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A Technique for the Wind Tunnel Simulation of Store Release at High Speeds

by

L. J. Beecham

LONDON: HER MAJESTY'S STATIONERY OFFICE

1966

FIVE SHILLINGS NET

U.D.C. No. 533.6.071 : 533.695.9 : 533.6.011.35/5

C.P. No.856
May 1964

A TECHNIQUE FOR THE WIND TUNNEL SIMULATION OF STORE RELEASE AT HIGH SPEEDS

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SUMMARY

A controlled-fall technique for the wind tunnel simulation of the release of a store from an aircraft at high flight speeds is presented. It is shown that the trajectory and incidence of the store may be simulated during the release phase for transonic and supersonic free stream speeds by use of on-line incremental digital computation in conjunction with balance measurements. The technique allows in principle full three-dimensional freedom on the motions of both store and aircraft at launch.

Replaces R.A.E. Tech Note Aero 2964 - A.R.C. 26074

CONTENTS

ILLUSTRATIONS

1 INTRODUCTION

In the dynamic simulation of the release of a store from an aircraft it is necessary that the correct relationship between the aerodynamic, gravitational and inertial forces, be preserved in magnitude and direction at corresponding points on the trajectory.

If the simulation is by means of a free-fall in a wind tunnel then a number of constraints are immediately imposed. Firstly the wind tunnel axis is fixed, usually horizontally, relative to the earth so that the release condition corresponds to straight, level, and usually unaccelerated flight of the parent aircraft. Secondly it follows that since the gravitational acceleration is the same at both model and full scale the other linear accelerations in the relative motion between the store and aircraft must also be preserved. Hence, since there is a change of scale, the relative velocity (store to aircraft) at corresponding points on the full scale and simulated trajectories cannot be the same. If r_L, r_V, r_T represent the model-to-full scale ratios of length, separation velocity and time respectively, it follows that $r_V = r_L^{\frac{1}{2}} = r_T$.

Again, the angular velocity ratio, r_S, must be made equal to $r_L^{-\frac{1}{2}}$ since $r_S\, r_V$ has the dimensions of linear acceleration and is to be preserved. The corresponding ratio of angle turned through ($\equiv r_S\, r_T$) is then unity so that the correct attitude of model is maintained along the trajectory. No distinction is necessary here between wind and earth axes since, as already mentioned, only straight and level flight at release is simulated.

At this point, since the relative velocity between store and aircraft is necessarily incorrectly simulated, it becomes necessary to decide on the parameter to which this velocity should be matched. Two methods are mainly used.

The first scales the free stream velocity in the same ratio as that of the relative velocity. This has the advantage of correctly matching the store trajectory with respect to a particle travelling with the free stream, i.e. $r_{V_\infty} = r_V = r_L^{\frac{1}{2}}$. The reduced frequency ratio, $r_{\bar{\omega}} \left(\equiv \frac{r_S\, r_L}{r_{V_\infty}} \right)$ is then unity, so that the aerodynamic loads due to angular velocity derivatives are correctly represented providing these do not depend on free stream Mach No. Similarly the aerodynamic loads arising from the incidence of the store (which is correctly simulated along the trajectory) are correct, providing they are not Mach No. dependent. This proviso necessarily confines the method to simulation at low aircraft speeds where the aerodynamic loads are nearly enough proportional to ρV_∞^2 . In dynamically scaling the aerodynamic and gravity force we may then write:-

$$\frac{r_\rho\, r_{V_\infty}^2\, r_L}{r_\delta\, r_L^2} = 1 \quad \text{i.e.} \quad r_\rho = r_\delta \;(\text{since } r_{V_\infty}^2 = r_L)$$

where suffices ρ and δ refer to the air and store densities respectively. Thus, for a given ambient air density in the tunnel, the model density is constant, independent of scale.

The necessary reduction of free stream velocity for smaller scale models is the shortcoming of this technique, for it can be used only where compressibility is not important, and for this reason is inapplicable to the simulation of release at transonic speeds.

In the second method the Mach No. of the free stream flow is preserved and for the present purposes we may take this to mean $r_{V_\infty} \doteqdot 1$ nearly enough. In this case the reduced frequency parameter ratio $\left(\equiv \frac{r_S\, r_L}{r_{V_\infty}}\right) = r_L^{\frac{1}{2}}$ and is thus incorrectly represented, so that the aerodynamic loads due to angular velocity are not correctly simulated. Furthermore, preserving aerodynamic and gravitational similarity with $r_{V_\infty} = 1$ gives $\frac{r_\rho}{r_\delta} = r_L$. The model density has therefore to be increased as the scale is reduced, thereby imposing a lower limit on the scale possible with available materials.

Both "free-fall" techniques, therefore, have deficiencies which in various respects make the simulations unrepresentative due to the preservation of the linear acceleration scale. In cases where the store is ejected from the aircraft with an initial velocity which is high compared with that which it would achieve under gravity whilst close to the aircraft, the acceleration scale need not be preserved and more freedom with the scaling is possible.

This note considers another method of simulation using a captive model. If the store model were supported independently of the aircraft such that its motion could be suitably prescribed and controlled, then the effective gravitational acceleration could be varied, and the limitations of the free-fall technique overcome. The equipment described in Ref.1 offers a possible facility for achieving this control.

There may well be difficulties to overcome in implementing such a scheme, notably in supporting the store at transonic speeds such that aerodynamic interference from the support may be ignored. This note is based on the premise that these are not insurmountable.

2 GENERAL METHOD

The problem is essentially that of determining the relative linear and angular motions between the several axes systems in which the forces and moments are specified. The gravity force, for example, is constant in a system of earth axes, whereas the aerodynamic loads are dependent upon the orientations of the body axes to the flight path, and are different for aircraft and store after release.

To determine the relative motion between store and aircraft following release we have to refer the displacements, etc, to one common set of axes, taking due account of the angular velocities between the various sets. For convenience the parent aircraft model would most probably be fixed in the wind tunnel, so that the common set has been chosen as those of the aircraft flight path. Since this is fixed in tunnel axes, the relative displacements and velocities, etc, can then be provided with respect to the tunnel structure.

