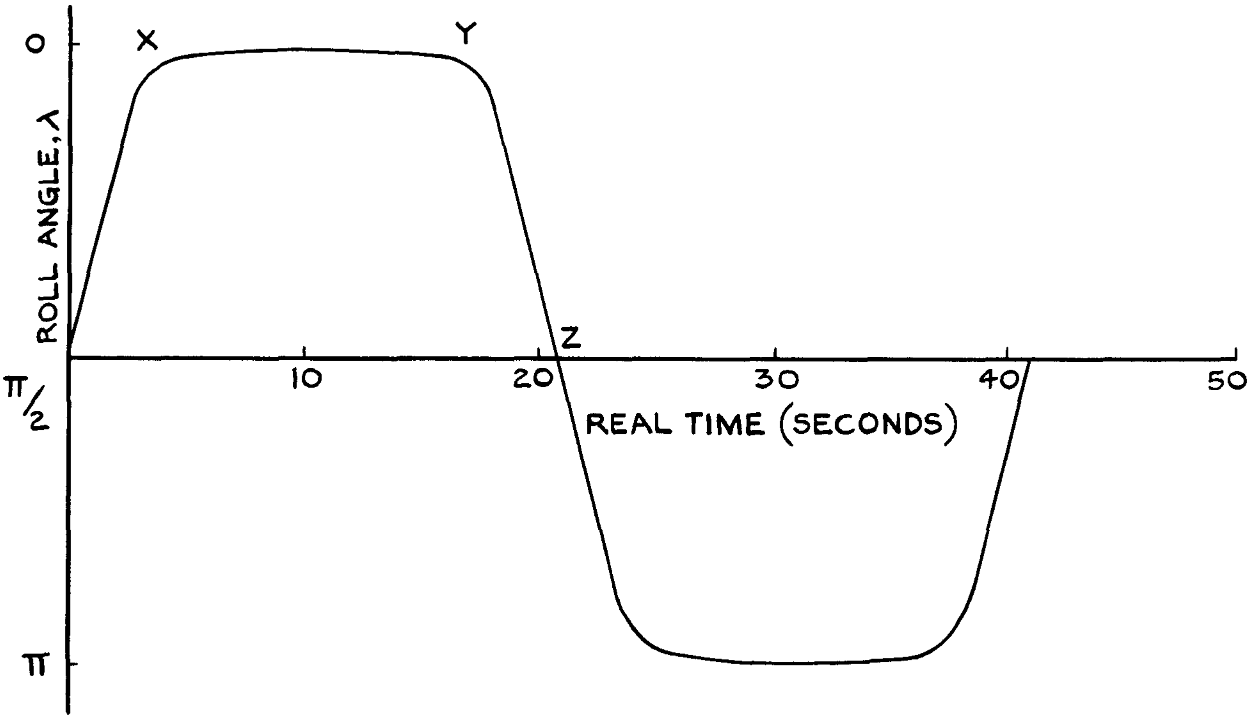


FIG. 8 (CONTD).
(b) APPLIED TO ROLL ANGLE λ.

