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THE GENERATION OF MOTION CUES ON A SIX-DEGREES-OF-FREEDOM MOTION SYSTEM

by

M. Baarspul

DELFT - THE NETHERLANDS

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"Experiencing the motions of a six-degrees-of-freedom motion system is like listening to an orchestra. If you concentrate on one degree of freedom, you only hear the clarinet."

Jaap Veldhuijzen van Zanten
Foreword

The motion simulation described in this report has been performed at the Flight Crew Training Center of KLM, Royal Dutch Airlines at Schiphol Airport in 1975.

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Summary

The mathematical formulation of motion cue generation on a six-degree-of-freedom motion base is described. From the mathematical model of the simulated aircraft, the specific forces and rotational accelerations at the aircraft c.g. are determined as primary control inputs to the motion drive laws. Because the specific forces are acting on the pilot inside the simulator cockpit, they should be transformed to the centroid location of the motion system. As the motion possibilities of the moving platform are constrained, filtering of the specific forces and rotational accelerations is necessary. As far as possible, tilt angles are used to reproduce sustained specific forces, providing the motion system with "co-ordinated washout".

The scaled equations as programmed in the digital computer, including values for the time constants and damping ratio of the motion filters as applied to the KSS B-747 flight simulator, are represented in Appendix A. The listing of the main motion program for the SDS Sigma 2 computer of this flight simulator is represented in Appendix B.
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Appendix A: Scaled equations as used in the KSS B-747 Main Motion Simulation Program (24 pages)

Appendix B: Listing of the "KSS B-747 Main Motion Simulation" Program (48 pages).

4 Tables
4 Figures
Symbols

\( A_{x_b} \)  body-axes longitudinal specific force at aircraft c.g.
\( A_{x_b,c} \)  body-axes longitudinal specific force at centroid location.
\( A_{y_b} \)  body-axes lateral specific force at aircraft c.g.
\( A_{y_b,c} \)  body-axes lateral specific force at centroid location.
\( A_{z_b} \)  body-axes vertical specific force at aircraft c.g.
\( A_{z_b,c} \)  body-axes vertical specific force at centroid location.

\( c.g. \)  center of gravity

\( F_x \)  total force along the X-axis, the subscript indicates the axes-system concerned.
\( F_y \)  total force along the Y-axis, the subscript indicates the axes-system concerned.
\( F_z \)  total force along the Z-axis, the subscript indicates the axes-system concerned.

\( g \)  acceleration due to gravity, \( m/sec^2 \).

\( H(P) \)  transfer function.

\( m \)  aircraft mass.

\( p_b \)  roll-rate in body axes, rad/sec.

\( p_{b,lp} \)  simulator roll-rate in body-axes to simulate lateral specific force, rad/sec.

\( p_{b,hp} \)  simulator roll-rate in body-axes to simulate roll acceleration, rad/sec.

\( p_s = p_{b,lp} + p_{b,hp} \)

\( P \)  Laplace operator.

\( q_b \)  pitch-rate in body-axes, rad/sec.

\( q_{b,hp} \)  simulator pitch-rate in body-axes to simulate pitch acceleration, rad/sec.

\( q_{b,lp} \)  simulator pitch-rate in body-axes to simulate longitudinal specific force, rad/sec.

\( q_s = q_{b,lp} + q_{b,hp} \)
Symbols cont'd

\( r_b \) yaw-rate in body-axes, rad/sec.

\( r_{b, hp} \) simulator yaw-rate in body axes to simulate yaw acceleration, rad/sec.

\( R_x = x_p - x_{p,c} \)

\( R_y = y_p - y_{p,c} \)

\( R_z = z_p - z_{p,c} \)

\( S \) scale factor, the index indicates the variable concerned.

\( u_b \) body-axis longitudinal velocity component, m/sec.

\( v_b \) body-axis lateral velocity component, m/sec.

\( w_b \) body-axis vertical velocity component, m/sec.

\( W \) aircraft weight, kgf.

\( W_{x_b} \) component of the aircraft weight along the \( X_b \)-axis.

\( W_{y_b} \) component of the aircraft weight along the \( Y_b \)-axis.

\( W_{z_b} \) component of the aircraft weight along the \( Z_b \)-axis.

\( x_{b,1} \) longitudinal motion base position to simulate longitudinal specific force.

\( x_{b,2} \) longitudinal motion base position to compensate for longitudinal specific force error.

\( x_c \) lead compensated longitudinal position command input to the motion system.

\( x_m \) inertial longitudinal position command input to the motion system.

\( x_p \) x co-ordinate of pilot's station relative to the aircraft c.g. in body-axes.

\( x_{p,c} \) x co-ordinate of centroid location relative to the pilot's station in body axes.

\( x_s = x_{b,1} + x_{b,2} \)

\( y_{b,1} \) lateral motion base position to simulate lateral specific force.

\( y_{b,2} \) lateral motion base position to compensate for lateral specific force error.
Symbols cont'd

$\gamma_c$ lead compensated lateral position command input to the motion system.
$\gamma_m$ inertial lateral position command input to the motion system.
$\gamma_p$ $y$ co-ordinate of pilot's station relative to the aircraft c.g. in body-axes.
$\gamma_{p,c}$ $y$ co-ordinate of centroid location relative to the pilot's station in body-axes.
$\gamma_s$ $= \gamma_{b,1} + \gamma_{b,2}$
$z_b$ body-axes vertical motion base position.
$z_c$ lead compensated vertical position command input to the motion system.
$z_m$ inertial vertical position command input to the motion system.
$z_p$ $z$ co-ordinate of pilot's station relative to the aircraft c.g. in body-axes.
$z_{p,c}$ $z$ co-ordinate of centroid location relative to the pilot's station in body-axes.
$a_b$ aircraft body angle of attack, rad.
$\beta$ angle of sideslip, rad.
$\theta$ aircraft body pitch attitude, rad.
$\theta_c$ lead compensated pitch-input to the motion system, rad.
$\theta_{h,p}$ body-axes simulator pitch angle, as a consequence of the simulation of pitch acceleration, rad.
$\theta_{\tau,p}$ body-axes simulator pitch angle to simulate longitudinal specific force, rad.
$\theta_m$ inertial pitch-input to the motion system, rad.
$\tau$ time constant, the index indicating the variable concerned.
$\phi$ roll angle, rad.
$\phi_c$ lead compensated roll-input to the motion system, rad.
$\phi_{h,p}$ body-axes simulator roll angle, as a consequence of the simulation of roll acceleration, rad.
$\phi_{\tau,p}$ body-axes simulator roll angle to simulate lateral specific force.
$\phi_m$ inertial roll-input to the motion system, rad.
Symbols cont'd

\( \psi \) yaw angle, rad.

\( \psi_h \) body-axes simulator yaw angle, as a consequence of the simulation of yaw acceleration, rad.

\( \psi_c \) lead compensated yaw-input to the motion system, rad.

\( \psi_m \) inertial yaw-input to the motion system, rad.

\( \zeta \) damping ratio, the index indicating the variable concerned.

Subscripts

b body-axes
c centroid location
h\(_p\) high-pass filtered
i inertial axes
l\(_p\) low-pass filtered
w flightpath - (wind) axes
x along x-axis
y along y-axis
z along z-axis.

A dot over a variable indicates the time derivative of that variable.
Systems of axes

1. The aircraft "body-axes": an aircraft-fixed right-handed reference-frame $O_b X_b Y_b Z_b$. The origin $O_b$ lies in the aircraft's center of gravity, the positive $X_b$-axis lies in the plane of symmetry $O_b X_b Z_b$ and points forward along the fuselage reference-line. The positive $Y_b$-axis is perpendicular to the $O_b X_b Z_b$-plane and points to starboard. The positive $Z_b$-axis is perpendicular to the $O_b X_b Y_b$-plane and points downward.

2. The flightpath-(wind) axes: a right-handed reference-frame $O_w X_w Y_w Z_w$. The origin $O_w$ coincides with the aircraft c.g. The positive $X_w$-axis lies along the velocity-vector of the aircraft c.g. The positive $Y_w$-axis is perpendicular to the $O_w X_w Z_w$-plane and points in the direction of the positive lateral force. The positive $Z_w$-axis is perpendicular to the velocity-vector, opposite to the direction of the lift and lies in the airplane plane of symmetry, see Fig. 3.

3. An earth-fixed reference-frame $O_e X_e Y_e Z_e$. This reference-frame is identical to the $O_b X_b Y_b Z_b$ reference-frame with the exception of the orientation of the origin $O_e$ and the direction of the $X_e$-axis. The origin $O_e$ coincides with the centroid location of the motion system, see Fig. 4.

The $X_e$-axis lies in the plane of symmetry $O_e X_e Z_e$ of the flight simulator and in the horizontal plane.
1. Introduction

The addition of six-degree-of-freedom motion to a flight simulator cockpit provides realism and gives a greater consistency of training results between simulator- and flight training. Ideally, the simulator cockpit would be commanded to move about in accordance with the states that the real aircraft would possess. Generally, it is impossible to do this since the cockpit is mounted in a mechanical structure with limited possibilities of movement. In each degree of freedom the motion system cannot exceed physical limits on position, velocity and/or acceleration. These limits are given in Table 1 for motion in single degree of freedom operation, of the KLM 747 motion base.

Now the following dilemma arises. The pilot manipulates the controls of the simulator. The computer determines the resultant motion of the aircraft being simulated and sets the flight instruments and visual display to show this motion.

The computer also commands the simulator cockpit to move, preferably just as the aircraft would. However, since only limited motion of the cockpit is possible, some modifications of the computed motion is necessary before it can be used to command cockpit motion. Otherwise, the motion system might be driven into its structural limits and hence give totally erroneous motion impressions to the pilot.

The way in which the motion variables of the aircraft must be modified is closely related to the properties of the human vestibular system. The exact quantities "sensed" by a pilot's motion perceptive organisms are not yet completely understood. However, empirical knowledge combined with theoretical and practical considerations leads to the assumption that a pilot can "sense" the same quantities as can be measured by three linear- and three rotational accelerometers mounted along three perpendicular axes, see Refs. 1, 2 and 3.

A linear accelerometer does not measure acceleration but rather the difference between acceleration and gravitation. This difference is called specific force, e.g. in inertial navigation literature, see Ref. 4.

Three linear accelerometers are assumed to be appropriately mounted to measure the specific forces, denoted as \( A_{x_b} \), \( A_{y_b} \) and \( A_{z_b} \) along the aircraft's \( X_b \), \( Y_b \) and \( Z_b \)-axis respectively. The sum of these specific forces is the specific force vector, which is defined here as the positive sum of all non-gravitational forces per unit mass. According to the foregoing a pilot's motion perceptive organisms sense the specific force vector.
Three rotational accelerometers are assumed to be mounted along the aircraft's $X_b$, $Y_b$ and $Z_b$-axis respectively, to measure the rotational accelerations along these axes. For sufficiently small rotations the rotational accelerations can be approximated by $\psi$, $\theta$ and $\phi$ respectively. During the simulation of aircraft motion the three components of specific force $A_X$, $A_Y$ and $A_Z$ and the rotational accelerations $\psi$, $\theta$ and $\phi$ acting on the pilot in the simulator cockpit should as much as possible agree with the magnitudes of the same variables in the aircraft cockpit during flight. As an example, the rolling response of an aircraft and the simulator are compared in a somewhat simplified form in Fig. 1. In the case considered here Fig. 1a shows that the bank angle $\phi$ of the real aircraft increases continuously. In about 1 sec. the aircraft roll rate $\dot{\phi}$ becomes constant, see Fig. 1b. The flight simulator cockpit however can only follow this motion partially, see Fig. 1a and has to return asymptotically to its neutral position, avoiding the generation of a false specific force, see section 9.2.

In spite of the great differences of the bank angle $\phi$ and the roll rate $\dot{\phi}$ between the aircraft and the simulator, Fig. 1c shows that the rotational accelerations agree very well.

The block diagram of Fig. 2 shows in great detail the modification of the specific forces and rotational accelerations of the simulated aircraft necessary to drive the motion system of the flight simulator.

In the subsequent Sections the motion drive signals for each degree of freedom of the motion system will be described. The motion limitations and restrictions mentioned in Table 1 are a major factor in the task suitability of the particular motion base as well as in the selection of the parameters in the motion simulation program, as further described in Appendix A.

The majority of the report is devoted to the mathematical formulation of motion generation, which aside from the physical characteristics of the hardware, see Ref. 5, is the major factor affecting the quality of a motion simulation.

2. General survey of the motion simulation concept

The emphasized parts of the motion simulation are illustrated in detailed form in Fig. 2. Frequent reference to Fig. 2 will be necessary in as much as the description of the motion cue generation consists of a block-by-block discussion.
From the equations of motion, describing the aircraft dynamics in flight and on the ground, the three total forces \( F_x \), \( F_y \) and \( F_z \) and the three rotational accelerations \( \dot{\theta}_b \), \( \dot{\phi}_b \) and \( \dot{\psi}_b \) are determined as primary control inputs of the motion drive laws. For the calculation of the body-axes specific forces, the total forces are required in body-axes. In the off-ground condition however, the total forces in the KSS B-747 flight simulation program are computed in flightpath- (wind) axes. They are transformed to body-axes before being used to compute the body-axes specific forces at the c.g. of the simulated aircraft, see Fig. 2, block 3.

The centroid transformation converts the specific forces at the aircraft c.g. into specific forces, which, when applied at the centroid of the motion system, see Fig. 4, would produce the actual specific forces at the pilot's seat of the aircraft or the pilot inside the simulator cockpit. As the motion possibilities of the base are constrained, filtering of the specific forces at centroid location and the rotational accelerations is necessary. Sustained longitudinal and lateral specific forces can only be represented on a motion simulator by tilting the cockpit and utilizing the gravity-vector to generate the cue. However, the tilt angle must be obtained without pilot knowledge. Therefore the rotational acceleration of the cab, necessary to obtain the tilt angle should be below the threshold level of the pilot's perception. The initial part of the specific force, the onset, can only be generated by translational motion until the tilt angle is obtained. In this way translational and rotational motion of the flight simulator cockpit are co-ordinated to generate longitudinal and lateral specific forces.

In the case of the simulation of a rotational acceleration about the longitudinal or lateral axis by means of rotation alone, a false specific force may be obtained because of temporary misalignment of the gravity-vector relative to the simulator cockpit. Translational motion of the base is required to compensate for this specific force error. This has been indicated in Fig. 2, see the boxes labeled "specific force error". The motion system operates in an earth-fixed, or inertial reference frame, so the filtered specific forces and rotational rates are transformed to inertial axes thereafter a second attenuation is applied.

Lead compensation of the six position and attitude command signals to the motion system is required to compensate for motion system lag. The actuator extension transformation transforms the six compensated position commands into the length of the servo-actuators of the motion system, see Fig. 2, block 13.
3. Flightpath to body-axes transformation of the total forces \( F_x, F_y \) and \( F_z \).

For the calculation of the body-axes specific forces from the total forces \( F_x, F_y \) and \( F_z \), see Fig. 2, the total forces are required in body-axes. However, in the off-ground condition, the total forces are computed in flightpath-(wind) axes. Therefore, in the off-ground condition, the total forces \( F_x, F_y \) and \( F_z \) have to be transformed to body-axes, see Fig. 3.

The transformation equations read:

\[
\begin{align*}
F_x &= + \cos \alpha_b \cdot \cos \beta \cdot F_x - \cos \alpha_b \cdot \sin \beta \cdot F_y - \sin \alpha_b \cdot F_z \\
F_y &= + \sin \beta \cdot F_x + \cos \beta \cdot F_y \\
F_z &= + \sin \alpha_b \cdot \cos \beta \cdot F_x - \sin \alpha_b \cdot \sin \beta \cdot F_y + \cos \alpha_b \cdot F_z \\
\end{align*}
\]

(3.1.)

where: \( \alpha_b \) is the aircraft body angle of attack and \( \beta \) is the side-slip angle.

When the aircraft is on the ground, the total forces \( F_x, F_y \) and \( F_z \) are computed in body-axes. As a consequence in the on-ground condition, transformation (3.1.) is not required, see Fig. 2, blocks 1, 2 and 3.

4. Calculation of the body-axes specific forces \( A_x, A_y \) and \( A_z \).

For the total forces \( F_x, F_y \) and \( F_z \) in body-axes can be written, see Ref. 6:

\[
\begin{align*}
F_x &= m \left( \dot{\alpha}_b - q_b \cdot v_b \right) \\
F_y &= m \left( \dot{v}_b + r_b \cdot u_b - p_b \cdot w_b \right) \\
F_z &= m \left( \dot{w}_b - q_b \cdot u_b + p_b \cdot v_b \right) \\
\end{align*}
\]

(4.1.)

where: \( m = \frac{W}{g} \) is the aircraft mass.

\( \dot{\alpha}_b \) is the aircraft body-axes longitudinal acceleration, denoted as \( V' \) in Ref. 6.

\( u_b \) is the body-axes longitudinal velocity component, denoted as \( V' \) in Ref. 6.

\( v_b \) is the aircraft body-axes lateral acceleration, denoted as \( V' \) in Ref. 6.

\( w_b \) is the body-axes lateral velocity component, denoted as \( V' \) in Ref. 6.

\( \dot{w}_b \) is the aircraft body-axes vertical acceleration, denoted as \( V' \) in Ref. 6.

\( w_b \) is the body-axes vertical velocity component, denoted as \( V' \) in Ref. 6.

2) In Ref. 6 the term \( q_b \cdot w_b \) in the equation for \( F_x \) is neglected, because its magnitude is small.
From the total forces, the specific forces in body-axes can be easily derived by subtraction of the component of the aircraft weight and deviding the result by the aircraft mass, see Fig. 2, block 4:

\[ A_x = (F_x - W_x) \cdot g/W \]

where: \( W_x \cdot g/W = -g \cdot \sin \theta \)

\[ A_y = (F_y - W_y) \cdot g/W \]

where: \( W_y \cdot g/W = +g \cdot \cos \theta \cdot \sin \phi \) \hspace{1cm} (4.2)

\[ A_z = (F_z - W_z) \cdot g/W \]

where: \( W_z \cdot g/W = +g \cdot \cos \theta \cdot \cos \phi \)

According to (4.1.):

\[ F_x \cdot g/W = \alpha_b - r_b \cdot v_b \]

\[ F_y \cdot g/W = \dot{v}_y + r_b \cdot u_b + p_b \cdot w_b \]

\[ F_z \cdot g/W = \dot{w}_z - q_b \cdot u_b + p_b \cdot v_b \] \hspace{1cm} (4.3)

Combination of (4.2.) and (4.3.) results in the specific forces in body-axes at the c.g. of the simulated aircraft:

\[ A_x = \dot{u}_b - r_b \cdot v_b + g \cdot \sin \theta \]

\[ A_y = \dot{v}_b + r_b \cdot u_b + p_b \cdot w_b - g \cdot \cos \theta \cdot \sin \phi \] \hspace{1cm} (4.4)

\[ A_z = \dot{w}_b - q_b \cdot u_b + p_b \cdot v_b + g \cdot \cos \theta \cdot \cos \phi \]

5. **Centroid transformation of \( A_{xb}, A_{yb} \) and \( A_{zb} \).**

The purpose of the centroid transformation is to provide the motion filters with the unconstrained motions of the base that would be necessary to produce all the cues to which a pilot would be subjected at the pilot's station, see Fig. 2 block 5. Thus it is necessary to locate hypothetically the centroid of the motion base, see Fig. 4, in the simulated aircraft with respect to the pilot's station, and then transform the motion, derived for the center of gravity of the simulated aircraft, to this hypothetical location. This location with respect to the aircraft c.g. is defined as:

\[ R_x = x_p - x_{p,c} \]

\[ R_y = y_p - y_{p,c} \]

\[ R_z = z_p - z_{p,c} \]
where \( x_p, y_p \) and \( z_p \) locate the pilot's station with respect to the aircraft c.g., and \( x_{p,c}, y_{p,c} \) and \( z_{p,c} \) locate the centroid with respect to the pilot's station.