The aerodynamic loads are most conveniently measured on balances moving with the models, and are hence referred to as body-fixed axes systems. We have, therefore, five sets of axes (two body-fixed, two flight path-fixed, and one earth system). The store trajectory is then defined by the relative disposition of the two wind axes systems, and the incidences of the aircraft and store by the dispositions of the respective body and wind axes.

3 NOMENCLATURE AND NOTATION

Because of the several axes systems involved, care is needed in specifying the vectorial quantities to indicate:-

(i) which system is being regarded as the reference,

(ii) in which system the component vectors are defined.

(i) and (ii) are independent. For example, the translational velocity of a system A moving with respect to a system B will be designated v^{AB}, and this quantity is invariant with (ii). The components may thus be expressed in a third system, C, which may be changed without affecting v^{AB}; for this reason the component axes system is denoted by a suffix, viz. v_C^{AB}.

The change from C to a new system, D, is effected by a transformation matrix, T, with suffixes such that:-

$$v_D^{AB} = T_{DC} \cdot v_C^{AB} \quad . \qquad (1)$$

The transformation matrix is 3×3 and orthogonal, so that the inverse, T_{CD}, is produced by interchanging rows and columns. It has the property that the product of any row (or column) with itself is unity, and, with any other, is zero. The elements are the direction cosines of the angles between the axes in the C and D systems and are arranged such that the terms in each row are all associated with an axis in the leading suffix system. Likewise the terms in the columns are associated with an axis in the trailing suffix system.

Herein the body-fixed, earth and flight path axes of the store are denoted by B, E and F respectively, and with primes for the corresponding system for the aircraft (the earth system is, of course, common to both store and aircraft). Thus $v_{B'}^{BE}$ would denote the resolution of the translational velocity of the store relative to the earth into components along the body axes of the aircraft.

Use is made of the property of orthogonal matrices whereby the product of a matrix and the differential of its inverse is a skew-symmetric matrix, the elements of which correspond to those of the relative angular velocity between the axes systems, i.e.

$$T_{BE}\,\dot{T}_{EB}\ (\equiv -\dot{T}_{BE}\,T_{EB}) = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}$$

in comparison with

$$s_B^{BE} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

where s (= spin) denotes the angular velocity vector. It should be remembered that matrix multiplication is non-commutative.

4 MOTION OF STORE AND AIRCRAFT FOLLOWING RELEASE

4.1 Store (or aircraft) in aerodynamic isolation

For convenience, although it is not essential, we take the store mass, m, and inertia, I_B, as constant, and we have, using the foregoing notation,

Force equation:

$$\underset{\text{(aerodynamic)}}{F_E} + \underset{\text{(gravitational)}}{m g_E} = m\,\dot{v}_E^{BE}$$

i.e.
$$T_{EB}\,F_B + m g_E = m\,\frac{d}{dt}\left(T_{EB}\,v_B^{BE}\right)$$

i.e.
$$\frac{F_B}{m} + T_{BE}\,g_E = \dot{v}_B^{BE} + T_{BE}\,\dot{T}_{EB}\,v_B^{BE} \qquad (3)$$

Moment equation:

$$\underset{\text{(aerodynamic)}}{M_E} = \dot{h}_E$$

i.e.

$$T_{EB}\, M_B = \frac{d}{dt}\left(T_{EB}\, I_B\, s_B^{BE}\right)$$

i.e.

$$\underline{M_B = I_B\, \dot{s}_B^{BE} + T_{BE}\, \dot{T}_{EB}\, I_B\, s_B^{BE}} \qquad (4)$$

where h = angular momentum

I = moment of inertia.

Equations (3) and (4) are the Euler equations of motion, and the technique given in Ref.1 solves these simultaneously to give v_B^{BE}, s_B^{BE} and T_{BE} .

The above equations with suitable primes give a similar pair for the aircraft.

In the above the terms F_B, M_B represent the total aerodynamic loads (in components along the body axes) and contain contributions from the several sources from which momentum is added to the traversed air, viz. through the linear and angular velocities of the body and flight path axes relative to the earth (wind is neglected here). Because $v^{BE} \equiv v^{FE}$, and $s^{FE} = s^{BE} - s^{BF}$ this may be expressed as

$$F_B(\text{or } M_B) = F_1(v_B^{BE}) + F_2(s_B^{BE}) + F_3(s_B^{BF})$$

$$= F_1(v_B^{BE}) + F_2(s_B^{BE}) + F_4(v_B^{BE}, \dot{v}_B^{BE})$$

since s_B^{BF} has the same elements as $T_{BF}\, \dot{T}_{FB}$, viz. products of the components of v_B^{BF} and $\dot{v}_B^{BF}$.

The first term, F_1, is usually the major term and is that due to the instantaneous orientation of the body to the airstream; this is provided directly by the measured loads on the static wind tunnel model. The remainder are "damping" terms which may usually be taken as proportional to the angular velocities involved, e.g.

$$F_2(s_B^{BE}) = \begin{bmatrix} L_p & 0 & 0 \\ 0 & M_q & 0 \\ 0 & 0 & N_r \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} .$$

Since s_B^{BE}, v_B^{BE} and $\dot{v}_B^{BE}$ are all obtained from the solution of equations (3) and (4) these damping terms may in principle be included as considered necessary providing the proportionality is known; they are usually omitted from the force equation but retained for the moment equation[1]. Fig.2 shows schematically the solution of (3) and (4) and includes for illustration the damping term due to s_B^{BE}.