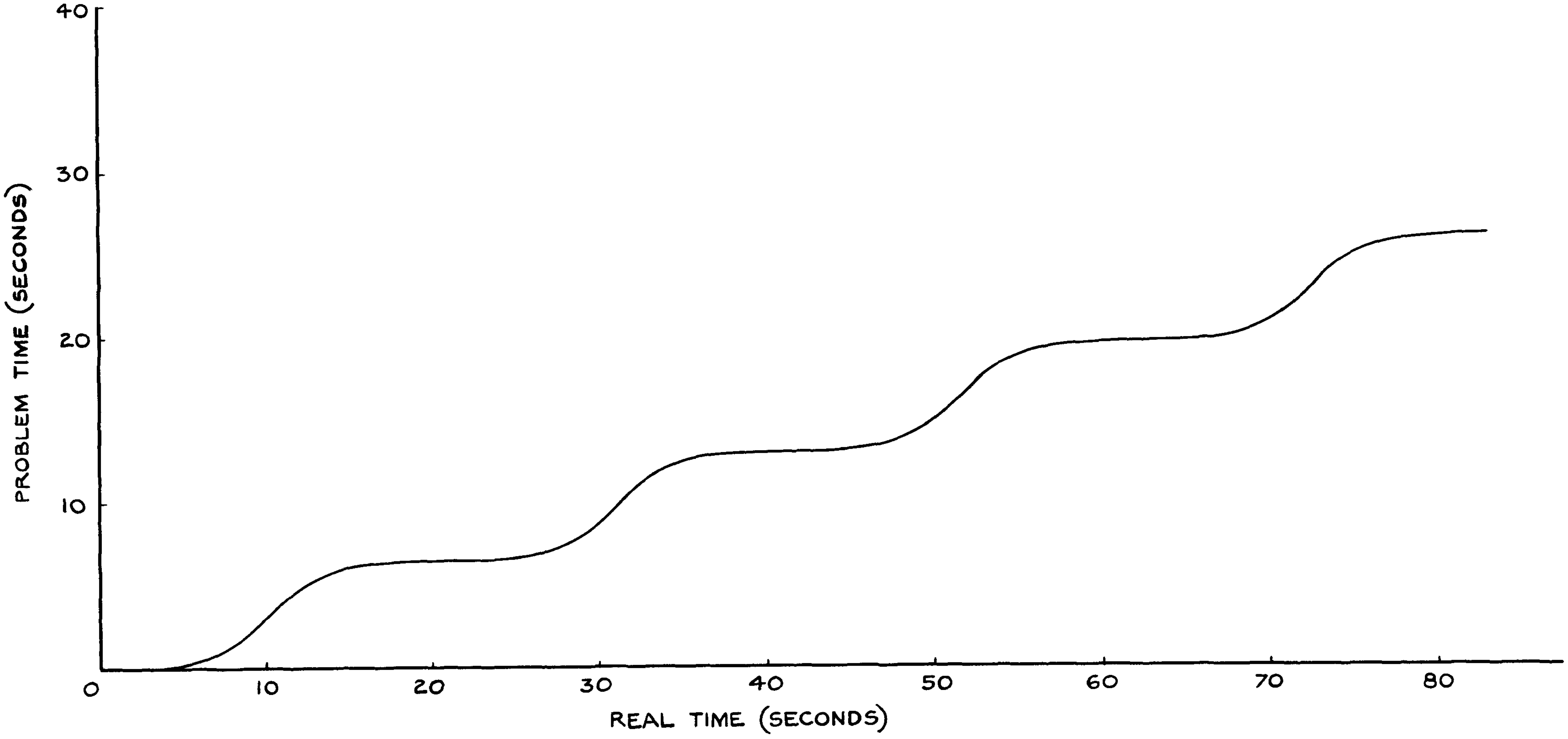


FIG. 8 (CONTD.).

(C) PROBLEM TIME HISTORY.