Now the specific forces \( A_{x_b}, A_{y_b}, \) and \( A_{z_b} \) (4.4.) can be computed at centroid location:

\[
\begin{align*}
A_{x_b,c} &= A_{x_b} - (q_b^2 + r_b^2) \cdot R_x + (q_b \cdot p_b - t_b) \cdot R_y + (r_b \cdot p_b + t_b) \cdot R_z \\
A_{y_b,c} &= A_{y_b} + (p_b \cdot q_b + t_b) \cdot R_x - (p_b^2 + r_b^2) \cdot R_y + (r_b \cdot q_b - t_b) \cdot R_z \\
A_{z_b,c} &= A_{z_b} + (p_b \cdot r_b - t_b) \cdot R_x + (q_b \cdot r_b + t_b) \cdot R_y - (p_b^2 + q_b^2) \cdot R_z
\end{align*}
\]

For the KSS B-747 flight simulator:

\[
\begin{align*}
y_p &= y_{p,c}, \text{ therefore: } R_y = 0 \\
z_p &= z_{p,c}, \text{ therefore: } R_z = 0
\end{align*}
\]

Introducing these simplifications and substitution of (4.4.) for \( A_{x_b}, A_{y_b} \) and \( A_{z_b} \) results in:

\[
\begin{align*}
A_{x_b,c} &= \dot{u}_b - r_b \cdot v_b + g \cdot \sin \theta - (q_b^2 + r_b^2) \cdot R_x \\
A_{y_b,c} &= \dot{v}_b + r_b \cdot u_b - p_b \cdot \omega_b - g \cdot \cos \theta \cdot \sin \phi + (p_b \cdot q_b + t_b) \cdot R_x \\
A_{z_b,c} &= \dot{w}_b - q_b \cdot u_b + p_b \cdot v_b - g \cdot \cos \theta \cdot \cos \phi + (p_b \cdot r_b - t_b) \cdot R_x
\end{align*}
\]

Now the following notations are introduced:

\[
\begin{align*}
\dot{u}_b,c &= \dot{u}_b - r_b \cdot v_b - (q_b^2 + r_b^2) \cdot R_x \\
\dot{v}_b,c &= \dot{v}_b + r_b \cdot u_b - p_b \cdot \omega_b + (p_b \cdot q_b + t_b) \cdot R_x \\
\dot{w}_b,c &= \dot{w}_b - q_b \cdot u_b + p_b \cdot v_b + (p_b \cdot r_b - t_b) \cdot R_x
\end{align*}
\]

Substituting \( \dot{u}_b,c, \dot{v}_b,c, \) and \( \dot{w}_b,c \) in the expressions (5.1.) results in the specific forces at the centroid location in the simulated aircraft:

\[
\begin{align*}
A_{x_b,c} &= \dot{u}_b,c + g \cdot \sin \theta & (5.2.) \\
A_{y_b,c} &= \dot{v}_b,c - g \cdot \cos \theta \cdot \sin \phi & (5.3.) \\
A_{z_b,c} &= \dot{w}_b,c - g \cdot \cos \theta \cdot \cos \phi & (5.4.)
\end{align*}
\]
6. **Motion filters for the translational degrees of freedom**

6.1. **Longitudinal motion**

The simulation of longitudinal specific forces is performed by means of the coordinated longitudinal and pitch motion of the simulator cockpit. The longitudinal motion is used to reproduce the high-frequency onset cue of the longitudinal specific force until the pitch motion has had time to align the simulator cockpit relative to the gravity vector to present the sustained, or low frequency portion of the longitudinal specific force.

High-pass filtering of $A_{X_b,c}$ removes the low-frequency portion of the longitudinal specific force, likely to exceed the motion platform position limits in X-direction, see Fig. 2, block 6.1.

The longitudinal specific force at the centroid position inside the simulator cockpit can be written as:

$$ (A_{X_b,c})_{sim} = A_{X_b,c} + g \cdot \theta_{1p} $$

where $A_{X_b,c}$ is the high-frequency portion of the longitudinal specific force, reproduced by means of the simulator longitudinal translational motion and $\theta_{1p}$ is the simulator pitch angle needed to reproduce sustained longitudinal specific force, see Section 9.1.

Combining the two expressions for the longitudinal specific force at the centroid location, (5.2) and (6.1), gives:

$$ A_{X_b,c} = \dot{u}_{b,c} + g \cdot \sin \theta - g \cdot \theta_{1p} $$

The low frequency gravity component $g \cdot \sin \theta$ of $A_{X_b,c}$ will be simulated separately by means of $\theta_{1p}$, as discussed in section 9.1.

So, for the simulator, the high-frequency longitudinal specific force becomes:

$$ A_{X_b,c} = \dot{u}_{b,c} - g \cdot \theta_{1p} $$

The transfer function of the applied high-pass second order filter reads:

$$ \frac{\ddot{x}_{b,1}(P)}{(\dot{u}_{b,c} - g \cdot \theta_{1p})(P)} = H(P) = \frac{\tau_x^2 \cdot P^2}{1 + 2 \cdot \tau_x \cdot \zeta_x \cdot P + \tau_x^2 \cdot P^2} $$

Substituting (6.2) and applying the inverse Laplace transform results in:

$$ x_{b,1} + 2 \tau_x \zeta_x \ddot{x}_{b,1} + \tau_x^2 x_{b,1} - \tau_x^2 (\dot{u}_{b,c} - g \cdot \theta_{1p}) = 0 $$

$x)$ **Note:** In order to stay with the existing notation of the KSS B-747 motion simulation program, time constants $\tau$ (sec) have been used, rather than the more usual natural frequencies $\omega_0$ (sec$^{-1}$), where $\tau = \frac{1}{\omega_0}$. 
The resulting longitudinal acceleration of the motion base now can be written as:
\[ \ddot{x}_{b,1} = \dot{\omega}_{b,c} - \mathbf{U}_p \cdot g \cdot \theta_1 \cdot \tau_x^{-1} \cdot \ddot{x}_{b,1} - \frac{2\tau_x}{\tau_x} \cdot \frac{1}{\tau_x} \cdot \ddot{x}_{b,1} \]  
(6.3.)

If the computer sample time for the sequential calculations is 50 msec (20 times/sec) rectangular integration of \( \ddot{x}_{b,1} \) gives at time \( t_n \):
\[ \ddot{x}_{b,1,n} = \ddot{x}_{b,1,n-1} + 0.05 \cdot \ddot{x}_{b,1,n-1} \]
\[ x_{b,1,n} = x_{b,1,n-1} + 0.05 \cdot \ddot{x}_{b,1,n} \]

The correction for specific force error as a consequence of the simulation of aircraft pitch acceleration, see section 9.1., reads:
\[ \ddot{x}_{b,2} = -g \cdot \theta_2 \]

where \( \theta_2 \) is the simulator pitch angle resulting as a consequence of the simulation of pitch acceleration, see Fig. 2, block 9.1.2.

The resulting body-axes longitudinal translational acceleration of the motion base now becomes:
\[ \ddot{x}_s = \ddot{x}_{b,1} + \ddot{x}_{b,2} \]  
(6.4.)

6.2. Lateral motion

The simulation of lateral specific forces is performed in a way similar to the longitudinal case by means of the co-ordinated lateral and roll motions of the motion base, see Fig. 2, block 6.2.

The lateral specific force at the centroid location inside the simulator cockpit is:
\[ (\text{A}_{y_{b,1,c}})_{\text{sim}} = \text{A}_{y_{b,1,c}} - g \cdot \phi_1 \]  
(6.5.)

where \( \text{A}_{y_{b,1,c}} \) is the high-frequency part of the lateral specific force, reproduced by the simulator lateral translational motion and \( \phi_1 \) is the simulator roll angle needed to reproduce sustained lateral specific force, see section 9.2.

Equating the lateral specific force at centroid location (5.3.) and (6.5.) gives:
\[ \text{A}_{y_{b,1,c}} = \dot{y}_{b,c} - g \cdot \cos \theta \cdot \sin \phi + g \cdot \phi_1 \]  
(6.6.)

The transfer function of the applied high-pass second order filter reads:
\[ \frac{\dot{y}_{b,1}(p)}{(\dot{y}_{b,c} - g \cdot \cos \theta \cdot \sin \phi + g \cdot \phi_1)(p)} = H(p) = \frac{\tau_y^2 \cdot p^2}{1 + 2 \tau_y \tau_y \cdot p + \tau_y^2 \cdot p^2} \]

x) See note on page 7.
Substituting (6.6.) and applying the inverse Laplace transform results in:
\[ y_{b,1} + 2 \tau_y \dot{y}_{b,1} + \tau_y^2 \dot{y}_{b,1} - \tau_y^2 (\dot{y}_{b,1} - g \cdot \cos \phi + g \cdot \phi_{\theta}) = 0 \]

The resulting lateral acceleration of the motion base now can be written as:
\[ \ddot{y}_{b,1} = \dot{y}_{b,1} - g \cdot \cos \phi + g \cdot \phi_{\theta} - \frac{2 \tau_y}{\tau_y} \dot{y}_{b,1} - \frac{1}{\tau_y} y_{b,1} \]  
(6.7.)

Rectangular integration at a rate of 20 times/sec results at time \( t_n \):
\[ \dot{y}_{b,1}^{(n)} = \dot{y}_{b,1}^{(n-1)} + 0.05 \dot{y}_{b,1}^{(n-1)} \]
\[ y_{b,1}^{(n)} = y_{b,1}^{(n-1)} + 0.05 \dot{y}_{b,1}^{(n)} \]

The correction for specific force error as a consequence of the simulation of aircraft roll acceleration, see section 9.2., reads:
\[ \ddot{y}_{b,2} = \phi_{h_p} \]

where \( \phi_{h_p} \) is the simulator roll angle resulting as a consequence of the simulation of roll acceleration, see Fig. 2, block 9.2.2.

The total body-axes lateral translational acceleration of the motion base now becomes:
\[ \ddot{y}_S = \ddot{y}_{b,1} + \ddot{y}_{b,2} \]  
(6.8.)

6.3. Heave motion
The simulation of vertical specific forces is, because of the restricted stroke of the servo-actuators, see Table 1, only possible in a very limited way. No tilt angle is available to reproduce the low-frequency part of the vertical specific force and thus the low-frequency part cannot be simulated. This results in the limitation of simulating only relatively small normal accelerations during a short time. Specific forces or normal accelerations as a result of atmospheric turbulence or touch down can therefore be simulated very well, but the longer lasting specific forces occurring in a steep turn or during a pull up from a dive can only be simulated approximately. That is why also in this degree of freedom a high-pass filter is applied, see Fig. 2, block 6.3., to suppress the low frequency changes of the vertical specific force.

The vertical specific force at the centroid location inside the simulator cockpit is:
\[ (A_{z_b,c})_{sim} = \ddot{z}_b - g \]  
(6.9.)
Combining the two expressions for the vertical specific force at the centroid location, (5.4.) and (6.9.), gives:
\[ \ddot{z}_{b,c} - g \cdot \cos \theta \cdot \cos \phi = \dot{z}_b^x - g \]
(6.10.)

where \( \dot{z}_b^x \) is the not yet filtered vertical acceleration of the simulator cockpit in body-axes.

The transfer function of the applied high-pass filter reads:
\[ H(P) = \frac{\dot{z}_b^x(P)}{\ddot{z}_b^x(P)} = \frac{\tau_{z}^2 \cdot P^2}{1 + 2 \tau_z \cdot P + \tau_{z}^2 \cdot P^2} \]

Substituting (6.10.) for \( \dot{z}_b^x \) and applying the inverse Laplace transform results in:
\[ z_b + 2 \tau_z \cdot \dot{z}_b = \tau_z^2 \cdot \ddot{z}_b - \tau_z^2 \cdot \ddot{z}_{b,c} - \tau_z^2 \cdot g(1 - \cos \theta \cdot \cos \phi) = 0 \]

The term \( \tau_z^2 \cdot g(1 - \cos \theta \cdot \cos \phi) \) in this equation will be neglected, because of its low magnitude and its relatively low frequency.
The resulting vertical acceleration of the simulator cockpit can now be written as:
\[ \ddot{z}_b = \ddot{z}_{b,c} - \dot{z}_b \cdot \frac{1}{\tau_z^2} \cdot z_b \]
(6.11.)

Rectangular integration of \( \ddot{z}_b \) at a rate of 20 times/sec gives at time \( t_n \):
\[ \dot{z}_{b,n} = \dot{z}_{b,n-1} + 0.05 \ddot{z}_{b,n-1} \]
\[ z_{b,n} = z_{b,n-1} + 0.05 \dot{z}_{b,n-1} \]

7. Body to inertial transformation of the motion platform translational accelerations.

The translational degrees of freedom of the motion base operate in an earth-fixed inertial reference frame. Therefore the body-axes translational accelerations \( \ddot{x}_b \) (6.4.), \( \ddot{y}_b \) (6.8.) and \( \ddot{z}_b \) (6.11.) are transformed to inertial co-ordinates.

According to Table 14 of Ref. 7, for the inertial translational accelerations can be written successively:

\[ \ddot{x}_i = \cos \theta_m \cdot \cos \psi_m \cdot \ddot{x}_s + (\sin \phi_m \cdot \sin \theta_m \cdot \cos \psi_m - \cos \phi_m \cdot \sin \psi_m) \cdot \ddot{y}_s \]
\[ + (\cos \phi_m \cdot \sin \theta_m \cdot \cos \psi_m + \sin \phi_m \cdot \sin \psi_m) \cdot \ddot{z}_b \]
(7.1.)

\[ \ddot{y}_i = \cos \theta_m \cdot \sin \psi_m \cdot \ddot{x}_s + (\sin \phi_m \cdot \sin \theta_m \cdot \sin \psi_m + \cos \phi_m \cdot \cos \psi_m) \cdot \ddot{y}_s \]
\[ + (\cos \phi_m \cdot \sin \theta_m \cdot \sin \psi_m - \sin \phi_m \cdot \cos \psi_m) \cdot \ddot{z}_b \]
(7.2.)

* See note on page 7.
\[
\ddot{x}_i = -\sin \theta_m \cdot \dot{x}_s + \sin \phi_m \cdot \cos \theta_m \cdot \dot{y}_s + \cos \phi_m \cdot \cos \theta_m \cdot \dot{z}_b \tag{7.3}
\]

where \(\psi_m, \theta_m\) and \(\phi_m\) are the simulator yaw, pitch and roll angles respectively, see Section 11.

8. Translational wash-out.

To prevent the motion platform from running into its limits, translational wash-out is carried out on the inertial accelerations \(\ddot{x}_i, \ddot{y}_i\) and \(\ddot{z}_i\) by means of second-order high-pass filters of the form:

\[
\dot{x}_m = \ddot{x}_i - \frac{2\tau_{X}}{\tau_{X}^2 + 1} \cdot x_m
\]

\[
\dot{y}_m = \ddot{y}_i - \frac{2\tau_{Y}}{\tau_{Y}^2 + 1} \cdot y_m
\]

\[
\dot{z}_m = \ddot{z}_i - \frac{2\tau_{Z}}{\tau_{Z}^2 + 1} \cdot z_m
\]

The inertial motion platform positions \(x_m, y_m\) and \(z_m\), not yet compensated for the motion system's dynamic lag, see section 12, and velocities \(\dot{x}_m, \dot{y}_m\) and \(\dot{z}_m\) are obtained by rectangular integration of \(\ddot{x}_m, \ddot{y}_m\) and \(\ddot{z}_m\) respectively at a rate of 20 times/sec.

9. Motion filters for the rotational degrees of freedom.

9.1. Pitch motion

The pitch motion of the flight simulator is used for the simulation of the sustained portion of the longitudinal specific force, see Section 6.1., and for the simulation of aircraft pitch acceleration, see Fig. 2, blocks 9.1.1. and 9.1.2.

The sustained portion of the longitudinal specific force \(A_{x_{b,c}}\) is created in the simulator by means of a component of gravity:

\[
A_{x_{b,c}} = g \cdot \sin \theta_p \tag{9.1}
\]

The generation of the simulator pitch angle \(\theta_p\) necessary for this purpose is inevitably associated with pitch acceleration. As the pilot should not notice this acceleration, it should be kept below the threshold level of the pilot's perception. That is why a low-pass filter is used in the computation of \(\theta_p\), see Fig. 2, block 9.1.1.

The computation of \(\theta_p\) occurs in the following way.
Equating the longitudinal specific force at the centroid location (5.2.) and the longitudinal specific force at the centroid position inside the simulator cockpit (9.1.) gives:

\[ \theta_{b,c} + g \cdot \sin \theta = g \cdot \sin \theta_{1p} \]

where \( \theta_{1p} \) is the not yet filtered pitch angle of the simulator cockpit to simulate the sustained portion of longitudinal specific forces.

As the longitudinal specific force acting inside a B-747 cockpit is normally less than 0.3g, resulting in \( \theta_{1p} < 16^\circ \), \( \theta_{1p} \) is approximated by \( \theta_{p} \):

\[ \sin \theta_{1p} = \theta_{p} \]

For \( \theta_{1p} \) now can be written:

\[ \theta_{1p} = \frac{\ddot{\theta}_{b,c}}{g} + \sin \theta \]  \hspace{1cm} (9.2.)

\( \theta_{1p} \) is fed through a low-pass filter, see Fig. 2, block 9.1.1., the transfer function of which reads:

\[ H(P) = \frac{\theta_{1p}(P)}{\theta_{1p}(P)} = \frac{1}{1 + 2 \cdot \tau_{\theta_{1p}} \cdot \tau_{\theta_{1p}} \cdot P + \tau_{\theta_{1p}}^2 \cdot P^2} \]

Substituting (9.2.) for \( \theta_{1p} \) and applying the inverse Laplace transform gives:

\[ \theta_{1p} + 2 \tau_{\theta_{1p}} \cdot \tau_{\theta_{1p}} \cdot q_{b,1p} + \tau_{\theta_{1p}}^2 \cdot \theta_{1p} - \frac{\ddot{\theta}_{b,c}}{g} \cdot \sin \theta = 0 \]

The resulting pitch acceleration reads:

\[ \ddot{\theta}_{b,1p} = \frac{\ddot{\theta}_{b,c}}{g} + \sin \theta \cdot \frac{2 \tau_{\theta_{1p}}}{\tau_{\theta_{1p}}^2 + g \cdot \tau_{\theta_{1p}}^2} \cdot q_{b,1p} \cdot \frac{1}{\tau_{\theta_{1p}}} \cdot \frac{1}{\tau_{\theta_{1p}}} \cdot \theta_{1p} \]  \hspace{1cm} (9.3.)

Rectangular integration at a rate of 20 times/sec gives at time \( t_n \):

\[ q_{b,1p} = q_{b,1p_{n-1}} + 0.05 \cdot \dot{\theta}_{b,1p_{n-1}} \]

\[ \theta_{1p} = \theta_{1p_{n-1}} + 0.05 \cdot \dot{\theta}_{b,1p_{n-1}} \]  \hspace{1cm} (9.4.)

* See note on page 7.
The simulation of the aircraft pitch acceleration \( \dot{\theta}_b \) on the simulator gives also rise to a simulator pitch angle \( \dot{\theta}_{hp} \).

According to the foregoing, \( \dot{\theta}_{hp} \), is sensed by the pilot as an erroneous specific force. Therefore, the pitch angle \( \dot{\theta}_{hp} \) of the simulator as a result of the simulation of the pitch acceleration \( \dot{\theta}_b \) should remain as small as possible. This can be achieved by applying a high-pass filter in the computation of the pitch acceleration \( \dot{\theta}_{hp} \) of the simulator.

The computation of the simulator pitch angle \( \dot{\theta}_{hp} \) for the simulation of pitch acceleration occurs in the following way. The transfer function of the applied high-pass second order filter reads:

\[
\dot{\theta}_{hp}(P) = \frac{\tau^2 \dot{\theta}_{hp}}{1 + 2\tau \dot{\theta}_{hp} \cdot \tau \dot{\theta}_{hp} \cdot P + \tau^2 \dot{\theta}_{hp} \cdot P^2}
\]

Applying the inverse Laplace transform results in:

\[
\dot{\theta}_{hp} + 2\tau \dot{\theta}_{hp} \cdot \tau \dot{\theta}_{hp} \cdot \dot{\theta}_{b, hp} + \tau^2 \dot{\theta}_{hp} \cdot \dot{\theta}_{b, hp} - \tau^2 \dot{\theta}_{hp} \cdot \dot{\theta}_b = 0
\]

The simulator pitch acceleration now can be written as:

\[
\dot{\theta}_{b, hp} = \dot{\theta}_b - \frac{2\tau \dot{\theta}_{hp}}{\tau \dot{\theta}_{hp}} \cdot \dot{\theta}_{b, hp} - \frac{1}{\tau^2 \dot{\theta}_{hp}} \cdot \dot{\theta}_b
\]

Rectangular integration at a rate of 20 times/sec gives at time \( t_n \):

\[
\begin{align*}
\dot{\theta}_{b, hp} &= \dot{\theta}_{b, hp}^{n-1} + 0.05 \cdot \dot{\theta}_{b, hp}^{n-1} \\
\dot{\theta}_h^{n} &= \dot{\theta}_h^{n-1} + 0.05 \cdot \dot{\theta}_h^{n-1}
\end{align*}
\]

The flight simulator pitch angle \( \theta_{hp} \) as a consequence of the simulation of pitch acceleration \( \dot{\theta}_b \) results in a specific force error:

\( (A_{\dot{x}_{b,c}})_{\text{error}} = -g \cdot \dot{\theta}_{hp} \)

This longitudinal specific force error can be compensated by means of the longitudinal translational motion of the base:

\( \dot{\dot{x}}_{b,z} = -g \cdot \dot{\theta}_{hp} \), see Section 6.1.

\( x \) See note on page 7.
The total body-axes pitch acceleration, used for lead-compensation of the motion system, see section 12, reads:
\[ \ddot{q}_s = \ddot{q}_{b,1_p} + \ddot{q}_{b,2_p} \]  \hspace{1cm} (9.5.)

The total body-axes pitch rate, to be transformed into inertial axes, see section 10, reads:
\[ \dot{q}_s = \dot{q}_{b,1_p} + \dot{q}_{b,2_p} \]  \hspace{1cm} (9.6.)

9.2. Roll motion

The roll motion of the flight simulator is used for the simulation of the sustained portion of the lateral specific force, see Section 6.2. and for the simulation of aircraft roll acceleration, see Fig. 2, blocks 9.2.1. and 9.2.2. respectively.