4.2 Relative motion between store and aircraft

After release the flight paths of aircraft and store are quite distinct and the separation velocity between the F' and F systems of axes defines the trajectory of the store relative to the aircraft. Because during the short release phase the aircraft incidence may be considered nearly enough constant (6.1) it is mechanically convenient to identify the tunnel free stream velocity vector with the reverse of that of the aircraft along its flight path, and to resolve other parameters of the motion into axes along and normal to it. Thus from values of v_B^{BE}, s_B^{BE} and T_{BE}, and $v_{B'}^{B'E}$, $s_{B'}^{B'E}$ and $T_{B'E}$, obtained in section 4.2 we require to determine the quantities T_{BF} and $v_{F'}^{BF'}$ ($\equiv v_{F'}^{FF'}$); these will define the incidence and trajectory of the store with respect to the flight path of the aircraft and the setting of the store model in a wind tunnel simulation.

A difficulty arises here because only the x-axis of the aircraft flight path ($x_{F'}$) is defined; the velocity components of the aircraft $v_{F'}^{B'E}$ are by definition zero along the y and z axes which therefore have to be arbitrarily defined. Again from mechanical considerations it is convenient to confine the total incidence of the aircraft to the tunnel vertical plane, so that if we choose the $z_{F'}$ axis to be positive vertically downwards,

$$T_{B'F'} = \begin{bmatrix} \bar{u}' & 0 & . \\ \bar{v}' & . & . \\ \bar{w}' & . & . \end{bmatrix}$$

where $\bar{u} = u' \div V'$, etc

$$V' = [u'^2 + v'^2 + w'^2]^{\frac{1}{2}}$$

$$\equiv |v^{B'E}| .$$

From the orthogonal properties of $T_{B'F'}$ it follows that all the other elements are now known, viz.

$$T_{B'F'} = \begin{bmatrix} \bar{u}' & 0 & -\sqrt{\bar{v}'^2 + \bar{w}'^2} \\ \bar{v}' & \dfrac{\bar{w}'}{\sqrt{\bar{v}'^2 + \bar{w}'^2}} & \dfrac{\bar{u}'\bar{v}'}{\sqrt{\bar{v}'^2 + \bar{w}'^2}} \\ \bar{w}' & \dfrac{-\bar{v}'}{\sqrt{\bar{v}'^2 + \bar{w}'^2}} & \dfrac{\bar{u}'\bar{w}'}{\sqrt{\bar{v}'^2 + \bar{w}'^2}} \end{bmatrix} \qquad (5)$$

Since T_{BE}, $T_{B'E}$ are also known we may now specify

$$T_{BF'} \equiv T_{BE}\, T_{EB'}\, T_{B'F'}$$

$$= \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

say, where each element is known.

In a release simulation, the store, to generate the representative aerodynamic loads, must be at the "correct" incidence, and here we encounter a difficulty which is common to all simulations except where the velocity of separation is matched to that of the free stream (1), viz. that the incidence cannot be simultaneously correct with respect to both store and aircraft flight paths.

The difference is due to the divergence angle between the flight paths, and at high flight speeds it is small. For example, under gravity only, the store will fall about 6 ft before the divergence angle amounts to 1° at $M = 1$; for an ejection velocity of 30 ft/sec the angle is 1.8° at the same separation distance. The period of particular interest in the release simulation is whilst the separation distance is small enough for the store to be influenced by the non-uniform flow field around the aircraft. Herein it has been assumed that the incidence of the store to its own flight path is of greater significance, so that the orientation of the store and body axes will be slightly incorrect. In practice the importance or otherwise of this could be checked by a repeat run programmed at a different time scale, or by runs comparing the effects when controlling the store motion by $T_{BF'}$ instead of T_{BF}.

Because, from the above, the simulation would not be accurate for large divergence angles it has been regarded here as justifiable to use small angle approximations in determining the flight path separation as determined by $T_{FF'}$.

Up to launch the flight paths are necessarily coincident. The aircraft flight path axes have already been defined with respect to the wind tunnel and it is convenient to define the store flight path axes as being reached from those of the aircraft by two rotations only, Δ_1 and Δ_2 about the $z_{F'}$ and $y_{F'}$ axes respectively. The small angle approximation makes the order of rotation immaterial, so that

$$T_{FF'} = \begin{bmatrix} 1 & \Delta_1 & -\Delta_2 \\ -\Delta_1 & 1 & 0 \\ \Delta_2 & 0 & 1 \end{bmatrix} + O(\Delta^2) \quad . \qquad (7)$$

But we also have the identity

$$\begin{aligned} T_{FF'} &= T_{FB}\, T_{BF'} \\ &= \begin{bmatrix} \bar{u} & \bar{v} & \bar{w} \\ * & * & * \\ * & * & * \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad . \end{aligned} \qquad (8)$$

The top row in equation (7) can be equated directly with the known elements in equation (8), viz.

$$\begin{aligned} \Delta_1 &= \bar{u}\, a_{12} + \bar{v}\, a_{22} + \bar{w}\, a_{32} \\ -\Delta_2 &= \bar{u}\, a_{13} + \bar{v}\, a_{23} + \bar{w}\, a_{33} \quad . \end{aligned} \qquad (9)$$

By virtue of the skew-symmetry resulting from the small angle approximation $T_{FF'}$ is fully defined. Furthermore the process may be inverted to provide the * terms in equation (8) and hence the angle between the store and aircraft incidence planes, viz.

$$T_{BF} = T_{BF'} \; T_{F'F}$$

$$= \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \text{ say} \qquad (10)$$

It should be noted that the small angle limitations apply only to the deviations of the flight paths - no limitations have been placed on the incidence of the store at release or subsequently.

The orientation of the store to the tunnel has now been defined, and it remains to determine the trajectory, i.e. the separation distance. The separation velocity matrix is

$$v_{F'}^{FF'} (\equiv v_{F'}^{BB'}) = T_{F'F} \, v_F^{FE} - v_{F'}^{F'E} \qquad (11)$$

$$= \begin{bmatrix} 1 & -\Delta_1 & \Delta_2 \\ \Delta_1 & 1 & 0 \\ -\Delta_2 & 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} V' \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} V - V' \\ \Delta_1 \; V \\ -\Delta_2 \; V \end{bmatrix} . \qquad (12)$$

Hence by integration we may obtain the displacement components $x_{F'}^{FF'}$, of the store relative to the tunnel.