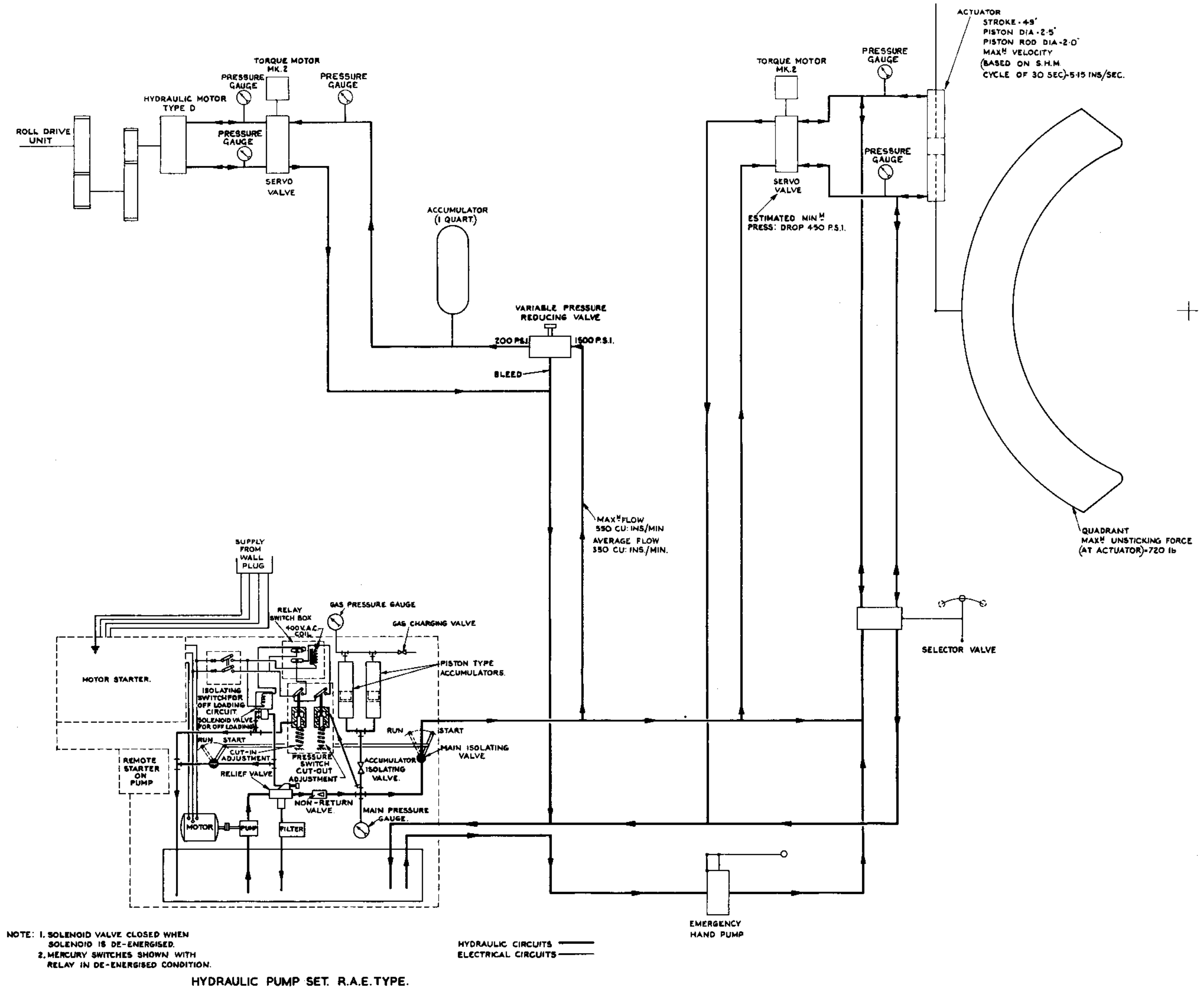


FIG. 9. SCHEMATIC LAY-OUT OF HYDRAULIC ACTUATION OF INCIDENCE QUADRANT & ROLL DRIVE.