The simulation of the lateral specific force \( A_{y_{b,c}} \) occurs in just the same manner as the simulation of the longitudinal specific force \( A_{x_{b,c}} \), described in the previous section:
\[ A_{y_{b,c}} = -g \cdot \sin \phi_{1_p} \]  \hspace{1cm} (9.7.)

where \( g \cdot \sin \phi_{1_p} \) is the lateral component of gravity inside the simulator cockpit. Note, that for the simulation of a positive lateral specific force \( \phi_{1_p} \) is negative.

Equating the lateral specific force at the centroid location (5.3.) and the lateral specific force at the centroid position inside the simulator cockpit (9.7.) results in:
\[ \dot{v}_{b,c} - g \cdot \cos \theta \cdot \sin \phi = -g \cdot \sin \phi_{1_p} \]

where \( \phi_{1_p} \) is the not yet filtered roll angle of the simulator to generate lateral specific forces.

Also here the approximation is made:
\[ \sin \phi_{1_p} \approx \phi_{1_p} \]

as \( A_{y_{b,c}} \) normally < 0.3g.

For \( \phi_{1_p} \) now can be written:
\[ \phi_{1_p} = -\frac{\dot{v}_{b,c}}{g} + \cos \theta \cdot \sin \phi \]  \hspace{1cm} (9.8.)

\( x) \) See note on page 7.
\( \phi_p \) is fed through a low-pass filter to keep the roll acceleration of the cab below the threshold level of the pilot's perception. The transfer function of this filter reads:

\[
\frac{\phi_p(P)}{\psi_p(P)} = \frac{1}{1 + 2\tau_p \phi_p \cdot \phi_p \cdot P + \tau_p^2 \cdot P^2}
\]

Substituting (9.8.) for \( \phi_p \) and applying the inverse Laplace transform gives:

\[
\phi_p + 2\tau_p \phi_p \cdot \zeta \phi_p \cdot p_b + \tau_p^2 \cdot \phi_p \cdot \frac{\dot{p}_b}{g} + \dot{p}_b \cdot \frac{\dot{p}_b}{g} - \cos \theta \cdot \sin \phi = 0
\]

The resulting roll acceleration \( \ddot{p}_b \) reads:

\[
\dot{p}_b = \frac{\dot{p}_b}{g} \cdot \cos \theta \cdot \sin \phi - \frac{2\tau_p \phi_p}{2\tau_p \phi_p} \cdot p_b - \frac{1}{\tau_p^2 \phi_p} \cdot \phi_p
\]  

(9.9.)

Rectangular integration at a rate of 20 times/sec gives at time \( t_n \):

\[
p_{b,1P_n} = p_{b,1P_{n-1}} + 0.05 \cdot \dot{p}_{b,1P_{n-1}}
\]

\[
\phi_{p_n} = \phi_{p_{n-1}} + 0.05 \cdot p_{b,1P_{n-1}}
\]

The computation of the simulator roll angle \( \phi_p \) to simulate aircraft roll accelerations occurs in the same manner as the computation of \( \phi_h \).

The transfer function of the applied high-pass second order filter reads:

\[
\frac{\phi_p(P)}{\psi_p(P)} = \frac{\tau_p^2 \cdot P^2}{1 + 2\tau_p \phi_h \cdot \zeta \phi_h \cdot P + \tau_p^2 \phi_h \cdot P^2}
\]

The resulting simulator roll acceleration \( \ddot{p}_b \) can be written as:

\[
\ddot{p}_b = \dot{p}_b - \frac{2\tau_p \phi_h}{2\tau_p \phi_h} \cdot p_{b,h} - \frac{1}{\tau_p^2 \phi_h} \cdot \phi_h
\]

Rectangular integration of \( \ddot{p}_b \) gives at time \( t_n \):

\[
p_{b,h_{p_n}} = p_{b,h_{p_{n-1}}} + 0.05 \cdot \dot{p}_{b,h_{p_{n-1}}}
\]

* See note on page 7.
\[ \phi_{p_n} = \phi_{p_{n-1}} + 0.05 \cdot p_{b,h_p} \]

The specific force error as a result of \( \phi_{h_p} \) reads:

\[ (A_{\gamma_{b,c}})_{\text{error}} = + g \cdot \phi_{h_p} \]

This lateral specific force error is compensated by means of the lateral translational motion of the base:

\[ \dot{y}_{b,2} = + g \cdot \phi_{h_p} \], see Section 6.2.

The total body-axes roll acceleration, used for lead-compensation of the motion system, see Section 12, reads:

\[ \dot{p}_s = \dot{p}_{b,1p} + \dot{p}_{b,h_p} \]  \hspace{1cm} (9.10.)

The total body-axes roll rate, to be transformed into inertial axes, see Section 10, reads:

\[ p_s = p_{b,1p} + p_{b,h_p} \]  \hspace{1cm} (9.11.)

9.3. Yaw motion

Because of the restricted freedom in yaw of the motion base, see Table 1, also here a high-pass filter is applied to suppress the low-frequency changes of aircraft yaw acceleration \( \dot{\tau}_b \).

The transfer function of the applied high-pass second order filter reads:

\[ \frac{t_{b,h_p}}{\dot{\tau}_b} = \frac{r^2_p \cdot p^2}{1 + 2r^2_p \cdot \tau_p \cdot p + r^4_p \cdot p^2} \]

The resulting body-axes yaw acceleration \( \dot{t}_{b,h_p} \) can be written as:

\[ \dot{t}_{b,h_p} = t_b - \frac{2r^2_p \cdot \tau_p \cdot \dot{r}_{b,h_p} - 1}{r^2_p \cdot \psi_p} \]  \hspace{1cm} (9.12.)

Rectangular integration gives at time \( t_n \):

\[ r_{b,h_{p_n}} = r_{b,h_{p_{n-1}}} + 0.05 \cdot \dot{r}_{b,h_{p_{n-1}}} \]  \hspace{1cm} (9.13.)

\[ \psi_{h_{p_n}} = \psi_{h_{p_{n-1}}} + 0.05 \cdot r_{b,h_{p_{n-1}}} \]  \hspace{1cm} (9.14.)

\( \pi \) See note on page 7.
10. Body to inertial transformation of the motion system rotational rates.

Just as the translational degrees of freedom, the rotational degrees of freedom of the motion base operate in an inertial axes system. Therefore, the rotational rates (9.6.), (9.11.) and (9.13.) are transformed to Euler rates. According to Table 33 of Ref. 7, the Euler rates \( \dot{\psi}_i, \dot{\theta}_i \) and \( \dot{\phi}_i \) can be written as:

\[
\dot{\psi}_i = \frac{\sin \phi_m}{\cos \theta_m} \cdot a_s + \frac{\cos \phi_m}{\cos \theta_m} \cdot r_b h_p
\]

\[
\dot{\theta}_i = \cos \phi_m \cdot a_s - \sin \phi_m \cdot r_b h_p
\]  \hspace{1cm} (10.1)

\[
\dot{\phi}_i = p_s + \sin \phi_m \cdot \tan \theta_m \cdot a_s + \cos \phi_m \cdot \tan \theta_m \cdot r_b h_p
\]

where \( \theta_m \) and \( \phi_m \) are the simulator pitch and roll angles respectively, see also section 11.

11. Rotational washout.

In accordance with section 8, an attenuation is applied also to the Euler rates \( \dot{\psi}_i, \dot{\theta}_i \) and \( \dot{\phi}_i \) of the motion platform, see Fig. 2, block 11, to prevent the platform from running into its limits.

Use is made here of first order high-pass washout filters.

\[
\ddot{\psi}_m = \dot{\psi}_i - \frac{1}{\tau_{\psi_R}} \cdot \psi_m
\]

\[
\ddot{\theta}_m = \dot{\theta}_i - \frac{1}{\tau_{\theta_R}} \cdot \theta_m
\]  \hspace{1cm} (11.1)

\[
\ddot{\phi}_m = \dot{\phi}_i - \frac{1}{\tau_{\phi_R}} \cdot \phi_m
\]

The yaw angle \( \psi_m \), pitch angle \( \theta_m \) and roll angle \( \phi_m \) of the motion platform, not yet compensated for the platform's dynamic lag, are obtained by rectangular integration of \( \dot{\psi}_m, \dot{\theta}_m \) and \( \dot{\phi}_m \) respectively at a rate of 20 times/sec.

12. Lead compensation for dynamic lag in the motion system's translational and rotational degrees of freedom.

An analysis of the motion system's response characteristics revealed that the hardware had dominant second-order phase lag characteristics, see Ref. 5.
Compensation for these lags could be achieved by introducing in the software program of the motion simulation appropriate second-order lead terms. Both the first and second derivatives are required of the signal to be compensated. For the rotational degrees of freedom, both the transformed first and second derivatives $\dot{\theta}_m$, $\ddot{\theta}_m$, $\dot{\phi}_m$, $\ddot{\phi}_m$, $\dot{\psi}_m$, and $\ddot{\psi}_m$ are available for this purpose, see section 8. For the rotational degrees of freedom, however, the second derivatives (9.5.), (9.10.) and (9.12.) are available only in body-axes and thus they will be used for the compensation. The six compensated position and attitude command signals, to be sent to the actuator extension transformation, see Fig. 2, block 13, read:

$$
\begin{align*}
X_c &= X_m + B_1 \cdot \dot{X}_m + A_1 \cdot \ddot{X}_m \\
Y_c &= Y_m + B_2 \cdot \dot{Y}_m + A_2 \cdot \ddot{Y}_m \\
Z_c &= Z_m + B_3 \cdot \dot{Z}_m + A_3 \cdot \ddot{Z}_m \\
\theta_c &= \theta_m + B_4 \cdot \dot{\theta}_m + A_4 \cdot \ddot{\theta}_m \\
\phi_c &= \phi_m + B_5 \cdot \dot{\phi}_m + A_5 \cdot \ddot{\phi}_m \\
\psi_c &= \psi_m + B_6 \cdot \dot{\psi}_m + A_6 \cdot \ddot{\psi}_m
\end{align*}
$$

(12.1.)

Numerical values for the "time-constants"\(x)\), damping ratio and other parameters as applied to the KSS B-747 motion simulation are presented in Appendices A and B.

13. **Summary of the equations as applied in the motion simulation.**

Flightpath to body-axes transformation of the total forces $F_x$, $F_y$, and $F_z$ in the off-ground condition:

$$
\begin{align*}
F_x &= \cos \alpha_b \cdot \cos \beta \cdot F_x - \cos \alpha_b \cdot \sin \beta \cdot F_y - \sin \alpha_b \cdot F_z \\
F_y &= + \sin \beta \cdot F_x + \cos \beta \cdot F_y \\
F_z &= + \sin \alpha_b \cdot \cos \beta \cdot F_x - \sin \alpha_b \cdot \sin \beta \cdot F_y + \cos \alpha_b \cdot F_z
\end{align*}
$$

(3.1.)

The body-axes specific forces:

$$
\begin{align*}
A_x &= \ddot{u}_b - \dot{r}_b \cdot \nu_b + g \cdot \sin \theta \\
A_y &= \dot{v}_b + \dot{r}_b \cdot u_b - p_b \cdot w_b - g \cdot \cos \theta \cdot \sin \phi \\
A_z &= \dot{w}_b - q_b \cdot u_b + p_b \cdot v_b - g \cdot \cos \theta \cdot \cos \phi
\end{align*}
$$

\(x)\) See note on page 7.
Centroid transformation:
\[ \dot{A}_{b,c} = \dot{u}_{b,c} + g \cdot \sin \theta \]  
(5.2)

where:
\[ \dot{u}_{b,c} = \dot{u}_b - r_b \cdot v_b - (a_b^2 + r_b^2) \cdot R_x \]

\[ \dot{A}_{b,c} = \dot{v}_{b,c} - g \cdot \cos \theta \cdot \sin \phi \]  
(5.3)

where:
\[ \dot{v}_{b,c} = \dot{v}_b + r_b \cdot u_b - p_b \cdot w_b + (p_b \cdot r_b - \dot{a}_b) \cdot R_x \]

\[ \dot{A}_{b,c} = \dot{w}_{b,c} - g \cdot \cos \theta \cdot \cos \phi \]  
(5.4)

where:
\[ \dot{w}_{b,c} = \dot{w}_b - a_b \cdot u_b + p_b \cdot v_b + (p_b \cdot r_b - \dot{a}_b) \cdot R_x \]

Longitudinal motion:
\[ \ddot{x}_{b,1} = \dot{u}_{b,c} - g \cdot \theta_1 \cdot \frac{2\xi_1}{\tau_1} \cdot x_{b,1} - \frac{1}{\tau_1^2} \cdot x_{b,1} \]  
(6.3)

\[ \ddot{x}_{b,2} = - \frac{g \cdot \theta_1}{\tau_1} \]  
(specific force error)

\[ \ddot{x}_s = \ddot{x}_{b,1} + \ddot{x}_{b,2} \]  
(6.4)

Lateral motion:
\[ \dot{y}_{b,1} = \dot{v}_{b,c} - g \cdot \cos \theta \cdot \sin \phi \cdot \phi_1 \cdot \frac{2\xi_1}{\tau_1} \cdot y_{b,1} - \frac{1}{\tau_1^2} \cdot y_{b,1} \]  
(6.7)

\[ \dot{y}_{b,2} = g \cdot \phi_1 \]  
(specific force error)

\[ \dot{y}_s = \dot{y}_{b,1} + \dot{y}_{b,2} \]  
(6.8)

Heave motion:
\[ \ddot{z}_b = \dot{w}_{b,c} - \frac{2\xi_2}{\tau_2} \cdot z_b - \frac{1}{\tau_2^2} \cdot z_b \]  
(6.11)

Body to inertial transformation of the motion platform translational accelerations:
\[ \ddot{x}_s = \cos \theta_m \cdot \cos \psi_m \cdot \ddot{x}_s + (\sin \phi_m \cdot \sin \theta_m \cdot \cos \psi_m - \cos \phi_m \cdot \sin \psi_m) \cdot \dot{y}_s 
+ (\cos \phi_m \cdot \sin \theta_m \cdot \cos \psi_m + \sin \phi_m \cdot \sin \psi_m) \cdot \ddot{z}_b \]  
(7.1)

\[ \ddot{y}_s = \cos \theta_m \cdot \sin \psi_m \cdot \ddot{x}_s + (\sin \phi_m \cdot \sin \theta_m \cdot \sin \psi_m + \cos \phi_m \cdot \cos \psi_m) \cdot \dot{y}_s 
+ (\cos \phi_m \cdot \sin \theta_m \cdot \sin \psi_m - \sin \phi_m \cdot \cos \psi_m) \cdot \ddot{z}_b \]  
(7.2)
\[ y_i = -\sin \theta_m \cdot \dot{x}_s + \sin \phi_m \cdot \cos \theta_m \cdot \dot{y}_s + \cos \phi_m \cdot \cos \theta_m \cdot \dot{z}_b \quad (7.3) \]

Translational washout:
\[ \ddot{x}_m = \dot{x}_i - \frac{2\tau_{x_T}}{\tau_{x_T}} \cdot \dot{x}_m - \frac{1}{\tau_{x_T}^2} \cdot x_m \]
\[ \ddot{y}_m = \dot{y}_i - \frac{2\tau_{y_T}}{\tau_{y_T}} \cdot \dot{y}_m - \frac{1}{\tau_{y_T}^2} \cdot y_m \quad (8.1) \]
\[ \ddot{z}_m = \dot{z}_i - \frac{2\tau_{z_T}}{\tau_{z_T}} \cdot \dot{z}_m - \frac{1}{\tau_{z_T}^2} \cdot z_m \]

Pitch motion:
\[ \dot{\theta}_{b,l_p} = \dot{\theta}_{b,h_p} + \frac{2\tau_{\theta_1}}{\tau_{\theta_1}^2 \cdot g} \cdot \theta_{b,l_p} - \frac{1}{\tau_{\theta_1}^2} \cdot \theta_{1_p} \quad (9.3) \]
\[ \dot{\theta}_{b,h_p} = \dot{\theta}_{b} - \frac{2\tau_{\theta_h}}{\tau_{\theta_h}^2} \cdot \theta_{b,h_p} - \frac{1}{\tau_{\theta_h}^2} \cdot \theta_{h_p} \]

\[ \dot{\alpha}_s = \alpha_{b,l_p} + \alpha_{b,h_p} \quad (9.5) \]
\[ \alpha_s = \alpha_{b,l_p} + \alpha_{b,h_p} \quad (9.6) \]

Roll motion:
\[ \dot{\phi}_{b,l_p} = -\frac{\tau_{x,c}}{\tau_{x}^2 \cdot g} + \frac{2\tau_{\phi_1}}{\tau_{\phi_1}^2} \cdot \phi_{b,l_p} - \frac{1}{\tau_{\phi_1}^2} \cdot \phi_{1_p} \quad (9.9) \]
\[ \dot{\phi}_{b,h_p} = \dot{\phi}_{b} - \frac{2\tau_{\phi_h}}{\tau_{\phi_h}^2} \cdot \phi_{b,h_p} - \frac{1}{\tau_{\phi_h}^2} \cdot \phi_{h_p} \]

\[ \dot{\phi}_s = \phi_{b,l_p} + \phi_{b,h_p} \quad (9.10) \]
\[ P_s = P_{b,l_p} + P_{b,h_p} \quad (9.11) \]
Yaw motion:
\[
\dot{\gamma}_{\text{b},h_p} = \dot{\gamma}_{\text{b}} - \frac{2\gamma_{\text{b}}}{\tau_{\psi}} \cdot r_{\text{b},h_p} - \frac{1}{\tau_{\psi}} \cdot \psi_{\text{h}_p} \tag{9.12.}
\]

Euler rates:
\[
\dot{\psi}_i = \frac{\sin \phi_m}{\cos \theta_m} \cdot q_s + \frac{\cos \phi_m}{\cos \theta_m} \cdot r_{\text{b},h_p}
\]
\[
\dot{\theta}_i = \cos \phi_m \cdot q_s - \sin \phi_m \cdot r_{\text{b},h_p} \tag{10.1.}
\]
\[
\dot{\phi}_i = p_S + \sin \phi_m \cdot \tan \theta_m \cdot q_s + \cos \phi_m \cdot \tan \theta_m \cdot r_{\text{b},h_p}
\]

Rotational washout:
\[
\dot{\psi}_m = \dot{\psi}_i - \frac{1}{\tau_{\psi_R}} \cdot \psi_m
\]
\[
\dot{\theta}_m = \dot{\theta}_i - \frac{1}{\tau_{\theta_R}} \cdot \theta_m \tag{11.1.}
\]
\[
\dot{\phi}_m = \dot{\phi}_i - \frac{1}{\tau_{\phi_R}} \cdot \phi_m
\]

Motion system lead compensation:
\[
\begin{align*}
\dot{x}_c &= x_m + B_1 \cdot \dot{x}_m + A_1 \cdot x_m \\
\dot{y}_c &= y_m + B_2 \cdot \dot{y}_m + A_2 \cdot y_m \\
\dot{z}_c &= z_m + B_3 \cdot \dot{z}_m + A_3 \cdot z_m \\
\dot{\theta}_c &= \theta_m + B_4 \cdot \dot{\theta}_m + A_4 \cdot \theta_m \\
\dot{\phi}_c &= \phi_m + B_5 \cdot \dot{\phi}_m + A_5 \cdot \phi_m \\
\dot{\psi}_c &= \psi_m + B_6 \cdot \dot{\psi}_m + A_6 \cdot \psi_{\text{h}_p}
\end{align*}
\tag{12.1.}
\]

14. Concluding remarks

In this report the mathematical formulation of the generation of motion cues is described. From the mathematical model of the simulated aircraft, the specific forces and rotational accelerations at the aircraft c.g. are determined as primary control inputs of the motion drive laws. Because the specific forces are acting on the pilot inside the simulator cockpit, they should be transformed to the so called centroid location of the motion system.
As the motion possibilities of the base are constrained, filtering of the specific forces and rotational accelerations is necessary and as far as possible, tilt angles are used to reproduce sustained specific forces, providing the motion system with so called "co-ordinated wash-out".

The dynamic characteristics of the motion system should be such, that for the reproduction of the high frequencies, the high frequency-response of the base is of sufficient quality. On the other hand the smoothness of the base is important to keep the low-frequency "wash-out" below the threshold level of the pilot's perception.

Experience obtained from the development of the motion simulation software, presented in Appendix B, has shown that realistic motion cues are obtained, especially in the approach, landing and take-off phases of flight. Among other difficulties, problems such as lateral pilot-induced-oscillations in the final part of the visual approach were solved.
15. **References**

1. S.F. Schmidt, B. Conrad  

2. R.L. Stapleford, R.A. Peters, F.K. Alex  


4. C. Broxmeyer  

5. M. Baarspul  
   "Hardware Modifications to improve the frequency response and smoothness of a synergistic six-degree-of-freedom motion system", (KLM report to be published).