5 MODEL SETTING

The required linear displacements of the store relative to the wind tunnel are given explicitly by the components of $x_{F'}^{FF'}$ above.

The information necessary to determine the angular disposition is contained in equation (7). The final (B) position may be reached from the original (F) position by three rotations successively about the current body axes, and the form of the A_{ij} elements will depend upon the order in which these rotations are applied. In a particular design of support mechanism being considered it has been found convenient to apply the rotation first about the y-axis (i.e. in the vertical plane), then about the new z-axis, and finally about the final x-axis, so that

$$T_{BF} \equiv \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{bmatrix} \begin{bmatrix} c_2 & s_2 & 0 \\ -s_2 & c_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_1 & 0 & -s_1 \\ 0 & 1 & 0 \\ s_1 & 0 & c_1 \end{bmatrix} \quad \ldots.(13)$$

where $c_i = \cos \theta_i$

$s_i = \sin \theta_i$

$i = 1, 2, 3$ denote the angular rotations in the order taken.

The three required angular rotations $\theta_{1,2 \text{ and } 3}$, may be conveniently extracted from a consideration of the terms $A_{12} (= s_2)$, $A_{13} (= -c_2\ s_1)$, and $A_{32} (= -c_2\ s_3)$ only; Fig.5 shows a possible analogue servo method for performing this.

The three linear and three angular deflections, which fully define the orientation of the store to the aircraft and to the wind vector at each instant, would probably be achieved in practice by position servos in the model support system.

6 SIMULATOR DESIGN

A network is shown schematically in Figs.1 to 4 suitable for the solution of the generalised, three-dimensional release problem. In this form, and in terms of existing components it would represent a sizeable installation. As an example, a full, 3 × 3 matrix multiplication, using digital integrators as the incremental digital computing elements, could require up to 63 integrators, i.e. more than the capacity of one CORSAIR unit.

In this section consideration is given to the possibility of streamlining the technique by:-

(i) justifiable simplification of the problem,

(ii) short cuts through the matrix algebra utilising zeros and redundancies,

(iii) possible provision of incremental matrix multipliers and redistributors.

6.1 Problem simplification

A number of simplifications may be justifiably applied in practical cases without prejudicing the usefulness of the method. Firstly it will probably be permissible to ignore the change of incidence of the aircraft during the period for which the store is still in close proximity. For typical store/aircraft mass ratios of 5-10%, computations have shown that the change in $v^{B'E}$ has negligible influence on the incidence of the aircraft, so that the latter may not need separate actuation during a release simulation. However it is still necessary to compute $v^{B'E}$ because the components, although small compared with free stream velocity, can provide a large contribution to the separation velocity between store and aircraft. The acceleration producing separation after release under gravity is increased initially by that of the aircraft, trimmed for the pre-release load, relative to the earth, and its subsequent change even during the short time of interest has been found to be significant.

Thus, although the aircraft model may be kept at a fixed incidence in the tunnel, the effect of its motion (relative to earth-fixed axes) will have to be taken into account in simulating the store trajectory. The same observation applies to the angular velocity, $s^{B'E}$. If, however, the aerodynamic influence of the store back on to the aircraft may be neglected, the change in $v^{B'E}$ and $s^{B'E}$ following the sudden change in mass and inertia on release may be simulated separately, and the correction continuously applied to the store trajectory during the actual release simulation. This effects a considerable saving in the simulator capacity required.

Practical release manoeuvres, may have one or more components of $s_{B'}^{B'E}$ zero, with a possible attendant simplification of $T_{B'E}$, $T_{B'F'}$ etc. Again, the release of over-slung stores may well be confined to manoeuvres where the aircraft is turning in a vertical plane, if at all. The above limitations apply to the aircraft conditions at release, but, even so, do not degenerate to straight and level launch. No conditions have been imposed upon the store velocities s^{BE} and v^{BE} after launch, so that release in an aerodynamically non-symmetrical environment, such as underwing or skew stowage may be simulated.

Inertial symmetry of the store about its longitudinal axis would also simplify the problem.

6.2 Elimination of zero and redundant terms

Many terms in the velocity and transformation matrices are zero and others are redundant through orthogonality. If, as in Ref.1, only the relevant terms from the matrix multiplications are evaluated this reduces the number of integrators required. The following gives an indication of the probable capacity required for various problems - present capacity[1] is 150.

	Integrators required
1. Symmetrical flight in the vertical plane prior to release $\left(p = r = 0, \text{ so that } s_{B'}^{B'E} \equiv \begin{bmatrix} 0 \\ q' \\ 0 \end{bmatrix}\right)$. Store mounted in aircraft symmetry plane, so that post-release behaviour of both store and aircraft is two-dimensional.	51
2. As for (1) prior to release, but with the store wing mounted (or otherwise aerodynamically asymmetric). Following release both store and aircraft are free to move three-dimensionally.	
(i) inertially symmetric store (B = C)	138
(ii) inertially asymmetric store	140
3. No restriction on aircraft motion at release - asymmetric store.	196

In 1 to 3 above the aerodynamic influence of the store on the aircraft motion after release is neglected, enabling the latter to be pre-computed; the aircraft incidence is regarded as constant during release (6.1).

Without these simplifications the aircraft and store loads would have to be measured simultaneously, and the capacity required for case 3 above would then be approximately 350 integrators.

It is clear from the above that although the present simulator capacity will enable some cases to be investigated, full exploitation of the technique requires additional CORSAIR units. This contingency was foreseen, and the present system has been designed to permit interconnection with additional CORSAIR units as required.

However, there is another possible line of development which might profitably be explored, and this is discussed in the next section.