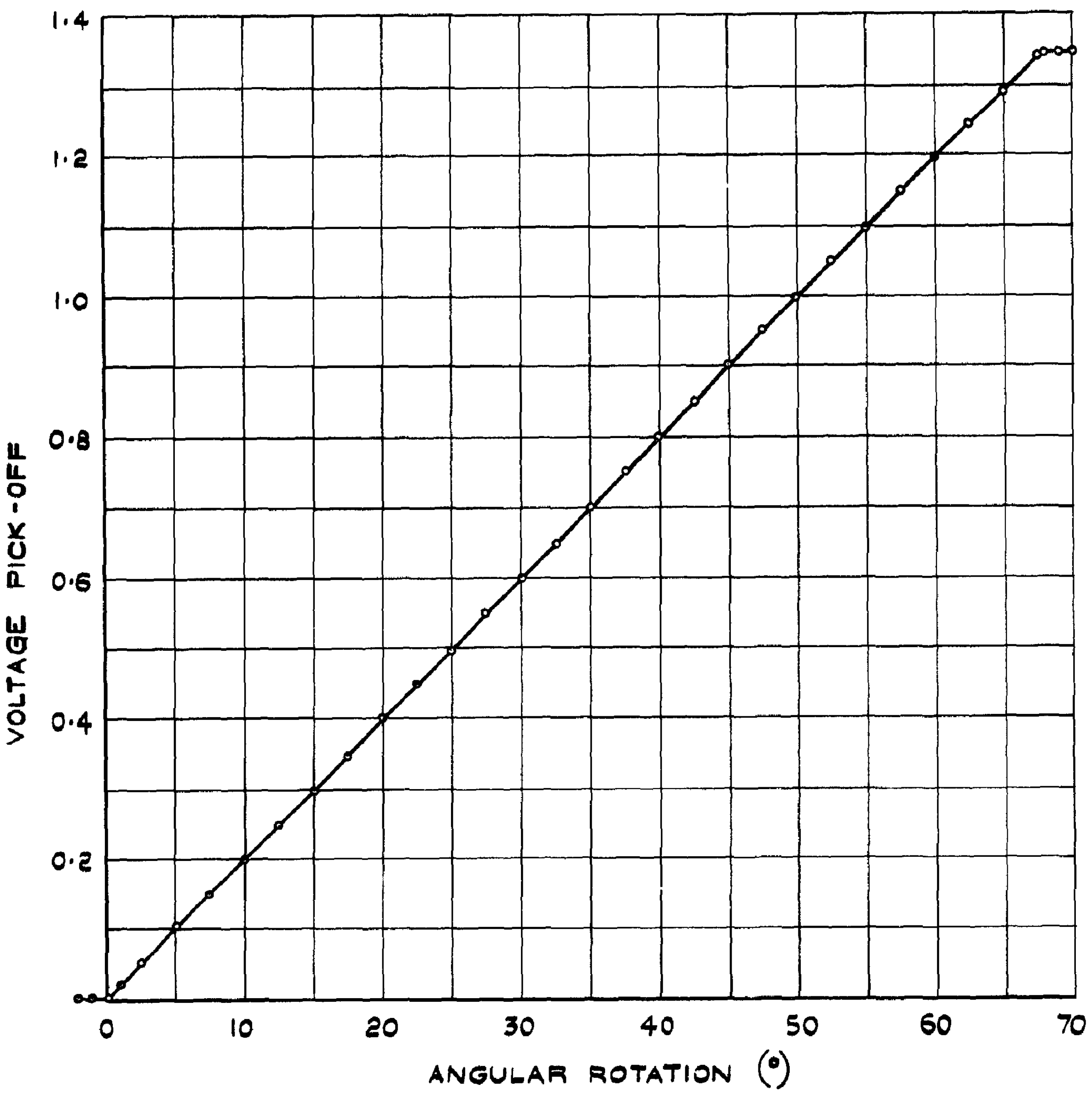


FIG. 11. CALIBRATION CURVE OF POTENTIOMETER.