6. J. Schlien  

7. W.G. Vermeulen  

16. **Acknowledgements**

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<table>
<thead>
<tr>
<th>Degree of freedom</th>
<th>Performance limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position</td>
</tr>
<tr>
<td>Horizontal x</td>
<td>forward 1.24 m</td>
</tr>
<tr>
<td></td>
<td>aft 1.24 m</td>
</tr>
<tr>
<td>Lateral y</td>
<td>left 1.21 m</td>
</tr>
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<td></td>
<td>right 1.21 m</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>down 0.85 m</td>
</tr>
<tr>
<td>Yaw   ( \psi )</td>
<td>± 36°</td>
</tr>
<tr>
<td>Pitch ( \theta )</td>
<td>± 34°, ± 32°</td>
</tr>
<tr>
<td>Roll ( \phi )</td>
<td>± 28°</td>
</tr>
</tbody>
</table>

Table 1: Performance limits for single degree of freedom operation.
FIG. 1 THE RESPONSES OF THE BANK ANGLE (φ) THE ROLL RATE (φ̇) AND THE ROLL ACCELERATION (φ̈) OF AN AIRCRAFT AND THE FLIGHT SIMULATOR TO AN AILERON STEP INPUT
FIG 3  THE RELATION BETWEEN BODY AXES AND FLIGHTPATH - (WIND) AXES
FIG 4: ARRANGEMENT OF THE KSS BOEING-747 MOTION SYSTEM,
DEFINING THE $\sigma_2 X_e Y_e Z_e$ REFERENCE FRAME AND THE CENTROID LOCATION
Appendix A: Scaled equations as used in the KSS Boeing 747 Main Motion
Simulation Program.

The scaled equations of the KSS Boeing 747 Main Motion Simulation Program
in the sequence as followed by the digital computer are given below.
The parameters used in the software are summarized in Table 2.

Computations in behalf of the specific forces, see section 4;
on ground:

\[ \dot{u}_b - \tau_b \cdot v_b = \frac{F_b}{W} \cdot g \]

\[ \frac{\dot{v}_b}{10} = \frac{F_b}{W \cdot (1,748) \cdot 9,81} \]

UBD = MF2WB . KXX1

Off ground:

LWD = MF2WB . KXX1

KXU1 = K SCALE = \frac{1,748}{10} \cdot 9,81 = 1,71479 = 0,428697 SALD 3. X)

On ground:

\[ \dot{u}_b - \tau_b \cdot u_b - p_b \cdot v_b = \frac{F_{y_b}}{W} \cdot g \]

\[ \frac{\dot{v}_b}{8} = \frac{F_{y_b}}{W \cdot 8} \cdot \frac{2}{8} \cdot 9,81 \]

VBDM = MF2WB . KYV1

Off ground:

WWD = MF2WB . KYV1

KYV1 = K SCALE = \frac{2}{8} \cdot 9,81 = 2,4525 = 0,613124 SALD 3.

On ground:

\[ \dot{q}_b - q_b \cdot u_b + p_b \cdot v_b = \frac{F_{\tau_b}}{W} \cdot g \]

\[ \frac{\dot{v}_b}{40} = \frac{F_{\tau_b}}{W \cdot 40} \cdot \frac{6}{40} \cdot 9,81 \]

WBD = MF2WB . KZW1

Off ground:

WWD = MF2WB . KZW1

X) Note: SALD 3 means arithm. left shift double (3 = 2\(^2\) effectively).
The above computations are performed by means of LOOP 1 and 2 in part 1 of KSS Boeing 747 Main Motion Simulation, see line 41 of Appendix B, part 3.

Wind-to-body-axes transformation of UMD, WD and WWD, when the aircraft is off-ground, see section 3:

\[ UBD = UMD \cdot \cos \alpha_b \cdot \cos \beta - WWD \cdot \cos \alpha_b \cdot \sin \beta - WWD \cdot \sin \alpha_b \]

\[ UBD = \frac{UMD \cdot \cos \alpha_b \cdot \cos \beta - WWD \cdot \cos \alpha_b \cdot \sin \beta - WWD \cdot \sin \alpha_b}{10} \cdot \left( \frac{WWD}{10} \right) \cdot \left( \frac{WWD}{8} \right) \cdot \left( \frac{WWD}{8} \right) \cdot \left( \frac{WWD}{40} \right) \cdot \frac{\sin \alpha_b}{1} \]

\[ UBD = \frac{UMD \cdot \cos \alpha_b \cdot \cos \beta - WWD \cdot \cos \alpha_b \cdot \sin \beta - WWD \cdot \sin \alpha_b}{10} \cdot \left( \frac{WWD}{10} \right) \cdot \left( \frac{WWD}{8} \right) \cdot \left( \frac{WWD}{8} \right) \cdot \left( \frac{WWD}{40} \right) \cdot \frac{\sin \alpha_b}{1} \]

To avoid discontinuity problems during the transition from on-to off-ground, the calculation is stopped for 1 sec in case of a condition change see line 141 of Appendix B, part 1.
Pitch acceleration, see section 9.1:

\[ \tau_{\theta_p} = 0.7 \]

\[ \tau_{\dot{\theta}_p} = 6 \text{ sec.} \]

\[ S_{\dot{\theta}_b, \theta_p} = 2 \text{ rad/sec}^2 \]

\[ S_{\dot{\theta}_b, \theta_p} = 1 \text{ rad/sec} \]

\[ S_{\dot{\theta}_b, \theta_p} = 1 \text{ rad} \]

\[ S_{\ddot{\theta}_b} = 2 \text{ rad/sec}^2 \]

\[ \delta_{\dot{\theta}_b, \theta_p} = \dot{q}_b - \frac{2\tau_{\theta_p}}{\tau_{\theta_p}} \cdot q_{\dot{\theta}_b, \theta_p} - \frac{1}{\tau_{\theta_p}^2} \cdot \theta_p \]

\[ \delta_{\ddot{\theta}_b, \theta_p} = \frac{\dot{q}_b}{2} - \frac{2\tau_{\theta_p}}{2\tau_{\theta_p}} \cdot q_{\ddot{\theta}_b, \theta_p} - \frac{1}{2\tau_{\theta_p}^2} \cdot \theta_p \]

\[ M_{\text{PITCHED}} = \text{VPRD} - (K\text{P1} \cdot M_{\text{PITCHED}} + K\text{P2} \cdot M_{\text{PITCHED}}) \]

\[ K\text{P1} = \frac{2\tau_{\theta_p}}{2 - 0.7} = \frac{0.11666}{0.3} \text{ (line 359)} \]

\[ K\text{P2} = \frac{1}{2\tau_{\theta_p}} = \frac{1}{2 \cdot 36} = 0.01388 \text{ (line 360)} \]

Rectangular integration:

\[ \dot{q}_b, \theta_p = \dot{q}_b, \theta_p + 0.05 \cdot \delta_{\dot{\theta}_b, \theta_p} \]

\[ \dot{q}_b, \theta_p = \dot{q}_b, \theta_p + 0.05 \cdot \left( \frac{\delta_{\ddot{\theta}_b, \theta_p}}{2} \right) \cdot 2 \]

\[ M_{\text{PITCHING}} = M_{\text{PITCHING}} + K\text{P3} \cdot M_{\text{PITCHED}} \]

\[ K\text{P3} = \frac{0.05}{4} = 0.1 \]
\[ \theta_{hp} = \theta_{hp} + 0.05 \cdot q_{b,hp} \]

\[ \frac{\dot{\theta}_{hp}}{1} = \frac{\dot{\theta}_{hp}}{1} + 0.05 \cdot \frac{q_{b,hp}}{1} \]

\[ \text{KP4} = \frac{0.05}{1} = 0.05 \]

Roll acceleration, see section 9.2:

\[ r_{\theta_{hp}} = 0.7 \]

\[ r_{\theta_{hp}} = 6 \text{ sec} \]

\[ S_{Pb,hp} = 4 \text{ rad/sec}^2 \]

\[ S_{Pb,hp} = 2 \text{ rad/sec} \]

\[ S_{\dot{\theta}_{hp}} = 2 \text{ rad} \]

\[ S_{\ddot{P}_{b,hp}} = 4 \text{ rad/sec}^2 \]

\[ \dot{P}_{b,hp} = \dot{P}_{b} - \frac{2z_{h_p}}{r_{\theta_{hp}}} \cdot P_{b,h_p} - \frac{1}{r_{\theta_{hp}}^2} \cdot \theta_{hp} \]

\[ \frac{\ddot{P}_{b,hp}}{4} = \frac{\dot{P}_{b}}{4} - \frac{2z_{h_p}}{4r_{\theta_{hp}}} \cdot \frac{P_{b,h_p}}{4r_{\theta_{hp}}} \cdot (-2z_{h_p}) \cdot 2 - \frac{1}{4r_{\theta_{hp}}^2} \cdot \frac{\theta_{hp}}{2} \cdot 2 \]

\[ \text{MROLLDD} = \text{VRDD} - (\text{KR1} \cdot \text{MROLLDM} + \text{KR2} \cdot \text{MROLLLM}) \]

\[ \text{KR1} = \frac{2z_{h_p}}{4r_{\theta_{hp}}} \cdot 2 = \frac{2 \cdot 0.7 \cdot 2}{4.6} = 0.11666 \]

\[ \text{KR2} = \frac{1}{4r_{\theta_{hp}}} \cdot 2 = \frac{2}{4.36} = 0.04688 \]
Rectangular integration:

\[ P_b, h_p = P_{b, h_p} \cdot 0,05 \cdot \Delta b, h_p \]

\[ P_b, h_p = P_{b, h_p} + 0,05 \cdot \Delta b, h_p \]

\[ P_b, h_p = P_{b, h_p} \cdot 0,05 \cdot \frac{P_{b, h_p}}{2} \cdot \left( \frac{P_{b, h_p}}{2} \right) \cdot 4 \]

\[ M\text{ROLL} = M\text{ROLL} + KR3 \cdot M\text{ROLL} \]

\[ KR3 = \frac{0,05}{2} \cdot 4 = 0,1 \]

\[ \phi h_p = \phi h_p + 0,05 \cdot P_{b, h_p} \]

\[ \phi h_p = \phi h_p + 0,05 \cdot \frac{P_{b, h_p}}{2} + \frac{P_{b, h_p}}{2} \cdot \left( \frac{P_{b, h_p}}{2} \right) \cdot 2 \]

\[ M\text{ROLL} = M\text{ROLL} + KR4 \cdot M\text{ROLL} \]

\[ KR4 = \frac{0,05}{2} \cdot 2 = 0,05 \]

Yaw acceleration, see section 9.3:

\[ \zeta_{\psi} = 0,7 \]

\[ \gamma_{\psi} = 1,5 \text{ sec} \]

\[ S r_b, h_p = 2 \text{ rad/sec}^2 \]

\[ S r_b, h_p = 1 \text{ rad/sec} \]

\[ S \phi h_p = 1 \text{ rad} \]

\[ S \tilde{r}_b = 2 \text{ rad/sec}^2 \]

\[ \tilde{r}_b, h_p = \tilde{r}_b \cdot \frac{2 \zeta_{\psi}}{\gamma_{\psi}} \cdot r_b, h_p - \frac{1}{2 \zeta_{\psi}} \cdot \psi h_p \]

\[ \tilde{r}_b, h_p = \tilde{r}_b \cdot \frac{2 \zeta_{\psi}}{\gamma_{\psi}} \cdot r_b, h_p - \frac{1}{2 \zeta_{\psi}} \cdot \psi h_p \]

\[ M\text{YAW} = VHRD + (KJ1 \cdot M\text{YAW}) \]

\[ KJ1 = \frac{2 \zeta_{\psi}}{2 \gamma_{\psi}} = \frac{2}{2} \cdot 0,7 = 0,233332 \cdot 2 \text{ (line 377)} \]

\[ KJ2 = \frac{1}{2 \gamma_{\psi}} = \frac{1}{2} \cdot 2,25 = 0,05552 \cdot 4 \text{ (line 378)} \]
Rectangular integration:
\[ r_{b,h_p} = r_{b,h_p} + 0.05 t_{b,h_p} \]
\[ \frac{r_{b,h_p}}{1} = \frac{r_{b,h_p}}{1} + 0.05 \cdot \frac{t_{b,h_p}}{1} \cdot (-\frac{h_p}{2}). \]

MYAMD = MYAMD + KJ3 * MYADD

KJ3 = \frac{0.05}{1} * 2 = 0.1

\[ \psi_{b,h_p} = \psi_{b,h_p} + 0.05 \cdot r_{b,h_p} \]
\[ \frac{\psi_{b,h_p}}{1} = \frac{\psi_{b,h_p}}{1} + 0.05 \cdot \frac{r_{b,h_p}}{1} \]

MYAMD = MYAMD + KJ4 * MYAKD

KJ4 = \frac{0.05}{1} = 0.05

Specific force errors, see section 9.1. and 9.2.:
\[ x_{b,2} = -g \cdot q_{b,h_p} \]
\[ \frac{x_{b,2}}{10} = \frac{-g}{10} \cdot q_{b,h_p} \]

MYDD = KX1 * MPITGM

The program value of KX1 has been adjusted to:

KX1 = -0.12 (see line 380 of Appendix B, part 1)

to prevent the motion platform from running into its longitudinal position limits.
\[ \psi_{b,2} = \psi_{b,h_p} \]
\[ \frac{\psi_{b,2}}{8} = \frac{-g}{8} \cdot \frac{q_{b,h_p}}{2} \]

MYDD = KY1 * MROLLK

For the same reason, KY1 has been adjusted to:

KY1 = 0.3 (see line 381).
Centroid transformation, see section 5:

\[ \Delta_{b,c} = \Delta_{b} - \tau_{b} \cdot \Delta_{b} = \left( q_{b}^{2} + r_{b}^{2} \right) \cdot R_{x} \]

\[ \frac{\Delta_{b,c}}{10} = \frac{\Delta_{b}}{10} - \frac{\tau_{b} \cdot q_{b}^{2} + r_{b}^{2}}{10} \cdot R_{x} \]

UBCD = UBD - (VPR . VPR + VHR . VHR) . KUBC

KUBC = \frac{25.9}{10} = 2.59 \times 0.6475 \text{ SALD 3 (line 353)}

\[ \dot{q}_{b,c} = \dot{q}_{b} + \tau_{b} \cdot u_{b} - p_{b} \cdot \Delta_{b} + (p_{b} - q_{b} \cdot \tau_{b}) \cdot R_{x} \]

\[ \frac{\dot{q}_{b,c}}{8} = \frac{\dot{q}_{b}}{8} + \frac{\tau_{b} \cdot u_{b} - p_{b} \cdot \Delta_{b} + (p_{b} - q_{b} \cdot \tau_{b})}{8} \cdot \frac{R_{x}}{8} \]

VBCD = VBD + (VPR . VPR + VRD). KVBC

KVBC = \frac{25.9 \cdot 2}{8} = 6.475 \times 0.8094 \text{ SALD 4 (line 354)}

\[ \dot{q}_{b,c} = \dot{q}_{b} - q_{b} \cdot \Delta_{b} + p_{b} \cdot \Delta_{b} + (p_{b} - q_{b} \cdot \tau_{b}) \cdot R_{x} \]

\[ \frac{\dot{q}_{b,c}}{40} = \frac{\dot{q}_{b}}{40} - \frac{q_{b} \cdot \Delta_{b} + p_{b} \cdot \Delta_{b} + (p_{b} - q_{b} \cdot \tau_{b})}{40} \cdot \frac{R_{x}}{40} \]

WBDC = WBD + (VPR . VHR - VPRD). KVBC

KVBC = \frac{2.9}{40} = 1.295 \times 0.6475 \text{ SALD 2 (line 355)}

**LONGITUDINAL SPECIFIC FORCE.**

Longitudinal highpass filter, see section 6.1.:

\[ \zeta_{x} = 0.7 \]

\[ \tau_{x} = 0.7 \]

\[ S_{\dot{x}} = 10 \text{ m/sec}^{2} \]

\[ S_{x} = 10 \text{ m/sec} \]

\[ S_{x} = 11,3952 \text{ m} \]

\[ S_{\dot{\theta}_{b,c}} = 10 \text{ m/sec}^{2} \]

\[ \ddot{x}_{b,1} = \dot{x}_{b,1} - 8 \cdot \theta_{b} + \frac{2x_{x}}{\tau_{x}} \cdot \ddot{x}_{b,1} - \frac{1}{\tau_{x}} \cdot \dot{x}_{b,1} \quad (6.3.) \]

\[ \frac{\ddot{x}_{b,1}}{10} = \frac{\dot{x}_{b,1}}{10} - \frac{\theta_{b}}{10} \cdot \frac{2}{10} \cdot \frac{2 \cdot \tau_{x}}{10} \cdot \frac{(\dot{x}_{b,1})}{10} - \frac{1}{10 \cdot \tau_{x}} \cdot (11,3952) \cdot 11,3952 \]

**BXXD = UBCD - SPITCHM - KX10 . BXCM - KX11 . BXM**
\[
\begin{align*}
KX10 &= \frac{2}{10} \cdot 0.7 \cdot 10 = 0.9999 \text{ SADL 2 (line 482)} \\
KX11 &= \frac{11.3952}{10} \cdot 0.49 = 2.3255 = 0.581377 \text{ SADL 3 (line 358)}
\end{align*}
\]

Rectangular integration:
\[
\begin{align*}
\dot{x}_{b,1} &= \dot{x}_{b,1} + 0.05 \cdot x_{b,1} \\
\dot{x}_{b,1} &= \frac{\dot{x}_{b,1}}{10} + \frac{0.05}{10} \cdot \frac{\dot{x}_{b,1}}{10} \cdot 10 \\
BX10 &= BX10 + XK12 \cdot BX10 \\
XK12 &= \frac{0.05}{10} \cdot 10 = 0.05 \\
\dot{x}_{b,1} &= \dot{x}_{b,1} + 0.05 \cdot x_{b,1} \\
\frac{\dot{x}_{b,1}}{11.3952} &= \frac{\dot{x}_{b,1}}{11.3952} + \frac{0.05}{11.3952} \cdot \frac{\dot{x}_{b,1}}{10} \cdot 10 \\
BX10 &= BX10 + XK11 \cdot BX10 \\
XK11 &= \frac{0.05}{11.3952} \cdot 10 = 0.043877
\end{align*}
\]

Longitudinal low-pass filter, see section 9.1.
\[
\begin{align*}
\omega_{\theta_{1,p}} &= 0.7 \\
\tau_{\theta_{1,p}} &= 2 \text{ sec} \\
S_{\theta_{b,1,p}} &= 1 \text{ rad/sec}^2 \\
S_{\theta_{b,1,p}} &= 1 \text{ rad/sec} \\
S_{\theta_{1,p}} &= 1 \text{ rad} \\
S_{\phi_{b,c}} &= 10 \text{ m/sec}^2
\end{align*}
\]

\[
\dot{\phi}_{b,1,p} = \frac{\dot{\phi}_{b,c}}{\tau_{\phi_{1,p}}} + \sin \theta \cdot \frac{2 \phi_{1,p}}{\tau_{\phi_{1,p}}} \cdot \phi_{b,1,p} \cdot \frac{1}{\tau_{\phi_{1,p}}} \cdot \theta_{1,p} \quad (9.3)
\]

\[
\begin{align*}
\dot{\phi}_{b,1,c} &= 1 \cdot \dot{\phi}_{b,c} \cdot 10 + \sin \theta \cdot \frac{2 \phi_{1,p}}{\tau_{\phi_{1,p}}} \cdot \phi_{b,1,p} \cdot \frac{1}{\tau_{\phi_{1,p}}} \cdot \theta_{1,p}
\end{align*}
\]
BPITCHDD = KP13 * VSCD + KP14 * VSNPB - KP15 * BPITCHDM - KP16 * BPITCHD

KP13 = \frac{10}{24} = 0.25 \quad \text{(line 361)}
KP14 = \frac{1}{4} = 0.25 \quad \text{(line 362)}
KP15 = \frac{2}{2} = 0.7 \quad \text{(line 363)}
KP16 = \frac{1}{4} = 0.25 \quad \text{(line 364)}

Rectangular integration of \( \dot{q}_{b,1_p} \):

\begin{align*}
\dot{q}_{b,1_p} &= \dot{q}_{b,1_p} + 0.05 \dot{q}_{b,1_p} \\
\frac{\dot{q}_{b,1_p}}{1} &= \frac{\dot{q}_{b,1_p}}{1} + 0.05 \frac{\dot{q}_{b,1_p}}{1} \\

\end{align*}

BPITCHDM = BPITCHDM + KP17 * BPITCHDD

KP17 = 0.05

\begin{align*}
\dot{\theta}_p &= \dot{\theta}_p + 0.05 \dot{q}_{b,1_p} \\
\frac{\dot{\theta}_p}{1} &= \frac{\dot{\theta}_p}{1} + 0.05 \frac{\dot{q}_{b,1_p}}{1} \\

\end{align*}

BPITCHDM = BPITCHDM + KP18 * BPITCHDM

KP18 = 0.05

Remark: AXDD and BPITCHD are forced to hold their momentary values for 1 sec, when the aircraft condition changes from on- to off ground and from off- to on ground, see page A-2.