6.3 Matrix multiplier modules

From Figs.2, 3, 4 it will be seen that genuine integration forms a small part of this simulation. In common with many other kinematic problems, the requirement is mainly one of axes transformations involving matrix multiplications, and this raises the question as to whether in the long term it would be feasible to produce 3 × 3 digital matrix modules to be used with, or instead of, integrators. This would increase very considerably the compactness and scope of the incremental digital computer, which in the present DDA form is somewhat clumsy for operations other than addition and integration, and would provide a unit of very high inherent accuracy. So far only preliminary consideration has been given to the practicability of such a unit, but from the limited expertise available within the department, the production of digital channels capable of accepting incremental inputs from two 3 × 3 matrices and giving the product as an incremental output appears quite feasible.

Because of the orthogonal properties of the transformation matrix (i.e. the sum of the product of any row (or column) with itself is unity, and, with any other, zero), it is not necessary to specify all of the nine elements to define the matrix uniquely. If this unification could be achieved automatically by digital servo logic the generation of components such as $T_{B'F'}$ for example, would be greatly simplified.

The redistribution units are required to alter the sequence in which the matrix inputs are accepted. If the matrix multiplier operates sequentially and contains its own storage units the redistribution unit need be no more than a plug-board for programming the multiplier.

The availability of such digital matrix multipliers would enable the present technique, applied to isolated aircraft or missiles[1] and represented effectively by Figs.2 and 3 to be extended without any increase in complexity. For example, the body axes used need not be confined to the principle. The use of any others would merely require the replacement of the zeros in

$$I_B^{-1} \equiv \begin{bmatrix} 1/A & 0 & 0 \\ 0 & 1/B & 0 \\ 0 & 0 & 1/C \end{bmatrix}$$

by terms involving products of inertia. In a similar way cross damping terms such as N_p, etc may be included in K_B if required, viz.

$$\begin{bmatrix} L_p & L_q & L_r \\ M_p & M_q & M_r \\ N_p & N_q & N_r \end{bmatrix} .$$

Possible applications in allied fields include other kinematic simulations such as guidance and homing, wind tunnel corrections in conventional force and moment tests, and theoretical stability computations, and clearly such units would have an application wherever accurate axes transformation is necessary.

7 CONCLUSIONS

1. Free-fall simulation techniques are limited to straight-and-level releases at low speeds because of the constraints introduced by the fixed gravitational acceleration. The technique described here, using a captive model on a suitably motivated support overcomes these limitations and permits simulation of the motion of store and aircraft immediately following release

(i) at transonic and supersonic speeds,

(ii) during aircraft manoeuvres,

(iii) from an asymmetric aerodynamic environment (e.g. under-wing, or skew, storage).

2. The capacity of the present simulator is adequate for some problems, but a full exploitation of the method would require supplementary CORSAIR units.

3. It is suggested that the development of an incremental digital matrix multiplier, preferably with self-orthogonalising properties, to operate with a CORSAIR DDA system would increase considerably the scope of such a system, and would have applications other than that proposed here.

ACKNOWLEDGEMENT

The author is indebted to R.N. Merson of Space Dept for suggesting the notation used herein.

SYMBOLS

a_{ij}, A_{ij}	matrix elements
A, B, C	principle moments of inertia
F	aerodynamic force
F_1, F_2, F_3	contributing terms in F from linear and angular velocities
M	aerodynamic moment
L, M, N	components of M about body axes
M_q etc	$\frac{\partial M}{\partial q}$ etc
p, q, r	components of the angular velocity of a body relative to earth (s^{BE}) resolved about axes in the body
r	ratio model/full scale of physical quantity defined by suffix
s	angular velocity vector
T	transformation matrix
v	translational velocity vector
u, v, w	components of translational velocity of body relative to earth (v^{BE}) resolved along axes in the body
V	velocity along flight path = $(u^2 + v^2 + w^2)^{\frac{1}{2}}$
$\Delta_{1,2}$	flight path deviation angles

SYMBOLS (Continued)

$\theta_{1, 2, 3}$	Euler angles defining store orientation to the wind tunnel
λ	incidence plane angle
σ	incidence angle

Suffixes

B, (B')	components along body axes in store (aircraft)
E	components along earth axes
F, (F')	components along store (aircraft) flight path axes
L	length
S	angular velocity
T	time
V	velocity
V_∞	free stream velocity
δ	store density
ρ	air density
$\bar{\omega}$	reduced frequency