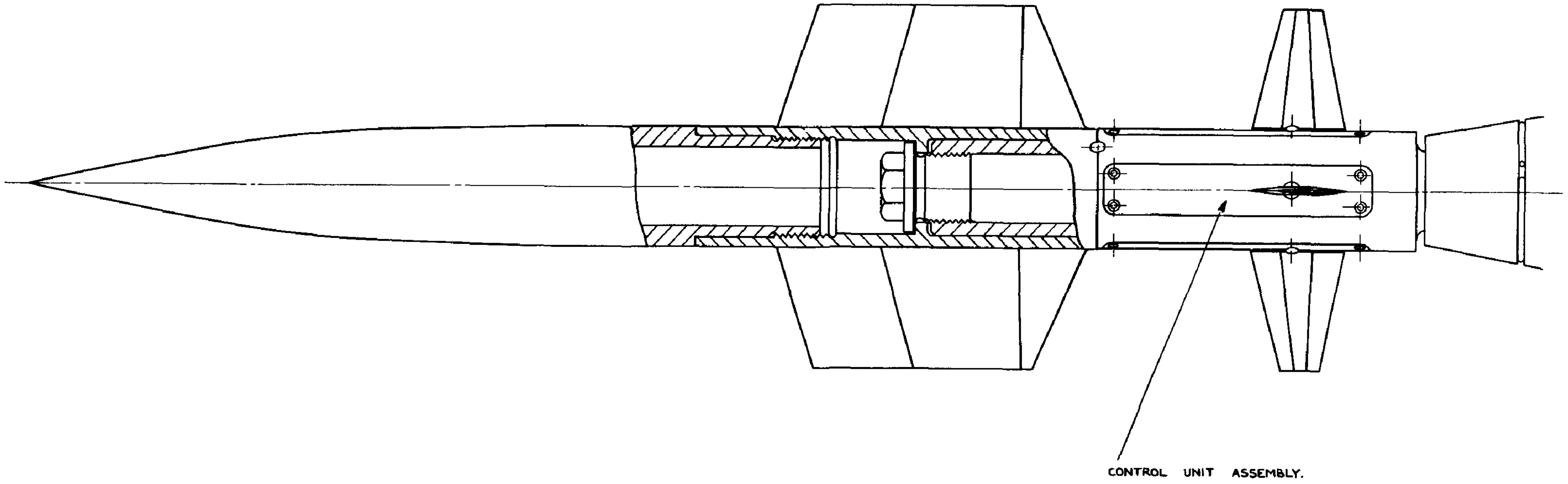
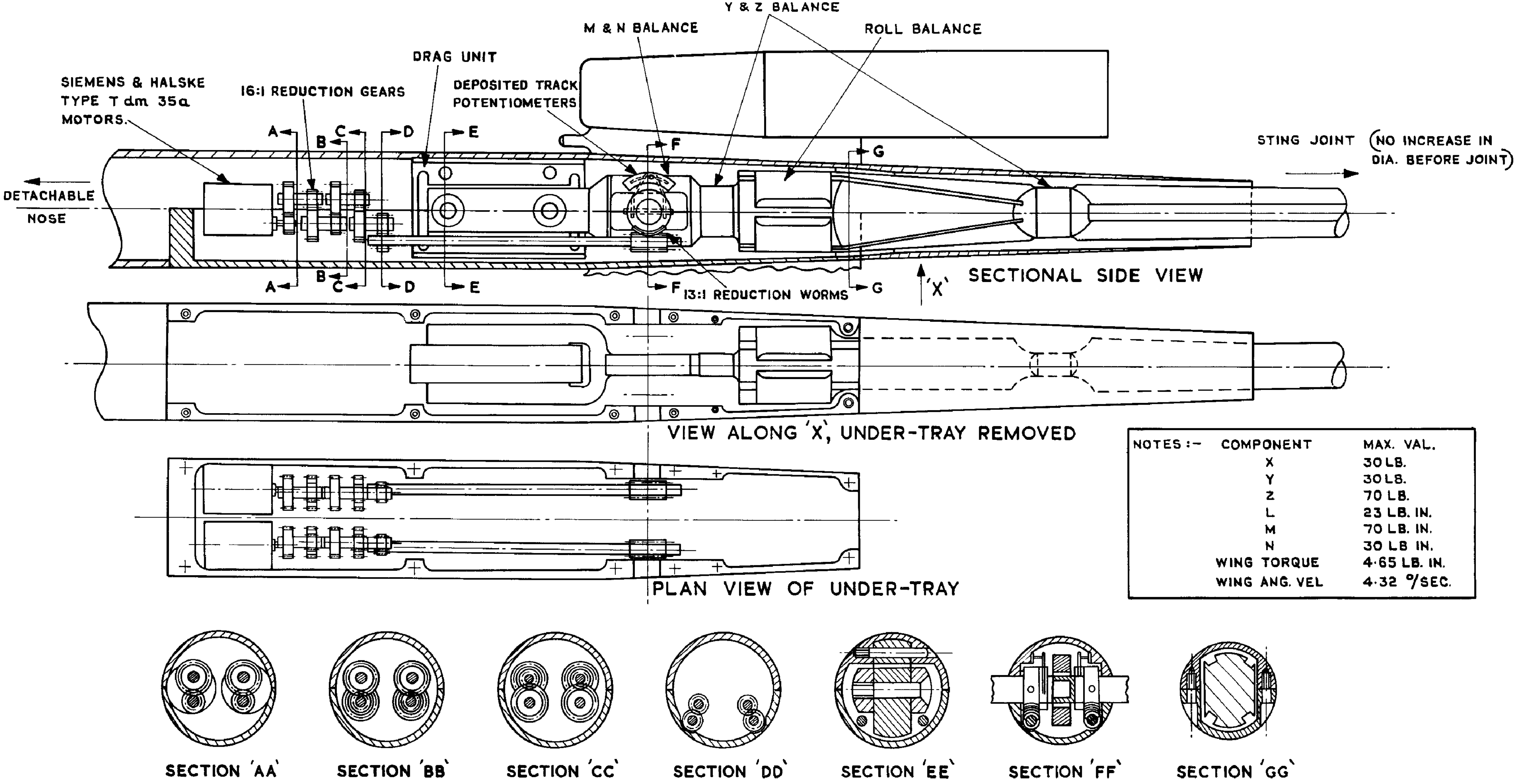


FIG. 12. CARTESIAN MISSILE MODEL EMBODYING REMOTELY OPERATED CONTROL SURFACES



NOTES :– COMPONENT	MAX. VAL.
X	30 LB.
Y	30 LB.
Z	70 LB.
L	23 LB. IN.
M	70 LB. IN.
N	30 LB IN.
WING TORQUE	4·65 LB. IN.
WING ANG. VEL	4·32 °/SEC.

FIG. 13. SKETCH OF SUGGESTED STING & WING DRIVE ARRANGEMENTS FOR A TWIST & STEER MISSILE MODEL.

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Beecham, L.J., Walters, W.L. and Partridge, D.W. November, 1962.

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