LATERAL SPECIFIC FORCE

Lateral high-pass filter, see section 6.2:

\begin{align*}
\zeta_y &= 0.7 \\
\tau_y &= 1 \text{ sec} \\
S_{\dot{q}_{b,1}} &= 8 \text{ m/sec}^2 \\
S_{\dot{q}_{b,1}} &= 10 \text{ m/sec} \\
S_{\dot{q}_{b,1}} &= 11.3952 \text{ m} \\
S_{\dot{q}_{b,c}} &= 8 \text{ m/sec}^2 \\

\end{align*}
\[
\dot{y}_{b,1} = \dot{y}_{b,c} - g \cdot \cos \phi + g \cdot \phi_1 + \frac{2\omega_y}{\gamma} \cdot \ddot{y}_{b,1} - \frac{1}{\alpha_1} \cdot y_{b,1} \quad (6.7)
\]

\[
\frac{\ddot{y}_{b,1}}{8} = \left(\frac{\ddot{y}_{b,c}}{8} - g \cdot \cos \phi + g \cdot \phi_1 + \frac{\ddot{y}_{b,1}}{8} - \frac{2}{8} \cdot \ddot{y}_{b,1} \cdot \gamma \right) \cdot (11.3952) \cdot 11.3952
\]

BYDD = VBCD + KR28 + VCSFB + VSNRB + KR12 + BROLM + KY10 + BYDM +
- KY11. BYM

KR28 = \frac{g}{8} \cdot \frac{1}{T} = 1.25 = 0.625 \text{ SADL 2 (line 371)}

KR12 = \frac{g}{8} \cdot \frac{1}{T} = 1.25. In Appendix B: KR12 has been experimentally reduced to 
\frac{1.25}{2} = 0.625 \text{ (line 367)}

KY10 = \frac{2}{8} \cdot \frac{0.07}{T} \cdot 10 = 1.750 \text{ SADL 2 (line 365)}

KY11 = \frac{1}{8} \cdot \frac{1}{T} \cdot 11.3952 = 1.4244 \text{ SADL 2 (line 366)}

Rectangular integration:

\[
\dot{y}_{b,1} = \dot{y}_{b,1} + 0.05 \ddot{y}_{b,1}
\]

\[
\frac{\ddot{y}_{b,1}}{10} = \dot{y}_{b,1} + 0.05 \cdot \ddot{y}_{b,1} \cdot 8
\]

BYDM = BYDM + KY12 + BYDD

KY12 = \frac{0.05}{10} \cdot 8 = 0.04

\[
y_{b,1} = y_{b,1} + 0.05 \ddot{y}_{b,1}
\]

\[
\frac{\ddot{y}_{b,1}}{11.3952} = \frac{y_{b,1}}{11.3952} + \frac{0.05}{11.3952} \cdot \left(\frac{\ddot{y}_{b,1}}{10}\right) \cdot 10
\]

BYM = BYM + KY13 + BYDM

KY13 = \frac{0.05 \cdot 10}{11.3952} = 0.043878

Lateral low-pass filter, see section 9.2.:

\[
\tau_{\dot{u}_1} = 0.7
\]

\[
\tau_{E_1} = 2 \text{ sec}
\]

\[
S_{\dot{p}_b,1} = 2 \text{ rad/sec}^2
\]
\[
S_{\theta,1p} = 1 \text{ rad/sec}
\]
\[
S_{\phi,1p} = 1 \text{ rad}
\]
\[
S_{\dot{\phi},bc} = 8 \text{ m/sec}^2
\]
\[
\dot{\theta}_{b,1p} = \frac{\dot{\phi}_{b,c}}{\tau_{\phi,1p}^2 \cdot g} - \frac{2 \tau_{\phi,1p}^2}{\tau_{\phi,1p}^2} \cdot P_{\theta,1p} - \frac{1}{\tau_{\phi,1p}^2} \cdot \dot{\phi}_{1p} \quad (9.9)
\]
\[
\ddot{\theta}_{b,1p} = \frac{1}{2 \tau_{\phi,1p}^2} \cdot \dot{\phi}_{b,c} \cdot g - \frac{1}{2 \tau_{\phi,1p}^2} \cdot \cos \theta - \frac{1}{2 \tau_{\phi,1p}^2} \cdot \sin \phi + \frac{2 \tau_{\phi,1p}^2}{2 \tau_{\phi,1p}^2} \cdot P_{\theta,1p} \cdot \dot{\phi}_{1p}
\]

\[
\frac{P_{\theta,1p}}{1} = \frac{1}{2 \tau_{\phi,1p}^2} \cdot \frac{\dot{\phi}_{1p}}{1}
\]


KR13 = \frac{1}{2 \cdot 1.10} \cdot 8 = 0.1

KR14 = - \frac{1}{2 \cdot 1.4} = -0.125 \text{ (line 368)}

KR15 = \frac{2 \cdot 0.7}{2 \cdot 2} = 0.35 \text{ (line 369)}

KR16 = \frac{1}{2 \cdot 4} = 0.125 \text{ (line 370)}

Rectangular integration:

\[
P_{\theta,1p} = P_{\theta,1p} + 0.05 \cdot P_{\theta,1p}
\]

\[
P_{\theta,1p} = P_{\theta,1p} + 0.05 \cdot \left( -\frac{P_{\theta,1p}}{2} \right) \cdot 2
\]

BROLLIM = BROLLDD + KR17, BROLLDD.

KR17 = \frac{0.05}{1} \cdot 2 = 0.1

\[
\dot{\phi}_{1p} = \dot{\phi}_{1p} + 0.05 \cdot P_{\theta,1p}
\]

\[
\frac{\dot{\phi}_{1p}}{1} = \frac{\dot{\phi}_{1p}}{1} + 0.05 \cdot \frac{P_{\theta,1p}}{1}
\]

BROLLIM = BROLLIM + KR18, BROLLIM
KR18 = 0,05

Vertical high-pass filter, see section 6.3:

\[ \zeta_z = 0,7 \]
\[ \tau_z = 0,7 \]
\[ S_{\zeta b} = 40 \text{ m/sec}^2 \]
\[ S_{\tau b} = 10 \text{ m/sec} \]
\[ S_{\zeta b} = 49,854 \text{ m} \]
\[ S_{\tau b} = 40 \text{ m/sec}^2 \]

\[ \beta_b = \beta_{0,b,c} \cdot \frac{2\zeta_z}{\tau_z} \cdot \frac{\tau}{\tau_z} \cdot \frac{1}{\tau_z} \cdot \beta_b \]  \hspace{1cm} (6.11.)

\[ \frac{\beta_b}{40} = \frac{\beta_{0,b,c}}{40} \cdot \frac{2\zeta_z}{\tau_z} \cdot \frac{\tau}{\tau_z} \cdot \left( \frac{\beta_b}{10} \right) \cdot 10 - \frac{1}{40\tau_z^2} \cdot \left( 49,854 \right) \cdot 49,854 \]

\[ \text{BZDD} = \text{WBCD} - KZ1 \cdot \text{BZDM} - KZ2 \cdot \text{BZM} \]

\[ KZ1 = \frac{2}{40} \cdot 0,7 \cdot 10 = 0,5 \] \hspace{1cm} (line 694)

\[ KZ2 = \frac{49,854}{40} \cdot 0,7 \cdot 10 = 2,54356 = 0,63589 \text{ Sald 3} \] \hspace{1cm} (line 382)

Rectangular integration:

\[ \frac{\beta_b}{10} = \frac{\beta_{\beta b}}{10} + 0,05 \cdot \beta_b \]

\[ \frac{\beta_b}{10} = \frac{\beta_{\beta b}}{10} + 0,05 \cdot \beta_b \]

\[ \text{BZDM} = \text{BZDM} + KZ3 \cdot \text{BZDD} \]

\[ KZ3 = \frac{0,05}{10} \cdot 40 = 0,2 \]

\[ \frac{\beta_b}{49,854} = \frac{\beta_b}{49,854} + \frac{0,05}{49,854} \cdot \left( \frac{\beta_b}{10} \right) \cdot 10 \]

\[ \text{BZM} = \text{BZM} + KZ4 \cdot \text{BZDM} \]

\[ KZ4 = \frac{0,05}{49,854} \cdot 10 = 0,0100294 \]
KSS Boeing 747 Main motion simulation, part 2:
Sum of body-axes rotational accelerations, see sections 9.1., 9.2. and 12.
\[ \dot{\alpha}_s = \dot{\alpha}_b,1_p + \dot{\alpha}_b,2_p \]  
\[ \dot{\alpha}_s = \frac{\dot{\alpha}_b,1_p}{2} + \frac{\dot{\alpha}_b,2_p}{2} \cdot 2 \]  
SPITCHEH = SPITCHED + K126 . MPITCHEH

KP26 = 2 (see line 41 of Appendix B, part 2)
\[ \dot{\beta}_s = \dot{\beta}_b,1_p + \dot{\beta}_b,2_p \]  
\[ \dot{\beta}_s = \frac{\dot{\beta}_b,1_p}{2} + \frac{\dot{\beta}_b,2_p}{2} \]  
SROLLDD = BROLLDD + MROLLDD

Sum of body-axes rotational rates, see sections 9.1., 9.2. and 10.
\[ \dot{\gamma}_s = \dot{\gamma}_b,1_p + \dot{\gamma}_b,2_p \]  
\[ \dot{\gamma}_s = \frac{\dot{\gamma}_b,1_p}{2} + \frac{\dot{\gamma}_b,2_p}{2} \]  
SPITCHHM = BPITCHHM + MPITCHHM

\[ p_s = p_b,1_p + p_b,2_p \]  
\[ p_s = \frac{p_b,1_p}{2} + \frac{p_b,2_p}{2} \]  
SROLLLM = BROLLLM + MROLLLM

Euler rates, see section 10:
\[ \dot{\theta}_1 = q_s \cdot \cos \phi_m - \tau_b,2_p \cdot \sin \phi_m \]  
\[ \dot{\theta}_1 = \frac{q_s}{1} \cdot \frac{\cos \phi_m}{1} - \frac{\tau_b,2_p}{1} \cdot \frac{\sin \phi_m}{1} \]  
MPITCHSD = SPITCHHM . cos(MROLLLM) - MYANUM . sin(MROLLLM)

\[ \dot{\phi}_1 = p_s + q_s \cdot \sin \phi_m \cdot \sin \phi_m \cdot \sin \phi_m + \tau_b,2_p \cdot \cos \phi_m \cdot \frac{\sin \phi_m}{\cos \phi_m} \]  
\[ \dot{\phi}_1 = \frac{p_s}{1} + \frac{q_s}{1} \cdot \frac{\sin \phi_m}{1} - \frac{\tau_b,2_p}{1} \cdot \frac{\cos \phi_m}{1} \cdot \frac{\sin \phi_m}{\cos \phi_m} \]

\[ \dot{\psi}_1 = \frac{\sin \theta_m}{\cos \theta_m} \cdot \frac{T_b \cdot h_p}{\cos \theta_m} \cdot \frac{\cos \phi_m}{\cos \theta_m} \]

\[ \dot{\psi}_1 = \frac{\sin \theta_m}{\cos \theta_m} \cdot \frac{T_b \cdot h_p}{\cos \theta_m} \cdot \frac{\cos \phi_m}{\cos \theta_m} \]

MYawSD = SPitchM . sin(MRollM) / cos(MPitchM) + MYawM . cos(MRollM) / cos(MPitchM).

Return to ground check: When the simulated aircraft is returned to ground by means of the "return to ground button" on the instructor's console, the following variables in the motion program are set to zero:

\[ \dot{\psi}_1, \dot{\phi}_m, \theta_m \]

\[ \dot{\lambda}_1, \dot{\phi}_m, \phi_m \]

\[ \dot{\theta}_m, \dot{\phi}_m, \phi_m \]

see Appendix B, part 2, line 142 - 157.

Rotational washout, see section 11:

Pitch: \( \gamma_{\theta_R} = 200 \) sec

\[ \dot{\theta}_m = \frac{1}{\tau_{\theta_R}} \cdot \theta_m \]

\[ \dot{\phi}_m = \frac{1}{\tau_{\theta_R}} \cdot \frac{\theta_m}{1} \]

MPitchMD = MPitchSD - KP24 . MPitchM

KP24 = \( \frac{1}{200} = 0.005 \)

Rectangular integration:

\[ \dot{\theta}_m = \dot{\theta}_m + 0.05 \cdot \dot{\theta}_m \]

\[ \frac{\dot{\theta}_m}{1} = \frac{\dot{\theta}_m}{1} + 0.05 \cdot \dot{\theta}_m \]
MPITCHSM = MPITCHSM + KP18 . MPITCHMD

KP18 = 0.05

Motion system lead compensation, see section 12:

\[ \theta_c = \theta_m + B_4 \cdot \dot{\theta}_m + A_4 \cdot \ddot{\theta}_m \]

\[ \dot{\theta}_c = \frac{\dot{\theta}_m}{1 + B_4 \cdot \frac{\dot{\theta}_m}{1 + A_4 \cdot \frac{\dot{\theta}_m}{1}} } \]

MPITCHC = MPITCHSM + KP19 . MPITCHMD + KP20 . SPITCHMD

KP19 = 0.28
KP20 = 0.044

Roll:

\[ \tau_\phi_R = 200 \text{ sec} \]

\[ S_{\phi_R} = 1 \text{ rad.} \]

\[ \dot{\phi}_m = \dot{\phi}_1 - \frac{1}{\tau_{\phi_R}} \cdot \phi_m \]

\[ \dot{\phi}_m = \frac{\dot{\phi}_1}{1 - \frac{1}{\tau_{\phi_R}}} - \frac{1}{1} \cdot \frac{\phi_m}{1} \]

MROLLMD = MROLLSD - KR23 . MROLLSM

KR23 = \frac{1}{200} = 0.005

Rectangular integration:

\[ \phi_m = \phi_m + 0.05 \cdot \dot{\phi}_m \]

\[ \dot{\phi}_m = \frac{\phi_m}{1} + 0.05 \cdot \frac{\dot{\phi}_m}{1} \]

MROLLSM = MROLLSM + KR18 . MROLLMD

KR18 = 0.05

Motion system lead compensation:

\[ \phi_c = \phi_m + B_5 \cdot \dot{\phi}_m + A_5 \cdot \ddot{\phi}_m \]

\[ \dot{\phi}_c = \frac{\dot{\phi}_m}{1 + B_5 \cdot \frac{\dot{\phi}_m}{1 + A_5 \cdot \frac{\dot{\phi}_m}{1}} } \]

\[ \frac{\dot{\phi}_c}{1} = \frac{\dot{\phi}_m}{1} + B_5 \cdot \frac{\dot{\phi}_m}{1} + A_5 \cdot \frac{\ddot{\phi}_m}{1} \]

KR19 = 0.28
KR20 = 0.044 · 2 = 0.088

Yaw:
\[ \tau_R = 20 \text{ sec} \]
\[ S_\psi = 1 \text{ rad} \]
\[ \psi_m \]
\[ \dot{\psi}_m = \dot{\psi}_1 \cdot \frac{1}{\tau_R} \cdot \psi_m \]
\[ \ddot{\psi}_m = \dot{\psi}_1 \cdot \frac{1}{\tau_R} \cdot \dot{\psi}_m \]
\[ \tau_R = \tau_1 \cdot \frac{1}{1} \cdot \psi_m \]

MYAWMD = MYAWSD - KJ11 . MYAWSM

KJ11 = \frac{1}{20} = 0.05

Rectangular integration:
\[ \dot{\psi}_m = \psi_m + 0.05 \dot{\psi}_m \]
\[ \frac{\dot{\psi}_m}{\tau_1} = \frac{\psi_m}{\tau_1} + 0.05 \cdot \frac{\dot{\psi}_m}{\tau_1} \]

MYAWSM = MYAWSM + KJ4 . MYAWMD

KJ4 = 0.05

Motion system lead compensation:
\[ \dot{\psi}_c = \dot{\psi}_m + B_6 \cdot \dot{\psi}_m + A_6 \cdot \frac{\tau_{b, h_p}}{2} \]
\[ \frac{\dot{\psi}_c}{\tau_1} = \frac{\dot{\psi}_m}{\tau_1} + B_6 \cdot \frac{\dot{\psi}_m}{\tau_1} + A_6 \cdot \frac{\tau_{b, h_p}}{2} \]

MYAWNC = MYAWSM + KJ5 . MYAWMD + KJ6 . MYAWDD

KJ5 = 0.28
KJ6 = 0.044 · 2 = 0.088.

Sum of body-axes translational accelerations, see section 6:
\[ \ddot{x}_b = \ddot{x}_{b,1} + \ddot{x}_{b,2} \]
\[ \frac{\ddot{x}_b}{\tau_1} = \frac{\ddot{x}_{b,1}}{\tau_1} + \frac{\ddot{x}_{b,2}}{\tau_1} \]
SXDD = BXDD + MXDD

\[ \vec{y}_s = \vec{y}_{s,1} + \vec{y}_{s,2} \]

\[ \frac{\vec{y}_s}{8} = \frac{\vec{y}_{s,1}}{8} + \frac{\vec{y}_{s,2}}{8} \]

SYDD = BYDD + MYDD (see line 351 - 357 of Appendix B, part 2)

Body to inertial transformation of the motion platform translational accelerations, see section 7:

\[ \ddot{x}_b = \ddot{x}_s \cdot \cos \phi_m \cdot \cos \psi_m + \dot{\psi}_m \cdot \sin \phi_m \cdot \sin \psi_m \]

\[ - \cos \phi_m \cdot \sin \psi_m \]  
\[ (7.1) \]

\[ \frac{\ddot{x}_b}{10} = \frac{\ddot{x}_s}{10} \cdot \cos \phi_m \cdot \cos \psi_m + \frac{\dot{\psi}_m}{10} \cdot \left( \frac{\ddot{\phi}_m}{8} \right) \cdot \frac{\sin \phi_m}{10} \cdot \sin \phi_m \cdot \frac{\sin \psi_m}{10} \cdot \cos \phi_m \cdot \sin \psi_m \]

MXDD = SXDD \cdot \cos(MPITCHSM) \cdot \cos(MYAWSM) + KY16 \cdot SYDD

\{ \sin(MROLLSM) \cdot \sin(MPITCHSM) \cdot \cos(MYAWSM) - \cos(MROLLSM) \cdot \sin(MYAWSM) \}

KY16 = \frac{8}{10} = 0.8

\[ \ddot{y}_b = \ddot{y}_s \cdot \cos \phi_m \cdot \sin \psi_m + \dot{\psi}_m \cdot \sin \phi_m \cdot \sin \psi_m \]

\[ + \cos \phi_m \cdot \cos \psi_m \]  
\[ (7.2) \]

\[ \frac{\ddot{y}_b}{8} = \frac{\ddot{y}_s}{8} \cdot \frac{\cos \phi_m}{8} \cdot \sin \psi_m + \frac{\dot{\psi}_m}{8} \cdot \left( \frac{\ddot{\phi}_m}{10} \right) \cdot \frac{\sin \phi_m}{8} \cdot \sin \phi_m \cdot \frac{\sin \psi_m}{8} \cdot \cos \phi_m \cdot \sin \psi_m \]

MYDD = KX16 \cdot SXDD \cdot \cos(MPITCHSM) \cdot \sin(MYAWSM) + SYDD

\{ \sin(MROLLSM) \cdot \sin(MPITCHSM) \cdot \sin(MYAWSM) - \cos(MROLLSM) \cdot \cos(MYAWSM) \}

KX16 = \frac{10}{8} = 1.25 = 0.625 \quad \text{SALD 2}

\( \ddot{z}_b \) Note: The contribution of \( \ddot{z}_b \) to \( \ddot{x}_b \) and \( \ddot{y}_b \) is neglected in the KSS Boeing 747 Motion Simulation Program, because this contribution is small and the computation-time required for the transformation is less.
\[ z_i = -x_i \cdot \sin \theta_m + y_i \cdot \sin \phi_m \cdot \cos \theta_m + y_b \cdot \cos \phi_m \cdot \cos \theta_m \]

\[ \frac{z_i}{40} = -\frac{1}{40} \cdot \frac{x_i}{10} \cdot (\frac{1}{8}) \cdot 10 \cdot \sin \theta_m + \frac{1}{40} \cdot (\frac{y_i}{8}) \cdot 8 \cdot \sin \phi_m \cdot \cos \theta_m + \frac{z_b}{40} \cdot \cos \phi_m \cdot \cos \theta_m \]

\[
M_{XSD} = KX17 \cdot SXDD \cdot \sin(MPITCHSM) + KY17 \cdot SYDD \cdot \sin(MROLLSM) \cdot \\
\cdot \cos(MPITCHSM) + BZDD \cdot \cos(MROLLSM) \cdot \cos(MPITCHSM) \cdot \\
\]

\[
KX17 = -\frac{10}{40} = -0.25 \\
KY17 = \frac{8}{40} = 0.2
\]

Translational washout, see section 8:

\[ T_{X,T} = 0.7 \]

\[ T_{X,T} = 2 \text{ sec} \]

\[
\frac{X_m}{10} = \frac{X_i}{10} - \frac{2x_i}{T_{X,T}} \cdot \left( \frac{x_i}{10} \cdot \frac{X_m}{10} \right) - \frac{1}{T_{X,T}} \cdot \left( \frac{x_i}{10} \cdot \frac{X_m}{10} \right) - \frac{1}{10 + x_i} \cdot \left( \frac{x_i}{10} \cdot \frac{X_m}{10} \right) 11,3952
\]

\[
M_{XSD} = M_{XSD} - KX18 \cdot M_{XDM} - KX19 \cdot M_{XOM}
\]

\[
KX18 = 2 \cdot \frac{X_i}{10} + 0.7 \cdot 10 = 0.7 \\
KX19 = \frac{11,3952}{4} = 0.28488
\]