Superscripts

–	normalised with respect to V
'	refers to aircraft
–1	inverse matrix

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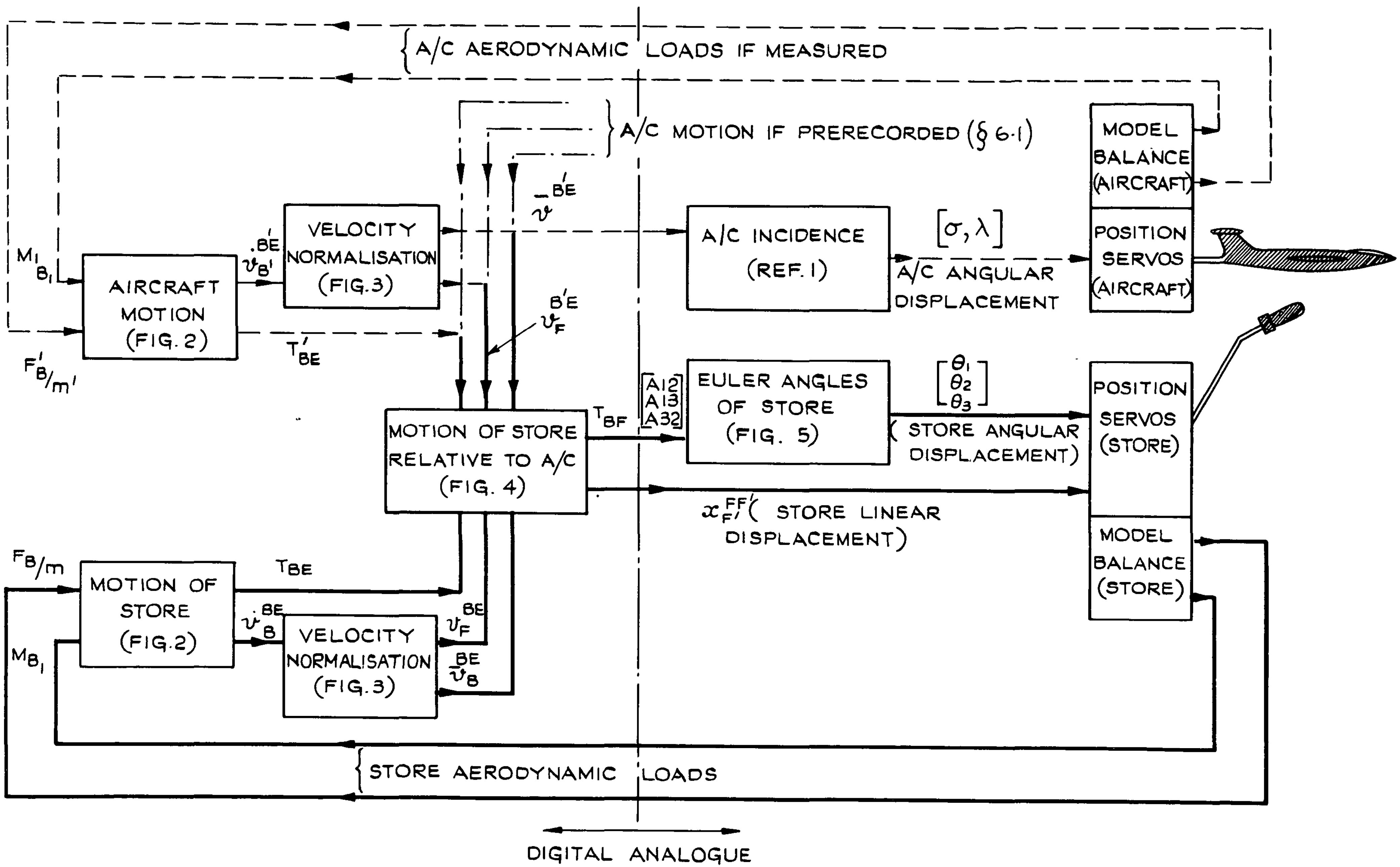

FIG.1 SYSTEM FLOW DIAGRAM

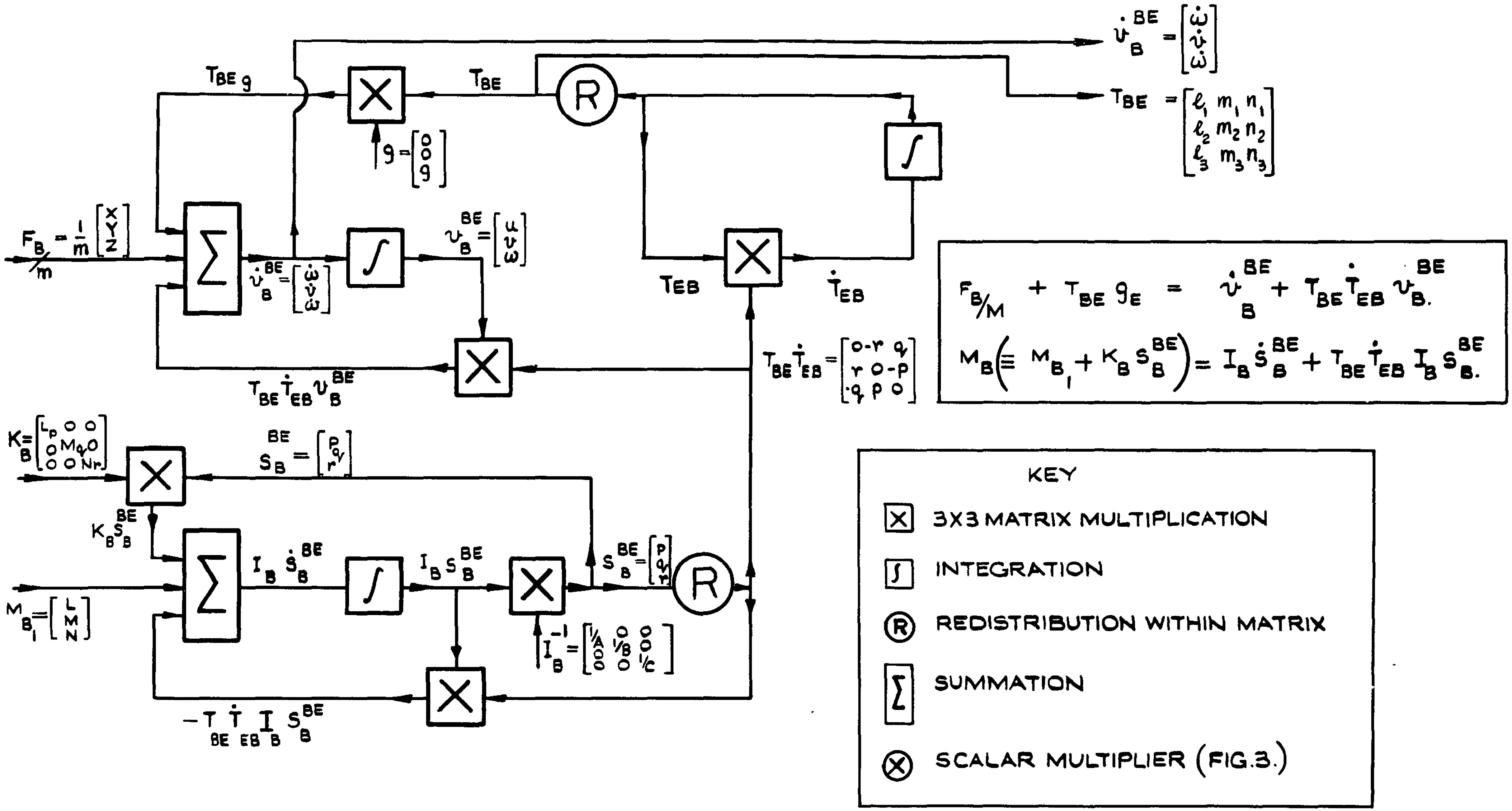

FIG. 2. STORE (OR AIRCRAFT) MOTION RELATIVE TO EARTH.

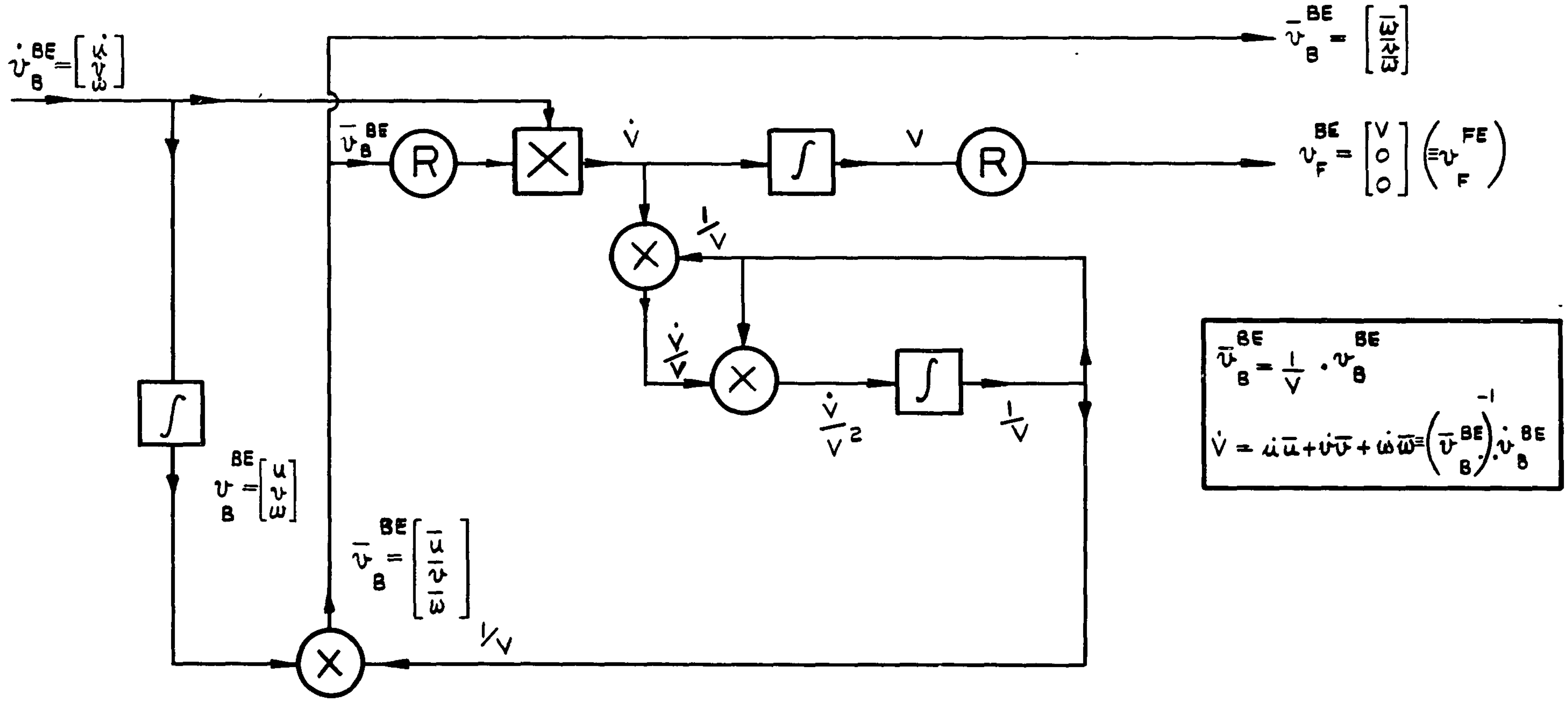

FIG. 3. VELOCITY NORMALISATION.