Rectangular integration:

\[ T_{X,T} = x_m + 0.05 \frac{x_m}{10} \]

\[ T_{X,T} = x_m + 0.05 \frac{x_m}{10} \cdot 10 \]

\[
M_{XDM} = M_{XDM} + KX12 \cdot M_{XDD}
\]

\[
KX12 = 0.05 \cdot 10 = 0.05 \\
x_m = x_m + 0.05 \frac{x_m}{10} \]

\[
\frac{x_m}{11,3952} = \frac{x_m}{11,3952} \cdot \frac{10}{10} \cdot 10
\]
\[ \text{MOM} = \text{MOM} + \text{XX13} \cdot \text{MOCM} \]
\[ \text{XX13} = \frac{0.05}{11,3952} \cdot 10 = 0.0045878 \]

Motion system lead compensation, see section 12:

\[ x_c = x_m + B_1 \cdot \frac{x_m - A_1 \cdot x_m}{10} \]
\[ x_c = \frac{x_m - B_1 \cdot \frac{x_m}{11,3952} \cdot \frac{1}{10} + A_1 \cdot x_m}{10} \]
\[ \text{MOC} = \text{MOM} + \text{XX14} \cdot \text{MOCM} + \text{XX15} \cdot \text{MOCMD} \]
\[ \text{XX14} = 0.28 \cdot 10 = 0.24572 \]
\[ \text{XX15} = 0.044 \cdot \frac{10}{11,3952} = 0.0038613 \]
\[ \tau_T = 0.7 \]
\[ \tau_T = 2 \text{ sec} \]
\[ \dot{y}_T = \frac{2 \cdot y_T}{y_T} \cdot \frac{y_m - y_m^-}{	au_T} \cdot y_T \]
\[ \ddot{y}_m = \frac{\dot{y}_m}{8} = \frac{2 \cdot y_T}{8 \cdot y_T} \cdot \frac{y_m - y_m^-}{(10)} \cdot 10 - \frac{1}{8 \cdot y_T^2} \cdot \frac{y_m}{(11,3952)} \cdot 11,3952 \]

\[ \text{MMMD} = \text{MMMD} - (\text{XX18} \cdot \text{MMCM}) - (\text{XX19} \cdot \text{MMM}) \]
\[ \text{XX18} = \frac{2}{8} \cdot \frac{0.7}{2} \cdot 10 = 0.875 \]
\[ \text{XX19} = \frac{11.3952}{8} \cdot \frac{4}{4} = 0.3561 \]

Rectangular integration:
\[ \dot{y}_m = \dot{y}_m + 0.05 \dot{y}_m \]
\[ \frac{\dot{y}_m}{10} = \frac{0.05}{10} \cdot \frac{y_m^-}{8} \cdot 8 \]

\[ \text{MYCM} = \text{MYCM} + \text{KY12} \cdot \text{MOCMD} \]
\[ \text{KY12} = \frac{0.05}{10} \cdot 8 = 0.04 \]
\[ y_m = y_m + 0.05 \dot{y}_m \]
\[ \frac{y_m}{11,3952} = \frac{y_m}{11,3952} + 0.05 \cdot \frac{\dot{y}_m}{10} \cdot 10 \]
MOM = MOM + KY13 . MYDM

KY13 = \frac{0.05}{TT,3952} \cdot 10 = 0.043878

Motion system lead compensation:

Y_C = y_m + B_2 \cdot y_m + A_2 \cdot y_m

\frac{Y_C}{TT,3952} = \frac{Y_m}{TT,3952} \cdot \frac{B_2}{TT,3952} \cdot \left(\frac{y_m}{10}\right) \cdot 10 + \frac{A_2}{TT,3952} \cdot \left(\frac{y_m}{8}\right) \cdot 8

MYC = MOM + KY14 . MYDM + KY15 . MMEO

KY14 = \frac{0.28}{TT,3952} \cdot 10 = 0.245718

KY15 = \frac{0.044}{TT,3952} \cdot 8 = 0.03089

\tau_T = 0.7

\tau_T = 2 \text{ sec.}

\tau_m = \frac{2\tau_T}{\tau_T} \cdot \frac{1}{\tau_T} \cdot \tau_m

\frac{\tau_m}{40} = \frac{2\tau_T}{40} \cdot \frac{1}{\tau_T} \cdot \left(\frac{\tau_T}{40}\right) \cdot 10 + \frac{1}{40 \tau_T} \cdot \left(\frac{\tau_m}{49,854}\right) \cdot 49,854

MMEO = MEIDD - (K28 . MEIM) - (K29 . MZM)

K28 = \frac{2}{40} \cdot \frac{0.2}{40} \cdot 10 = 0.175

K29 = \frac{49,854}{40} \cdot \frac{0.311587}{40}

Rectangular integration:

\int \theta_m = \int \theta_m + 0.05 \cdot \theta_m

\int \theta_m \int 10 = \frac{\theta_m}{10} + 0.05 \cdot \left(\frac{\theta_m}{40}\right) \cdot 40

MEIM = MEIM + KZ3 . MMEO
The KSS Boeing 747 main motion simulation program, represented in Appendix B, is executed each 50 msec on a SDS Sigma 2 computer. Timing runs of this program show that the average computation time required for execution amounts to 7 msec, see Table 3. Table 4 shows a timing-run of the complete KSS Boeing 747 flight simulation program, including motion simulation, with the aircraft in the on-ground condition. The average time required for the computation remains within 50 msec.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in SI units</th>
<th>Program value</th>
<th>Parameter</th>
<th>Value in SI units</th>
<th>Program value</th>
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Table 2: Parameter values as used in the KSS B-747 Motion simulation.
<table>
<thead>
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<th>Program value</th>
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<td>$\tau_{\phi_{1p}}$, sec</td>
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Table 2: Parameter values as used in the KSS B-747 Motion simulation.
(cont'd)
### Table 3: Timing-run of KSS Boeing 747 main motion simulation program.

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<th>Avg (in msecs)</th>
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<tr>
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<tr>
<td>#03</td>
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### Table 4: Timing-run of total system; aircraft on ground.

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<th>Avg (in msecs)</th>
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<td>47.5</td>
</tr>
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<tr>
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<tr>
<td>#13</td>
<td>47.0</td>
<td>40.9</td>
<td>43.5</td>
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</table>
APPENDIX B, PART 1

1 * KSS B-747 MAIN MOTION SIMULATION, PART 1
2 * MAINNN1 FILE NO : K-817-1
3 * MAINNN2 FILE NO : K-817-2
4 *
5 *
6 *
7 * TEST PILOT : CAPTAIN J.L. VELDHUYSEN VAN ZANTEN
8 *
9 * DESIGN : IR. W. BAARSBLU
10 *
11 * SOFTWARE : B. BAARSCHERS
12 *
13 * ASSEMBLE THIS PROGRAM WITH :
14 * EXTR. X-REF
15 * SLV SP
16 * MOTION X-REF
17 * FLIGHT INT. X-REF
18 *
19 * ISSUE J
20 *
21 * AUG. 1975
22 *
23 * DEF MAINNN1
24 *
25 CSECT
26 ORG X'0000'
27 0000 3ECC A MAINNN1 LDA ACIFLG04 FLIGHT OR TOTAL FREEZE ?
28 0001 9BC9 A AND BITA4B
29 0002 6402 A BAZ NOFRIE
30 0003 44F0 A B *PROGRTEM YES
31 *
32 BASE X'1000'
33 *
34 0004 80B0 A NOFRIE LDA BASE10
35 0005 7407 A RCPY A4, B
36 *
61  PAGE
62  
63  TRANSFORMATION OF X WIND TO BODY-AXIS ACCEL'S.
64  UBD = (UWD*VCSAB*VCSB)-(VMD*VCSAB*VSNB*KUBBD)
65  -(VWD*VSNAB*K4)  (=SALD 3)
66  
67  0017 81AB A TRANSFOR  LDA  UWD  W-AXIS X ACCEL.
68  0018 3CA2 A  MUL  VCSAB  COS.ALPHA BODY
69  0019 20A1 A  SALD  1
70  001A 7AF6 A  RCPY  E,A
71  001B 3CA0 A  MUL  VCSB  COS.BETA
72  001C 20A1 A  SALD  1
73  001D 7AF6 A  RCPY  E,T  SAVE IT
74  001E 81AC A  LDA  VWD  W-AXIS Y ACCEL.
75  001F 3CB8 A  MUL  VCSAB  COS.ALPHA BODY
76  0020 20A1 A  SALD  1
77  0021 7AF6 A  RCPY  E,A
78  0022 3CB9 A  MUL  VSNB  SINE BETA
79  0023 20A1 A  SALD  1
80  0024 7AF6 A  RCPY  E,A
81  0025 3CB9 A  MUL  KUBBD  .8
82  0026 20A1 A  SALD  1
83  0027 703E A  RADDI  *E,T  SUBTRACT IN T REG.
84  0028 81AB A  LDA  UWD  W-AXIS Z ACCEL.
85  0029 3CB9 A  MUL  VSNAB  SINE ALPHA BODY
86  002A 20A3 A  SALD  3
87  002B 703E A  RADDI  *E,T  SUBTRACT IN T REG.
88  002C 7AF3 A  RCPY  T,A
89  002D E1AE A  STA  UBD
90  
91  TRANSFORMATION OF Y WIND TO BODY-AXIS ACCEL.
92  VBDM = (UWD*VSNB) + (VMD*KVBD) + (VWD*VCSB)
93  
94  002E 81AB A  LDA  UWD  W-AXIS LONGITUDINAL ACCEL.
95  002F 3CB9 A  MUL  VSNB  SINE BETA
96  0030 20A1 A  SALD  1
97  0031 7AF6 A  RCPY  E,A
98  0032 3CB9 A  MUL  KVBD  .625
99  0033 20A2 A  SALD  2
100  0034 7AF6 A  RCPY  E,T  SAVE IT
101  0035 81AC A  LDA  VWD  W-AXIS LATERAL ACCEL.
102  0036 3CB9 A  MUL  VCSB  COS.BETA
103  0037 20A1 A  SALD  1
104  0038 7CF6 A  RADDI  E,T  SUM IT
105  0039 7AF3 A  RCPY  T,A
106  003A E1AF A  STA  VBDM
TRANSFORMATION OF Z WIND TO BODY AXIS ACCEL.

\[ \mathbf{WBD} = (\mathbf{UMD} \cdot \mathbf{VSNAB} \cdot \mathbf{VCSB} \cdot \mathbf{KWB01}) - (\mathbf{VMD} \cdot \mathbf{VSNAB} \cdot \mathbf{VSNB} \cdot \mathbf{KWB02}) + (\mathbf{WMO} \cdot \mathbf{VCSAB}) \]

LDA UMD
MUL VSNAB
RCPY E,A
W-AXIS X ACCEL.
SINE ALPHA BODY

SLD 1
COS.BETA

MUL VCSB
SALD 1

SLD 1
SAVE IT

MUL KWB01
RCPY E,T
.25

SLD 1
SAVE IT

MUL KWB02
RADD E,T
SUBTRACT IN T REG.

LDA VMD
MUL VCSAB
W-AXIS Y ACCEL.
SINE ALPHA BODY

SLD 1

MUL VSNB
RCPY E,A
SINE BETA

SLD 1

MUL VSNB
RCPY E,A
.2

MUL KWB02
RADD E,T
SUM IT

RCTY T,A

STA WBD
Z-BODY AXIS ACCEL.
PAGE 137

* TIMER TO STOP THE CALCULATIONS DURING ON/OFF GRO TRANSITION

141 0053 888A A TIMEX
142 0054 6403 A BAZ TIMEUP
143 0055 F88A A IM TIMER
144 0056 480C A B D01
145 0057 8C71 A TIMEUP LDA V88G
146 0058 0B66 A CP LTCOND
147 0059 6203 A BNC $+3
148 005A 7A0A A RCPY Z,A
149 005B 480A A B $+4
150 005C 888A A LDA 20ITERS
151 005D E880 A STA TIMER
152 005E 7A8A A RCPY $+2,A
153 005F E881 A STA STOPFLAG
154 0060 8C68 A LDA V88G
155 0061 E870 A STA LTCOND

TIME WAS NOT YET UP
CONDITION CHANGED?
YES
NO
RESET STOPFLAG
1 SECOND
SET STOPFLAG
STORE PRESENT CONDITION
IN LAST TIME CONDITION
156  PAGE
157  *  PITCH BODY ACCELERATIONS
158  *
159  *
160  *  TAU  THEETA HI-PASS  =  6 SEC
161  *  ZETA  THEETA HI-PASS  =  7
162  *  S  THEETA HP DD  =  2 RAD/SEC 2
163  *  S  THEETA HP D  =  1 RAD/SEC
164  *  S  THEETA HP  =  1 RAD
165  *
166  *  VPRO  =  2 RAD/SEC 2
167  *
168  *  MPITCHDD = VPRO - (KP1*MPITCHDM) + (KP2*MPITCHO)
169  *
170  0062 81B7  A  001  LDA  MPITCHDM
171  0063 386F  A  MUL  KP1
172  0064 7A86  A  RCPY  E,T  SAVE
173  0065 81B8  A  LDA  MPITCHO
174  0066 386D  A  MUL  KP2
175  0067 7C36  A  RADD  E,T
176  0068 10C0  A  RD  X'CO'
177  0069 8C50  A  LDA  VPRO
178  006A 7D78  A  RADDI  *T,A  ADD 2TH COMPLEMENT = SUBTRACT
179  006B E1B4  A  STA  MPITCHDD
180  *
181  *  PITCH RATE
182  *
183  *  MPITCHDM = MPITCHDM + (KP3*MPITCHDD)
184  *
185  006C 31CE  A  MUL  KP3
186  006D 8A79  A  ADD  MPITCHDL  L/S PART
187  006E 8E78  A  STA  MPITCHDL  NEW L/S PART
188  006F 10C0  A  RD  X'CO'
189  0070 81B7  A  LDA  MPITCHDM  M/S PART
190  0071 7E76  A  RADD  E,A
191  0072 E1B7  A  STA  MPITCHDM  M/S PART
192  *
193  *  MPITCHH = MPITCHH + (KP4*MPITCHDM)
194  *
195  0073 31CF  A  MUL  KP4
196  0074 8A75  A  ADD  MPITCHL  L/S PART
197  0075 8E74  A  STA  MPITCHL  NEW L/S PART
198  0076 10C0  A  RD  X'CO'
199  0077 81B8  A  LDA  MPITCHH
200  0078 7E76  A  RADD  E,A
201  0079 E1B8  A  STA  MPITCHH  M/S PART
ROLL BODY ACCELERATIONS

TAU  PHI  HI-PASS = 6 SEC
ZETA PHI HI-PASS = 1
S PHI HP DD = 4 RAD/SEC 2
S PHI HP D = 2 RAD/SEC
S PHI HP = 2 RAD
VRAD = 4 RAD/SEC 2

WROLLDD = VRAD - ((KR1*WROLLDD) + (KR2*WROLLDD))

ROLL CHAN

LDA WROLL
MUL KR1
RCPY E,T
LDA WROLL
MUL KR2
RADD E,T
RD X*CO' RESET COF
LDA VRAD ROLL ACCEL
RADDI T,A ADD 2TH COMPLEMENT = SUBTRACT
STA WROLLDD

ROLL RATE

WROLL = WROLLDD + (KR3*WROLLDD)

MUL KR3
ADD WROLLDL L/S PART
STA WROLLDL NEW L/S PART
RD X*CO' RESET COF
LDA WROLL W/S PART
RADD E,A
STA WROLLDD NEW W/S PART

WROLL = WROLLDD + (KR4*WROLLDD)

MUL KR4
ADD WROLLLL L/S PART
STA WROLLLL NEW L/S PART
RD X*CO' RESET COF
LDA WROLL W/S PART
RADD E,A
STA WROLL W/S PART
YAW BODY ACCELERATIONS

TAU PSI HI-PASS = 1.5 SEC
ZETA PSI HI-PASS = 1.7
S PSI HP DD = 2 RAD/SEC
S PSI HP D = 1 RAD/SEC
S PSI HP = 1 RAD

VHRO = 2 RAD/SEC

MYA suitability = VHRO - ((KJ1*MYAOM) + (KJ2*MYAWM))

MYAWM = MYAOM + (KJ3*MYAWD)

L/S PART

L/S PART

NEW L/S PART

NEW M/S PART

NEW M/S PART

NEW M/S PART
DATA AND ADRL'S. WHEN SCALED OTHER THAN 0
THIS IS DONE TO AVOID NECESSARY SHIFTS
WIND TO BODY RESCALING USED WITH SALD 3

0083 36ED A  XU1  DEC  428697E-6
0084 4E7B A  YV1  DEC  613125E-6
0085 2F17 A  ZW1  DEC  367879E-6
0086 KSCALE RES  0
0086 6666 A  KBB00  DEC  8E-1
0087 5000 A  KVB00  DEC  625E-3
0088 4000 A  KVB01  DEC  25E-281
0089 3333 A  KBB02  DEC  2E-181

008A 0851 A  ADR1  VCSAB  COSINE ALPHA BODY
008B 0853 A  ADR1  VCSB  COSINE BETA
008C 0885 A  ADR1  VSNB  SINE BETA
008D 0883 A  ADR1  VSNAB  SINE ALPHA BODY
008E 0888 A  ADR1  VSNAB  SINE ROLL BODY
008F 0887 A  ADR1  VSNPB  SINE PITCH BODY
00C0 0895 A  ADR1  VCSPB  COS. PITCH BODY
00C1 08E0 A  ADR1  VXBP  GROUND SPEED
00C2 08D1 A  ADR1  VPR  PITCH RATE
00C3 08C5 A  ADR1  VHR  YAW RATE
00C4 08D5 A  ADR1  VRR  ROLL RATE
00C5 08C6 A  ADR1  VHRD  YAW ACCEL. 281
00C6 08D2 A  ADR1  VPRD  PITCH ACCEL. 281
00C7 08D6 A  ADR1  VRD  ROLL ACCEL. 282
00C8 0883 A  ADR1  VBDG  ON/OFF GRD FLAG
00C9 0F0A A  ADR1  ACTFLG0A  FOR FREEZE
00CA 0880 A  BIT4&8  DATA  X'0B80'  FLT & TOTAL FREE

00CB 0000 A  WCDO  DATA  0  BODY-CENTROID ACCEL. 10M/SEC 2. LONGITUDINAL
00CC 0000 A  WBDO  DATA  0  BM/SEC 2. LATERAL
00CD 0000 A  WCDO  DATA  0  GCM/SEC 2. VERTICAL

00CE 52E1 A  KUBC  DEC  6475E-4  SALD  3
00CF 679A A  KUBC  DEC  8094E-4  SALD  4
00DD 52E1 A  KUBC  DEC  6475E-4  SALD  2
356   *  PAGE
357  
358 0001 4480 A KX11  DEC  581377E-6  SALD 3
359 0002 1000 A KP1   DEC  116666E-581
360 0003 0380 A KP2   DEC  01388E-581
361 0004 4000 A KP13  DEC  25E-281
362 0004 R KP14       EQU  KP13
363 0005 000A A KP15  DEC  7E-1   SALD 1
364 0004 R KP16       EQU  KP13
365 0006 7000 A KY10  DEC  875E-3   SALD 2
366 0007 5929 A KY11  DEC  7122E-4   SALD 2
367 0008 5000 A KR12  DEC  625E-3
368 0009 0000 A KR13  DEC  -125E3-381
369 0004 0000 A KR15  DEC  35E-281
370 000B 0000 A KR16  DEC  125E-381
371 000C 5000 A KR28  DEC  625E-3   SALD 2
372 000D 0000 A TIMER DATA  0
373 000E 0000 A LICONDOT DATA  0
374 000F 0000 A STPFLG DATA  -20
375 000E 0000 A STOPFLG DATA  0
376  *  -1 IMPLIES 1 STOP CALCULATION
377 00E1 7777 A KJ1   DEC  233332E-682
378 00E2 38E3 A KJ2   DEC  0555552E-683
379  *
380 00E3 E148 A KX1   DEC  -03E-283
381 00E4 4ECD A KY1   DEC  3E-181
382 00E5 5165 A KZ2   DEC  635893E-6  SALD 3
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<td>389</td>
<td>PITCH BODY DOT L/S INTEGRATION</td>
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<td>X BODY L/S INTEGRATION</td>
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<td>X BODY DOT MOST INTEGRATION</td>
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<td>PITCH BODY MOST INTEGRATION</td>
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PAGE
SPECIFIC FORCES
CENTROID TRANSFORMATION
UBCD = UBD - (((VPR*VPR) + (VHR*VHR)) * KUBC)
LDA VPR
MUL VPR
PITCH RATE MOST
RCPY E,T
SAVE
RCPY VHR
yaw rate
RCPY E,T
SAVE IN E
REG.