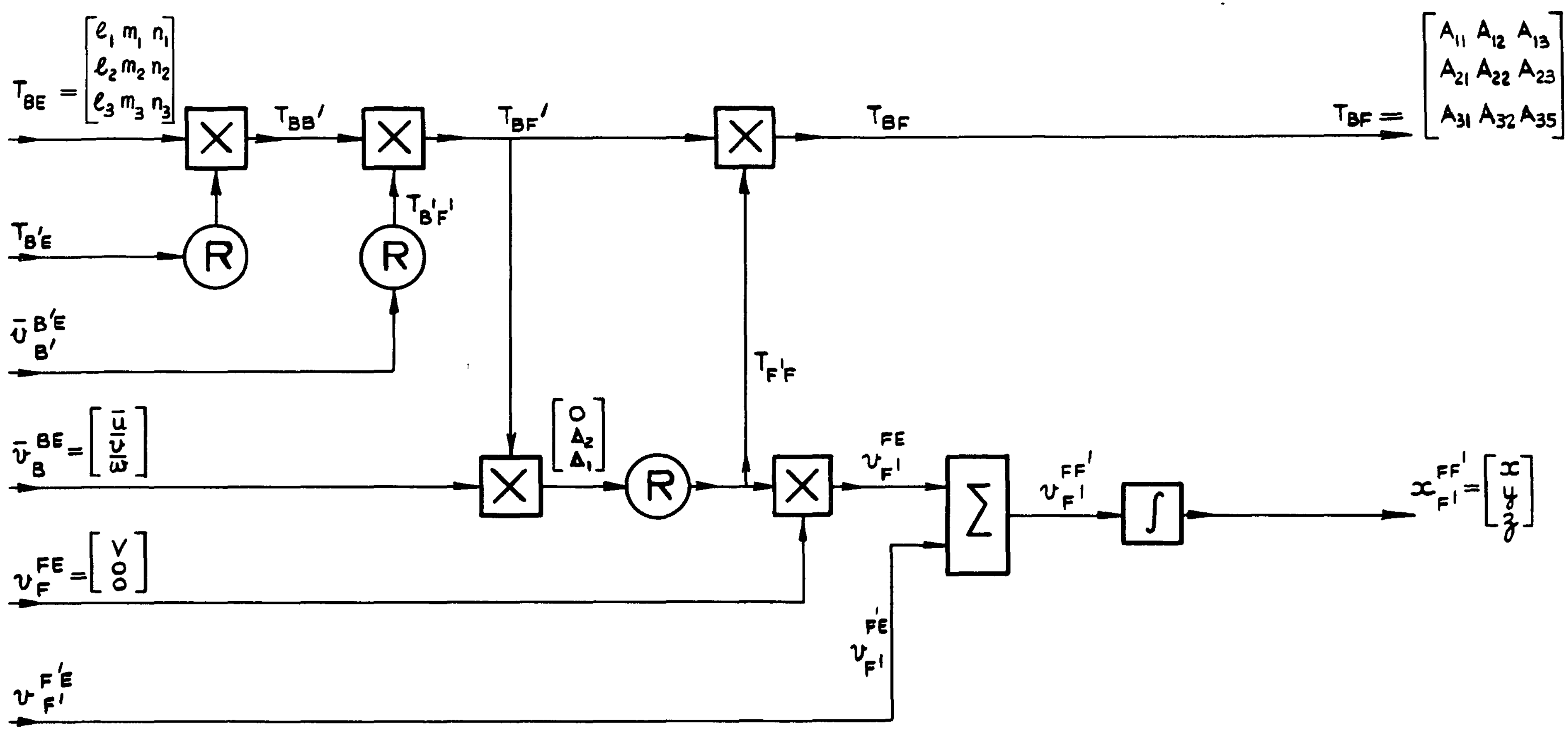

FIG. 4. MOTION OF STORE RELATIVE TO AIRCRAFT FLIGHT PATH.

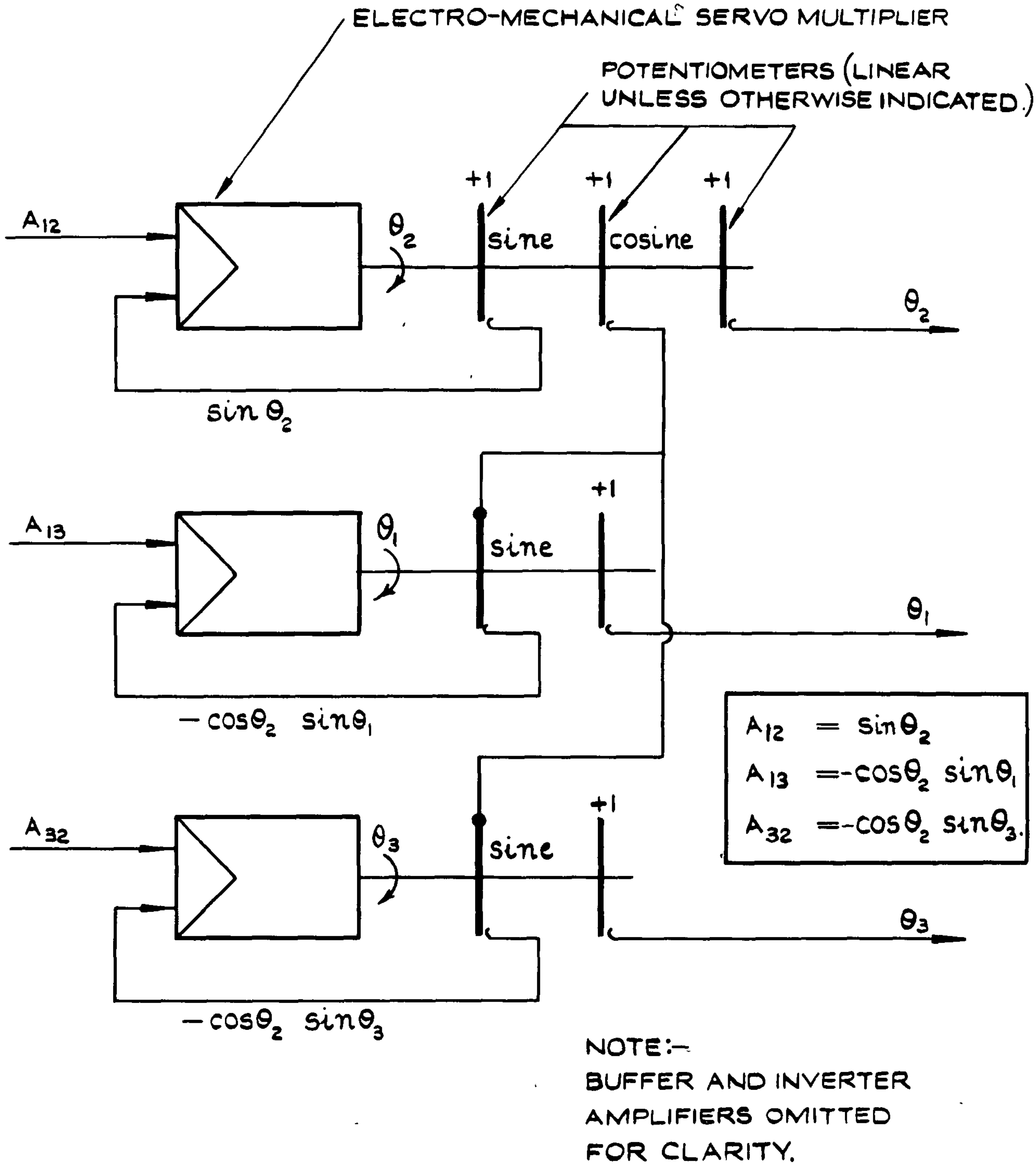

FIG.5. EXTRACTION OF EULER ANGLES DEFINING STORE ORIENTATION TO TUNNEL.

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