LDA UBD
MOT.B-AXIS LATERAL ACC.
SUBTRACT

STA UBCD
MOT.B-AXIS LONG. ACC. AT CENTROID

V6CD = V6DM + (((VRR*VPR) + VHRD) * KVBC)

LDA VRR
ROLL RATE
MUL VPR

RCPY E,A

ADD VHRD

MUL KVBC
RCPY E,A

ADD V6BM
MOT.B-AXIS LATERAL ACC.

STA VBCD
MOT.B-AXIS QT. ACC. AT CENTROID

WBD = WBD + (((VRR*VHR) - VPRO) * WBC)

LDA VRR

MUL VHR

RCPY E,A
SUB VPRO

MUL KVBC

ADD WBD
MOT.B-AXIS VERTICAL ACC.

STA WBCD
MOT.B-AXIS VERT. ACC. AT CENTROID
LONGITUDINAL SPECIFIC FORCE.

LONGITUDINAL HI-PASS FILTER

\[ \tau = 0.7 \text{ sec} \]
\[ \zeta = 0.7 \]
\[ s \times \text{HI DD} = 10 \text{ m/sec}^2 \]
\[ s \times \text{HI D} = 10 \text{ m/sec} \]
\[ s \times \text{HI} = 11.3952 \text{ m} \]

\[ \text{BXDD} = \text{UBCD} - (\text{BPITCHM} - (\text{KKX10*BXDM}) - (\text{KKX11*BXM}) \]

LDA STOPFLAG CALC TO BE STOPPED?

BAN Q03 YES

RADD A,A FOR KKX10 = 2.0

ADD BPITCHM

RCPY A,T SAVE IT

LDA BXDM

MUL KKX11

SALD J

RADD E,T SUM IT

LDA UBDD

RADDI T*A SUBTRACT

STA BXDD

INTEGRATION

BXDD = BXDD + (KKX12*BXDD)

LDA BXDD

MUL KKX12

ADD BXOL L/S PART

STA BXOL NEW L/S PART

RD X*CO

LDA BXDM M/S PART

STA BXDM NEW M/S PART

BXM = BXM + (KKX13*BXDM)

MUL KKX13

ADD BXL L/S PART

STA BXL NEW L/S PART

RD X*CO

LDA BXM M/S PART

STA BXM NEW M/S PART

STA BXM NEW M/S PART
LONGITUDINAL LOW-PASS FILTER

TAU   TAU   LOW-PASS  =  2 SEC
ZETA  THEA  LOW-PASS  = .7
S   THEA  LP 00  =  1 RAD/SEC 2
S   THEA  LP 0  =  1 RAD/SEC
S   THEA  LP  =  1 RAD

BPITCHDD = (KP 13*UBCD) + (KP 14*VSNPB) - (KP 16*BPITCHM)
-(KP 15*BPITCHM)

LDA BPITCHM
MUL KP 15
SALD 1
RCPY E,T
LDA UBCD  SINE PITCH BODY
LDA XNSPB
MUL KP 14
RADD E,L
LDA BPITCHM  SUM IN L REG.
LDA XNSPB
MUL KP 16
RADD *E,L
STA BPITCHDD  SUBTRACT IN L REG.

INTEGRATION

BPITCHDD = BPITCHM + (KP 17*BPITCHDD)

LDA BPITCHDD
MUL KP 17
ADD BPITDL  L/S PART
STA BPITDL
ADD X’CO’
RST CDF
LDA BPITDL
M/S PART
RADD E,L
STA BPITDD  NEW M/S PART

BPITCHM = BPITCHM + (KP 18*BPITCHM)

LDA BPITCHDD
MUL KP 18
ADD BPITDL  L/S PART
STA BPITDL
ADD X’CO’
RST CDF
LDA BPITDL
M/S PART
RADD E,L
STA BPITDD  NEW M/S PART
PAGE

LATERAL SPECIFIC FORCE

LATERAL HI-PASS FILTER

TAU Y HI-PASS = 1 SEC
ZETA Y HI-PASS = .7
S Y HI DD = 8W/SEC 2
S Y HI D = 10W/SEC
S Y HI = 11.3952 M

BYDD = VBCD * (KR12 * BROLLM * (KY10 * BYDM * (KY11 * BYM)) * (KR28 * VSNR8 * VCSPB))

BYDD =

015B 899A A G03
015C 397A A LDA BYDM
015D 20A2 A MUL KY10
015E 74F6 A SALD 2 = KY10^2
015F 8990 A RCPY E,T SAVE
0160 3977 A LDA BYM
0161 20A2 A MUL KY11
0162 7C36 A SALD 2 = KY11^2
0163 8D5B A RADD E,T SAVE SUM
0164 8D5B A LDA VSNR8 SINE ROLL BODY
0165 3D5C A MUL VCSPB COS.PITCH BODY
0166 20A1 A SALD 1
0167 74F6 A RCPY E,A
0168 3975 A MUL KR28
0169 20A2 A SALD 2
016A 7C36 A RADD E,T
016B 8993 A LDA BROLLM
016C 3960 A MUL KR12
016D 20A1 A SALD 1 
016E 895F A LDA VBCD AND SAVE IN E REG.
016F 7C76 A RADD E,A SUBTRACT T REG. CONTENTS
0170 5182 A STA BYDD
PAGE
INTEGRATION
BYOM = BYOM + (KY12*BYDD)

608 0171 310A A MUL KY12 L/S PART
609 0172 9986 A ADD BYDL NEW L/S PART
610 0173 E985 A STA BYDL RST CDF
611 0174 10C0 A RD X*CO
612 0175 8980 A LDA BYDM M/S PART
613 0176 7E76 A RADD E4A
614 0177 E97E A STA BYDM NEW M/S PART
615
616
617

618 0178 3100 A MUL KY13 L/S PART
619 0179 A979 A ADD BYL NEW L/S PART
620 017A E978 A STA BYL RST CDF
621 017B 10C0 A RD X*CO
622 017C 8973 A LDA BYM M/S PART
623 017D 7E76 A RADD E4A
624 017E E971 A STA BYM NEW M/S PART
625  *  PAGE
626  *  LATERAL LOW-PASS FILTER
627  *  TAU  PHI  LOW-PASS  =  2 SEC
628  *  ZETA  PHI  LOW-PASS  =  .7
629  *  S  PHI  LP  DD  =  2 RAD/SEC 2
630  *  S  PHI  LP  D  =  1 RAD/SEC
631  *  S  PHI  LP  =  1 RAD
633  *  (KR16*BROLLW))
634  *
635  636  017F  0940  A  LDA  VBCD
637  0180  31CE  A  MUL  KR13
638  0181  74B6  A  RCPY  E,J  SAVE
639  0182  803C  A  LDA  VSNRB  SINE ROLL BODY
640  0183  3956  A  MUL  KR14
641  0184  74F6  A  RCPY  E,A
642  0185  3D30  A  MUL  VCSPB
643  0186  2041  A  SALD  1
644  0187  7C36  A  RADD  E,T  SAVE SUM
645  0188  81CD  A  LDA  BROLLDM
646  0189  3951  A  MUL  KR15
647  018A  7C36  A  RADD  E,T  SAVE SUM
648  018B  8972  A  LDA  BROLLM
649  018C  394F  A  MUL  KR16
650  018D  7C36  A  RADD  E,T  SAVE SUM
651  018E  75FB  A  RCPYI  *T,A  FOR - SIGN
652  018F  E1BE  A  STA  BROLLDD
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678 PAGE
679 *
680 * VERTICAL HI-PASS FILTER
681 *
682 * TAU Z HI-PASS = .7 SEC
683 * ZETA Z HI-PASS = .7
684 * S Z HP DD = 40 M/SEC 2
685 * S Z HP D = 10 M/SEC
686 * S Z HP = 40.894 M
687 * BZDD = WCDD - (.5*BZDM) - (KZ2*BZM)
688 *
689 019E 8952 A LDA BZM
690 019F 3946 A MUL KZ2
691 01A0 2043 A SALD J
692 01A1 7486 A RCpy E,T SAVE
693 01A2 8954 A LDA BZDM
694 01A3 2001 A SARS 1 *.5
695 01A4 7337 A RADD A,T SAVE SUM
696 01A5 8928 A LDA WCDD
697 01A6 7D78 A RADDI *T,A SUBTRACT
698 01A7 E183 A STA BZDD
699 *
700 * INTEGRATION
701 *
702 * BZDM = BZDM + (KZ3*BZDD)
703 *
704 01A8 3D05 A MUL KZ3
705 01A9 A950 A ADD BZDL L/S PART
706 01AA E94F A STA BZDL NEW L/S PART
707 01AB 10C0 A RD X'CO' RST CDF
708 01AC 894A A LDA BZDM M/S PART
709 01AD 7E76 A RADDI E,A
710 01AE E948 A STA BZDM NEW M/S PART
711 *
712 * BZM = BZM + (KZ4*8ZDM)
713 *
714 01AF 3106 A MUL KZ4
715 01B0 A943 A ADD BZL L/S PART
716 01B1 E942 A STA BZL NEW L/S PART
717 01B2 10C0 A RD X'CO' RST CDF
718 01B3 8930 A LDA BZM M/S PART
719 01B4 7E76 A RADDI E,A
720 01B5 E938 A STA BZM NEW M/S PART
721 01B6 4404 A 0 *PROGRETN
722 • PAGE
723 • EQUALS TABLE AT END OF PROGRAM
724 •
726 10CE A KP3 EQU KPRJ3
727 10CE A KR3 EQU KPRJ3
728 10CE A KJ3 EQU KPRJ3
729 •
730 10CE A KR17 EQU KPRJ3
731 10CE A KR13 EQU KPRJ3
732 •
733 10CF A KP4 EQU KPRJ4
734 10CF A KR4 EQU KPRJ4
735 10CF A KJ4 EQU KPRJ4
736 •
737 10CF A KJ11 EQU KPRJ4
738 10CF A KX12 EQU KPRJ4
739 •
740 10CF A KR18 EQU KPRJ4
741 10CF A KP17 EQU KPRJ4
742 10CF A KP18 EQU KPRJ4
743 •
744 •
745 1000 A KX13 EQU KXY13
746 1000 A KY13 EQU KXY13
747 •
748 •
749 1001 A KP19 EQU KR19
750 1001 A KJ5 EQU KR19
751 •
752 •
753 1003 A KP24 EQU KPRJ24
754 1003 A KR23 EQU KPRJ24
755 •
756 •
757 1002 A KR20 EQU KPRJ20
758 1002 A KJ6 EQU KPRJ20
759 •
760 0002 R KR1 EQU KP1
761 0003 R KR2 EQU KP2
762 •
763 •
764 0000 A END

0 ERRORS
EQUALS ERROR MAINWN1
APPENDIX B, PART 2

1. KSS B-747 MAIN MOTION SIMULATION. PART 2.
2. TEST PILOT: CAPTAIN J.L. VELDHUYSEN VAN ZANTEN
3. DESIGN: IR. W. BAARSFUL
4. SOFTWARE: B. BAARSCHERS
5. ASSEMBLE THIS PROGRAM WITH:
6. EXT. X-REF
7. SLV SP
8. MOTION X-REF
9. FLIGHT INT. X-REF
10. ISSUE: 3
11. AUG.: 1975
12. DEF: MAINMNN2
13. SREF: MOTIONMZ
14. CSECT
15. ORG: X'0000'
16. 20 0000 BC61 A MAINMNN2
17. 0001 9861 A LOA ACTFLGO
18. 0002 6404 A AND BIT48
19. 0003 6408 A BAZ NOFREEZE
20. 0004 7407 A LDA BASEA
21. 0005 7407 A RCPY A, B
22. 0006 7407 A B "PROGREIN"
23. 0007 7407 A "EXIT"
24. 0008 7407 A "BASE X'1000'"
PAGE

SUM OF BODY ROTATIONAL ACCELERATIONS

SPITCHDD = BPITCHDD + ( 2.0 * MPITCHDD )

NDFREEZE LDA MPITCHDD
SALS 1 2.0 *
ADD BPITCHDD
STA SPITCHDD

SRollDD = BRollDD + MRollDD

LDA MRollDD
ADD BRollDD
STA SRollDD

SUM OF BODY ROTATIONAL RATES

SPITCHDM = BPITCHDM + MPITCHDM

LDA MPITCHDM
ADD BPITCHDM
STA SPITCHDM

SRollDM = BRollDM + MRollDM

LDA MRollDM
ADD BRollDM
STA SRollDM
64  PAGE
65  EULER RATE = PITCH
66  MPITCHSD = (SPITCHDM*COS(MROLLSM))-(MYANDM*SIN(MROLLSM))
67  
68  
69  
70  0013 8857 A  LDA  MROLLSM
71  0014 3848 A  MUL  KR24
72  0015 74F6 A  RCPY  E,A
73  0016 75A1 A  RCPYI  P,L
74  0017 44E9 A  B  *LOCKYcos
75  0018 E89B A  STA  OMROLLSM
76  0019 398E A  MUL  SPITCHDM
77  001A 20A1 A  SALD  T
78  001B 74F6 A  RCpy  E,T
79  001C 884E A  LDA  MROLLSM
80  001D 383F A  MUL  KR24
81  001E 74F6 A  RCpy  E,A
82  001F 75A1 A  RCPYI  P,L
83  0020 44E8 A  B  *LOCKYSIN
84  0021 E84F A  STA  SMROLLSM
85  0022 31B9 A  MUL  MYANDM
86  0023 20A1 A  SALD  T
87  0024 7D3E A  RADDI  *E,T
88  0025 74F3 A  RCpy  T,A
89  0026 E840 A  STA  MPITCHSD

SCALING FOR SINE/COS

COSINE ROLLSM

SAVE

SCALING FOR SINE/COS

SINE ROLLSM

ADD 2TH COMPL.TO T REG. = SUB.
EULER RATE : ROLL

```
90  PAGE
91  EULER RATE : ROLL
92  
93  WROLLSD = SROLLW
94  +*(SPITCHM*SIN(WROLLSM)*SIN(WPITCHM)) / COS(WPITCHM)
95  +*(MYAWDM*COS(WROLLSM)*SIN(WPITCHM)) / COS(WPITCHM))
96  0027 8842 A  LDA  WPITCHM
97  0028 3634 A  MUL  KP25
98  0029 74F6 A  RCY  E,A
99  002A 75A1 A  RCY  P,L
100  002B 445A E  B  *LDPK5IN
101  002C E843 A  STA  SPITCHM
102  002D 883C A  LDA  WPITCHM
103  002E 382E A  MUL  KP25
104  002F 74F6 A  RCY  E,A
105  0030 75A1 A  RCY  P,L
106  0031 4A9 A  B  *LDPK5CS
107  0032 E840 A  STA  CPITCHM
108  0033 8844 A  LDA  SPITCHM
109  0034 383C A  MUL  SROLLW
110  0035 20A1 A  SALD  1
111  0036 74F6 A  RCY  E,A
112  0037 3838 A  MUL  SPITCHM
113  0038 383A A  DIV  CPITCHM
114  0039 74B7 A  RCY  A,T
115  003A 81B9 A  LDA  MYAWDM
116  003B 3838 A  MUL  CMROLLW
117  003C 20A1 A  SALD  1
118  003D 74F6 A  RCY  E,A
119  003E 3831 A  MUL  SPITCHM
120  003F 5833 A  DIV  CPITCHM
121  0040 7C73 A  RADD  T,A
122  0041 A837 A  ADD  SROLLW
123  0042 E825 A  STA  WROLLSD
124  
125  
126  EULER RATE : YAW
127  
128  
129  MYAWSD = (SPITCHM*SIN(WROLLSM)*SIN(WPITCHM)) / COS(WPITCHM)
130  
131  0043 8842 A  LDA  SPITCHM
132  0044 382A A  MUL  CMROLLW
133  0045 5820 A  DIV  CPITCHM
134  0046 74B7 A  RCY  A,T
135  0047 81B9 A  LDA  MYAWDM
136  0048 3829 A  MUL  CMROLLW
137  0049 5829 A  DIV  CPITCHM
138  004A 7C73 A  RADD  T,A
139  004B E810 A  STA  MYAWDM
```
RETURN TO GROUND CHECK

LDA DISP075

AND BIT12

BAZ REINGRD

B G05

LDX N3

OPY Z,A

STA MPITCHMD+3,1

CLEAR EULER RATE WASHOUT

MPITONSD+3,1

CLEAR EULER RATE

MPITCHSM+3,1

CLEAR EULER ANGLE MOST

MPITCHSL+3,1

CLEAR EULER ANGLE LEAST

REINGRD+1

LOOP

STA VXVBX

TO ZERO THE GROUND SPEED

B G05
ALL CONSTANTS SCALED OTHER THAN BO, THIS SCALING IS TO AVOID SHIFTING AFTER A MULTIPLY

62 0059 5000 A KX16 DEC 625E-3 SALO 2
63 005A C000 A KX17 DEC -25E-281
64 005B 0844 A KP20 DEC 044E-381
65 005C 5170 A KP25 DEC 31831E-581 SCALE FOR SINE/COSINE
66 *
67 005D 6666 A KY16 DEC 8E-1 IN BASE
68 10D5 A KY17 EQU K23
69 *
70 005C R KR24 EQU KP25 SCALE FOR SINE/COS
71 *
72 005E 0888 A ADRL VSNRB SINE ROLL BODY AT 280
73 005F 0189 A ADRL DISPB075
74 0060 0860 A ADRL VVX08P
75 0061 OFE0 A ADRL ACTFLG04
76 *
77 0062 0880 A BITAND DATA X'0880' FOR FLIGHT & TOTAL FREEZE
78 *
79 005C R KJ9 EQU KP25 SCALE FOR SINE/COS
80 *
81 0063 0000 A MIPITCHM DATA 0 EULER RATE WASHOUT
82 0064 0000 A MROLLMD DATA 0
83 0065 0000 A MYAWMD DATA 0
84 *
85 0066 0000 A MIPITCHSD DATA 0 EULER RATE
86 0067 0000 A MROLLSD DATA 0
87 0068 0000 A MYAWSD DATA 0
88 *
89 0069 0000 A MIPITCHM DATA 0 EULER ANGLE M/S PART
90 006A 0000 A MROLLMS DATA 0
91 006B 0000 A MYAWSM DATA 0
92 *
93 006C 0000 A MIPITCHSL DATA 0 EULER ANGLE L/S PART
94 006D 0000 A MROLSSL DATA 0
95 006E 0000 A MYAWSL DATA 0
96 *
97 006F 0000 A SPITCHM DATA 0 SINE MPITCHM (EULER ANGLE M/S MROLLSM
98 0070 0000 A SMROLLMS DATA 0 MYAWSM
99 0071 0000 A SMYAWSM DATA 0
200 *
201 0072 TFFF A CIPITCHM DATA X'7FF' COSINE MPITCHM (EULER ANGLE M MROLLSM
202 0073 TFFF A CMROLLMS DATA X'7FF' MYAWSM
203 0074 TFFF A CMYAWSM DATA X'7FF'
<table>
<thead>
<tr>
<th>Page</th>
<th>SUM of Rotational Accel' &amp; Rates</th>
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<tbody>
<tr>
<td>204</td>
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<td>208</td>
<td>0075 0000 A SPITCHDD DATA 0</td>
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<td>209</td>
<td>0076 0000 A SROLLDD DATA 0</td>
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<td>210</td>
<td>0077 0000 A SPITCHDD DATA 0</td>
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<tr>
<td>211</td>
<td>0078 0000 A SROLLDD DATA 0</td>
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<tr>
<td>212</td>
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</tbody>
</table>
213 • PAGE
214 • ROTATIONAL WASHOUT.
215 •
216 •
217 • TAU THEA ROTATIONAL = 200 SEC
218 • S THEA (MOTION) = 1 RAD
219 •
220 • MPITCH = MPITCHO - (KP24*MPITCHOM)
221 •
222 0079 89FD A GD5
223 007A 3103 A
224 007B 89EB A
225 007C 7D7E A
226 007D E9E6 A
227 •
228 • LDA MPITCHOM
229 • MUL K18
230 • LDA MPITCHO
231 • ADD MPITCHSL
232 007E 31CF A
233 007F 89ED A
234 0080 E9EC A
235 0081 10C0 A
236 0082 89E7 A
237 0083 7E76 A
238 0084 E9E5 A
239 •
240 • RADD *E,A
241 • ADD 2TH COMPLEMENT
242 • STA MPITCHOM
243 •
244 0085 89DE A
245 0086 3101 A
246 0087 7486 A
247 0088 89ED A
248 0089 3902 A
249 008A 7C36 A
250 008B 89DE A
251 008C 7C37 A
252 008D E1C7 A
253 • INTEGRATION
254 • MPITCH = MPITCHOM + (KP18*MPITCHOM)
255 •
256 • MUL K18
257 • ADD MPITCHSL
258 008E 31CF A
259 • STA MPITCHSL
260 • RADD X*,CO'
261 • ADD 2TH COMPLEMENT
262 • STA MPITCHSL
263 •
264 008F 89D0 A
265 0090 E9EC A
266 0091 10C0 A
267 0092 89E7 A
268 0093 7E76 A
269 0094 E9E5 A
270 0095 MPITCHSL
271 •
272 • COMPENSATION
273 • MPITCHC = MPITCHOM + (KP19*MPITCHOM) + (KP20*SPITCHOM)
274 •
275 • LDA MPITCHOM
276 • LDA MPITCHO
277 •
278 • RADD *T,A
279 • ADD 2TH COMPLEMENT
280 • STA MPITCHOM
281 •
282 1085 89DE A
283 1086 3101 A
284 1087 7486 A
285 1088 89ED A
286 1089 3902 A
287 108A 7C36 A
288 108B 89DE A
289 108C 7C37 A
290 108D E1C7 A
291 • SUM OF PITCH ACCELERATIONS
292 •
293 • LDA SPITCHOM
294 • LDA MPITCHOM
295 • NUL KP19
296 • RADD E,T
297 • NUL KP20
298 • LDA MPITCHOM
299 •
300 0085 89DE A
301 0086 3101 A
302 0087 7486 A
303 0088 89ED A
304 0089 3902 A
305 008A 7C36 A
306 008B 89DE A
307 008C 7C37 A
308 008D E1C7 A
309 • STA MPITCHC

PAGE

ROTATIONAL WASHOUT.

TAU, PHI ROTATIONAL = 200 SEC
S PHI (MOTION) = 1 RAD

MROLLWD = MROLLSD - (KR23*MROLLSM)

008E 89DC A
008F 3103 A
0090 8907 A
0091 707E A
0092 E902 A

LDA MROLLSM
MUL KR23
LDA MROLLSD
RADD *E,A
STA MROLLWD

INTEGRATION

MROLLSM = MROLLSM + (KR18*MROLLWD)

0093 31CF A
0094 4909 A
0095 E908 A
0096 1000 A
0097 8903 A
0098 7E76 A
0099 E901 A

MUL KR18
ADD MROLLLS
STA MROLLLS
RD X"CO" RESET CDF
LDA MROLLSM
RADD E,A
STA MROLLSM

COMPENSATION

MROLLC = MROLLSM + (KR19*MROLLWD) + (KR20*SROLLOD)

009A 89CA A
009B 3101 A
009C 7A68 A
009D 8909 A
009E 3102 A
009F 7C36 A
00A0 89CA A
00A1 7C73 A
00A2 E1C8 A

LDA MROLLWD
MUL KR19
RCPY E,T
LDA SROLLOD
SUM OF ROLL ACCELERATIONS
MUL KR20
RADD E,T
LDA MROLLSM
RADD T,A
STA MROLLC
PAGE

ROTATIONAL #ASHOUT

TAU PSI ROTATIONAL = 20 SEC
S PSI (MOTION) = 1 RAD

MYAWD = MYAWSD - (KJ1*MYAWSM)

LOA MYAWSM
MUL KJ11
LOA MYAWSD
RADDI *E,A ADD 2TH COMPLEMENT
STA MYAWD

LOA MYAWSM + (KJ4*MYAWD)
MUL KJ4
ADD MYAWSL L/S PART
STA MYAWSL NEW L/S PART
RD X'CO' RESET CDF
LOA MYAWSM M/S PART
RADO E,A
STA MYAWSM NEW M/S PART

MYAWC = MYAWSM + (KJ5*MYAWD) + (KJ6*MYAWD)

LOA MYAWD
MUL KJ5
RCFY E,T SAVE
LOA MYAWD
MUL KJ6
RADD E,T
LOA MYAWSM
RADO T,A
STA MYAWC
PAGE

GENERATE SINE AND COSINE OF MYAWSM
FOR BODY TO INERTIAL TRANSFORMATION.

348

SUMMATION OF TRANSLATIONAL ACCELERATIONS

350

351 00C4 8101 A
LDA BX00

352 00C5 A1C1 A
ADD MX00

353 00C6 E1CC A
STA SX00

354

355 00C7 8102 A
LDA BY00

356 00C8 A1C2 A
ADD NY00

357 00C9 E1CD A
STA SY00

358

359 0088 8903 A
LDA MYAWSM

360 0089 39A3 A
MUL KJ9

361 008A 7466 A
RCPY EiA

362 008B 7541 A
RCPYI P1L

363 008C 4468 A
B \*LOOKSIN

364 008D E98A A
STA SMYAWSM

365

366 008E 89AD A
LDA MYAWSM

367 008F 3990 A
MUL KJ9

368 00C0 7466 A
RCPY EiA

369 00C1 7541 A
RCPYI P1L

370 00C2 4469 A
B \*LOOKCOS

371 00C3 E981 A
STA CMYAWSM

372

373
<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction 1</th>
<th>Instruction 2</th>
<th>Instruction 3</th>
<th>Instruction 4</th>
<th>Instruction 5</th>
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<tr>
<td>359</td>
<td>PAGE</td>
<td>BOD TO INERTIAL TRANSFORMATION OFTRANSLACCEL'S 1 X CH</td>
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<tr>
<td>367</td>
<td>00CA 89AA A</td>
<td>LDA CMYAWSM</td>
<td>COS CMYAWSM</td>
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<tr>
<td>368</td>
<td>00CB 99AA A</td>
<td>MUL SPITCHSM</td>
<td></td>
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<tr>
<td>369</td>
<td>00CC 20A1 A</td>
<td>SALD 1</td>
<td></td>
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<tr>
<td>370</td>
<td>00CD 74F6 A</td>
<td>RCOPY E,A</td>
<td></td>
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<tr>
<td>371</td>
<td>00CE 39A2 A</td>
<td>MUL SMROLLSM</td>
<td></td>
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<tr>
<td>372</td>
<td>00CF 20A1 A</td>
<td>SALD 1</td>
<td></td>
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<tr>
<td>373</td>
<td>00D0 74F6 A</td>
<td>RCOPY E,T</td>
<td>SAVE</td>
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<tr>
<td>374</td>
<td>00D1 89A2 A</td>
<td>LDA CMROLLSM</td>
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<tr>
<td>375</td>
<td>00D2 39FF A</td>
<td>MUL SYAWSM</td>
<td>SINE OF MYAWSM</td>
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<tr>
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<td>00D3 20A1 A</td>
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<td>377</td>
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<td>00D5 70F7 A</td>
<td>RADD *E,A</td>
<td></td>
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<td>379</td>
<td>00D6 31CD A</td>
<td>MUL SYOD</td>
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<tr>
<td>380</td>
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<td>SALD 1</td>
<td></td>
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<td>MUL KY16</td>
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<tr>
<td>383</td>
<td>00DA 20A1 A</td>
<td>SALD 1</td>
<td></td>
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<tr>
<td>384</td>
<td>00DB 74F6 A</td>
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<td>SAVE</td>
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<tr>
<td>385</td>
<td>00DC 8998 A</td>
<td>LDA CMYAWSM</td>
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<td>386</td>
<td>00DD 3995 A</td>
<td>MUL CPITCHSM</td>
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<tr>
<td>387</td>
<td>00DE 20A1 A</td>
<td>SALD 1</td>
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<tr>
<td>388</td>
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<td>RCOPY E,A</td>
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<td>389</td>
<td>00EE 31CC A</td>
<td>MUL SYOD</td>
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<tr>
<td>390</td>
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<td>SALD 1</td>
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<td>SUM IT</td>
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<tr>
<td>392</td>
<td>00F1 74F3 A</td>
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<tr>
<td>393</td>
<td>00F2 11C9 A</td>
<td>STA WSMOD</td>
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PAGE
BODY TO INERTIAL TRANSFORMATION FOR i, 1, Y

\[ \text{MYSDD} = (XX16*SKDD*COS(WPITCHSM)*SIN(WYAWSM)) \]
\[ + (YY16*SPITCM)*SIN(WPITCHSM)*SIN(WYAWSM)) \]
\[ + (ZZ16*CROLLSM)*COS(WYAWSM))) \]

401 00E5 89BE A  LDA   CMROLLSM
402 00E6 39BE A  MUL   CMYAWSM
403 00E7 2B01 A  SALD  1
404 00E8 7A86 A  RCPY  E,T     SAVE
405 00E9 8987 A  LDA   CMROLLSM
406 00EA 3985 A  MUL   SPITCM
407 00EB 2B01 A  SALD  1
408 00EC 7A46 A  RCPY  E,A
409 00ED 3984 A  MUL   CMYAWSM
410 00EE 2B01 A  SALD  1
411 00EF 7C36 A  RADD  E,T
412 00F0 7A43 A  RCPY  T,A
413 00F1 31CD A  MUL   SYDD
414 00F2 2B01 A  SALD  1
415 00F3 7A86 A  RCPY  E,T     SAVE
416 00F4 81CC A  LDA   SKDD
417 00F5 3964 A  MUL   XX16
418 00F6 2B02 A  SALD  2
419 00F7 7A46 A  RCPY  E,A
420 00F8 397A A  MUL   CPITCM
421 00F9 2B01 A  SALD  1
422 00FA 7A46 A  RCPY  E,A
423 00FB 3976 A  MUL   CMYAWSM
424 00FC 2B01 A  SALD  1
425 00FD 7C36 A  RADD  E,T
426 00FE 7A43 A  RCPY  T,A
427 00FF 81CA A  STA   MYSDD
PAGE

BODY TO INERTIAL TRANSFORMATION OF TRANSLACCEL'S : Z C

\[ W_{Z\text{DD}} = (XX_{17}\cdot SADD\cdot \sin(WPITCH_{SM})) \]
\[ + (YY_{17}\cdot SYDD\cdot \sin(HROLL_{SM})\cdot \cos(WPITCH_{SM})) \]
\[ + (ZZ_{20}\cdot \cos(HROLL_{SM})\cdot \cos(WPITCH_{SM})) \]

0100 896FA LDA SPIITCHSM SINE WPITCHSM
0101 31CC A MUL SXDD
0102 20A1 A SALD 1
0103 74F6 A RCOPY EA
0104 3956 A MUL KX17
0105 74B6 A RCOPY ET SAVE IT
0106 896CA LDA CPITCHSM COSINE WPITCHSM
0107 3949 A MUL SMROLLSM
0108 20A1 A SALD 1
0109 74F6 A RCOPY EA
010A 31CD A MUL SYDD
010B 20A1 A SALD 1
010C 74F6 A RCOPY EA
010D 3105 A MUL KY17
010E 7C36 A RADD ET SUM IT IN T REG
010F 8963 A LDA CPITCHSM
0110 3963 A MUL CMROLLSM
0111 20A1 A SALD 1
0112 74F6 A RCOPY EA
0113 31B3 A MUL BZDD
0114 20A1 A SALD 1
0115 7C36 A RADD ET SUM IT IN T REG
0116 74F3 A RCOPY TA
0117 E1C8 A STA WZDD
PAGE

TRANSLATIONAL WASHOUT FOR 1 X

TAU X TRANSLATIONAL = 2 SEC

ZETA X TRANSLATIONAL = .7

MAXMOD = MAXDD - (KX18*MAXD) - (KX19*MAXM)

LDA MXDD
MUL KX18
SALD 1
RCPY E,T
LDA MXM
MUL KX19
RADD E,T
LDA MXDD
RADD T,A
STA MAXMOD

INTEGRATION

MAXD = MAXD + (KX12*MAXDD)

MUL KX12
ADD MXDL
STA MXD
RD X'CO'
LDA MAXM
RADD E,A
STA MXDD

L/S PART
NEW L/S PART
RESID CDF
RESET CDF
NEW M/S PART

MUL MX13
ADD MXL
STA MXL
RD X'CO'
LDA MAXM
RADD E,A
STA MXM
COMPENSATION

\[ MXC = MXM + (KX14 \times MXD) + (KX15 \times MXO) \]
TRANSLATIONAL WASHOUT FOR \( T \): Y

\[
\begin{align*}
\text{TAU} & \quad \text{Y TRANSLATIONAL} = 2 \text{ SEC} \\
\text{ZETA} & \quad \text{Y TRANSLATIONAL} = 0.7 \\
\text{MYNOD} & \quad \text{MYSDD} - (\text{KY18} \times \text{MYDM}) - (\text{KY19} \times \text{MYN}) \\
\end{align*}
\]

LOD MYDM
MUL KY18
SAID 1
REPL E,T
LOD MYM
MUL KY19
RADD E,T
LOD MYSDD
RADDI \( *T_A \) ADD 2TH COMPLEMENT OF SUM
STA MYNOD

INTEGRATION

MYDM = MYDM + (KY12 \times \text{MYNOD})

MUL KY12
ADD MYDL
STA MYDM NEW L/S PART
RD \( X^*CO^* \)
LOD MYDM
RADD E,A
STA MYDM M/S PART

MYM = MYM + (KY13 \times \text{MYDM})

MUL KY13
ADD MYL
STA MYL NEW L/S PART
RD \( X^*CO^* \)
LOD MYM
RADD E,A
STA MYM M/S PART
558  PAGE
559  *
560  *  COMPENSATION
561  *
562  *  MYC = MYM + (KY14*MYOM) + (KY15* MYMOD)
563  *
564  0151 883F A  LDA MYDM
565  0152 3839 A  MUL KY14
566  0153 7A86 A  RCPY E1,T
567  0154 883F A  LDA MYMOD
568  0155 383F A  MUL KY15
569  0156 7C36 A  RADD E1,T
570  0157 8838 A  LDA MYM
571  0158 7C73 A  RADD T1,A
572  0159 E1C4 A  STA MYC
TRANSLATIONAL WASHOUT FOR Z

TAU Z TRANSLATIONAL = 2 SEC
ZETA Z TRANSLATIONAL = 0.7

MZWDD = MZDD - (KZ8*MZW) - (KZ9*MZW)

LDA MZW
MUL KZ8
RCPY E, T
SAVE IT
LDA MZW
RADD E, T
SUM IT IN T REG
LDA MZWDD
RADD *T, A
SUBTRACT T IN A REG
STA MZWDD

INTEGRATION

MZW = MZW + (KZ3*MZWDD)

MUL KZ3
ADD MZDL
L/S PART
STA MZDL
NEW L/S PART
RD X"CO" RESET COF
LDA MZW
M/S PART
RADD E, A
MZWDD
M/S PART
STA MZW
NEW M/S PART

MZW = MZW + (KZ4*MZW)

MUL KZ4
ADD MZL
L/S PART
STA MZL
NEW L/S PART
RD X"CO" RESET
LDA MZW
M/S PART
RADD E, A
MZWDD
M/S PART
STA MZW
NEW M/S PART
613  *                  PAGE
614  *                  COMPENSATION
615  *                  MZC = (MZD + (KZ5*MZD) + (KZ6*MZDD))
616  *
617  *
618 0171 8827 A        LOA  MZD
619 0172 382A A        MUL  KZ5
620 0173 7486 A        RLPY  E,T  SAVE IT
621 0174 8827 A        LOA  MZDD
622 0175 3828 A        MUL  KZ6
623 0176 7C36 A        RADD  E,T  SUM IT IN T REG
624 0177 8823 A        LOA  MZD
625 0178 7C73 A        RADD  T,A
626 0179 E1C5 A        STA  MZC
SUMMATION OF OUTPUTS TO MOTION OUTPUT PROGRAM.

COMPENSATED SIGNALS

INTO OUTPUT PROGRAM

LOOP

RESTORE BASE FOR OUTPUT PROGRAM

RESTORE BASE REG.

COMPUTED BUMPS FROM RN#YBMPs

HEAVE MOTION

EXIT
650 PAGE
653 • ALL CONSTANTS SCALED OTHER THAN B0. THIS SCALING
654 • IS TO AVOID SHIFTING AFTER A MULTIPLY
655
656 0184 0000 E ADRL MOTION FOR OUTPUT PROGRAM
657 0185 0000 E ADRL NZ HEAVE MOTION
658
659 0186 0000 A MXDL DATA 0
660 0187 0000 A MXDM DATA 0
661 0188 0000 A MXL DATA 0
662 0189 0000 A MXM DATA 0
663 018A 0000 A MXMOD DATA 0
664 018B 3E8 A KX14 DEC 24572E-581
665 018C 09E3 A KX15 DEC 038613E-681
666 018D 59A A KX18 DEC 7E-1
667 018E 4BEE A KX19 DEC 28488E-581
668
669 018F 0000 A MYDL DATA 0
670 0190 0000 A MYDM DATA 0
671 0191 0000 A MYL DATA 0
672 0192 0000 A MYM DATA 0
673 0193 0000 A MYMOD DATA 0
674 018B R KY14 EQU KX14
675 0194 07E8 A KY15 DEC 03089E-581
676 0195 7000 A KY18 DEC B75E-3
677 0196 5B29 A KY19 DEC 35614E-4B1
678
679 0197 0000 A MZDL DATA 0
680 0198 0000 A MZDM DATA 0
681 0199 0000 A MZL DATA 0
682 019A 0000 A ZM DATA 0
683 019B 0000 A MXMOD DATA 0
684 019C OE61 A KZ6 DEC 05616E-681
685 019D 090A A KZ6 DEC 039302E-681
686 019E 2CCD A KZ8 DEC 175E-3B1
687 019F 4FC4 A KZ9 DEC 311587E-681
0 ERRORS
EQUALS ERROR MAINMN2
APPENDIX B, PART 3

1  X-REF PART FOR MOTION SYSTEM.
2
3  B-747  FILE NO: K 820
4  JULY 1975
5  B. BAARSCHERS.
6  ISSUE 1
7
8  ASEC
9  ORG X'10A8'
10
11
12 10A8 0000 A MFYWB DATA 0  WING/BODY AXIS LONG FORCE/GW
13 10A9 0000 A MFYWB DATA 0  WING/BODY-AXIS LAT FORCE/GW
14 10AA 0000 A MFZWS DATA 0  WING/BODY-AXIS VERT FORCE/GW
15
16  ON/OFF GROUND FUNCTIONS AFTER RESCALING.
17
18 10AB 0000 A WMO DATA 0  W/B-AXIS LONGITUDINAL ACCEL.
19 10AC 0000 A YMO DATA 0  W/B-AXIS LATERAL ACCEL.
20 10AD 0000 A WMO DATA 0  W/B-AXIS VERTICAL ACCEL.
21
22  ON/OFF GROUND FUNCTIONS.
23
24 10AE 0000 A UBD DATA 0  MOTION BODY-AXIS LONGITUD ACCEL.
25 10AF 0000 A VBDM DATA 0  MOTION BODY-AXIS LATERAL ACCEL.
26 10AG 0000 A WDO DATA 0  MOTION BODY-AXIS VERTICAL ACCEL.
27
28  BODY - AXIS FUNCTIONS
29
30 10B1 0000 A BXXD DATA 0  "X BODY DOUBLE DOT
31 10B2 0000 A BYOD DATA 0  Y BODY DOUBLE DOT
32 10B3 0000 A BZOD DATA 0  Z BODY DOUBLE DOT
33
34 10B4 0000 A MPITCH0 DATA 0  PITCH ACCEL
35 10B5 0000 A WPROLL0 DATA 0  ROLL
36 10B6 0000 A MYAW0 DATA 0  YAW
37
38 10B7 0000 A MPITCH0 DATA 0  PITCH RATE
39 10B8 0000 A WPROLL0 DATA 0  ROLL
40 10B9 0000 A MYAW0 DATA 0  YAW
41
42 10BA 0000 A MPITCHW DATA 0  PITCH ACCEL BODY
43 10BB 0000 A WPROLLW DATA 0  ROLL
44 10BC 0000 A MYAWW DATA 0
45
46 10BD 0000 A BPITCHW DATA 0  PITCH ACCEL BODY
47 10BE 0000 A BRROLLW DATA 0  ROLL
48 10BF 0000 A BIPITCH0 DATA 0 PITCH RATE BODY
50 10C0 0000 A BROLL0 DATA 0 ROLL
51 =
52 10C1 0000 A WAXD DATA 0 X SPEC. FORCE ERROR
53 10C2 0000 A WYDD DATA 0 Y
54 =
55 =
56 =
57 =
58 10C3 0000 A WX0C DATA 0 X-AXIS
59 10C4 0000 A WYC DATA 0 Y-AXIS
60 10C5 0000 A WZC DATA 0 Z-AXIS
61 =
62 10C6 0000 A WYAWC DATA 0 YAW
63 10C7 0000 A WMPITCHC DATA 0 PITCH
64 10C8 0000 A WROLLC DATA 0 ROLL
65 =
66 =
67 =
68 10C9 0000 A MX800 DATA 0 X INERTIAL ACCEL
69 10CA 0000 A MY800 DATA 0 Y
70 10CB 0000 A MZ800 DATA 0 Z
71 =
72 =
73 =
74 10CC 0000 A SXO0 DATA 0 SUM OF TRANSLATIONAL ACCEL'S
75 10CD 0000 A SY00 DATA 0
76 =
77 =
78 =
79 10CE 199A A KPRJ3 DEC 1E-181
80 10CF 0000 A KPRJ4 DEC 05E-281
81 10D0 083C A KXY13 DEC 043878E-681
82 10D1 47AE A KR19 DEC 28E-281
83 10D2 1687 A KPRJ206 DEC 088E-381
84 10D3 0148 A KPR2423 DEC 000E-381
85 10D4 0A30 A KXY12 DEC 04E-281
86 10D5 3333 A KZ3 DEC 2E-181
87 10D6 0291 A KZ4 DEC 010029E-681
88 =
89 =
TAPE

1 KEY-IN
168
2 0000 A END