Flap-Lag Equations of Motion of Rigid, Articulated Rotor Blades with Three Hinge Sequences

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NOMENCLATURE

\( A_1 \) symbol used to represent a gravitational term, 
\[ A_1 = \sin i \cos \phi \cos \theta_a - \cos i \sin \theta_a \]

\( A_2 \) symbol used to represent a gravitational term, 
\[ A_2 = \sin \phi \cos \theta_a \]

\( A_3 \) symbol used to represent a gravitational term, 
\[ A_3 = \cos i \cos \phi \cos \theta_a + \sin i \sin \theta_a \]

\( A_{1s} \) lateral cyclic pitch measured from hub plane and in hub-body system, rad (or deg)

\( a_x, a_y, a_z \) components of total linear acceleration at the aircraft center of gravity expressed in the hub-body system, ft/sec\(^2\) (m/sec\(^2\))

\( B \) tip loss factor

\( B_{1s} \) longitudinal cyclic pitch measured from hub plane and in hub-body system, rad (or deg)

\( c \) blade chord, ft (m)

\( c_d \) blade section drag coefficient

\( c_{\ell} \) blade section lift coefficient

\( C_{\beta} \) flapping damper coefficient, lb-ft-sec/rad (N-m-sec/rad)

\( C_{\tau} \) lag damper coefficient, lb-ft-sec/rad (N-m-sec/rad)

\( c.g. \) center of gravity

\( dD \) incremental drag force on blade element, lb (N)

\( dL \) incremental lift force on blade element, lb (N)

\( e_{\beta} \) flapping hinge offset, ft (m)

\( e_{\tau} \) lag hinge offset, ft (m)

\( \delta e \) distance between the flapping and lag hinges, ft (m)

\( g \) gravitational acceleration, ft/sec\(^2\) (m/sec\(^2\))

\( i \) tilt angle of the rotor shaft in the rotorcraft \( x_a-z_a \) plane, positive tilt forward, rad (deg)
mass moment of inertia of the rotor blade about the lag hinge, slug-ft² (kg-m²)

mass moment of inertia of the rotor blade about the flapping hinge, slug-ft² (kg-m²)

mass moment of inertia of the rotor blade segment between the flapping and lag hinges about the inner hinge (flapping or lag hinge), slug-ft² (kg-m²)

pitch-flap coupling ratio

pitch-lag coupling ratio

flapping spring constant, lb-ft/rad (N-m/rad)

lag spring constant, lb-ft/rad (N-m/rad)

components of the offset between the aircraft center of gravity and the hub center in hub-body system ($\xi$, positive when the hub center is forward of aircraft c.g.; $\eta$, positive when the hub center is to the right of aircraft c.g.; $\zeta$, positive when the hub center is below aircraft c.g.), ft (m)

mass of blade per unit of radius, slug/ft (kg/m)

mass of blade from lag hinge to blade tip, slug (kg)

mass of blade from flapping hinge to blade tip, slug (kg)

local Mach number at blade element ($M_r = U/a$, with $a$ being the speed of sound)

mass moment of rotor blade about lag hinge in a horizontal position, slug-ft (kg-m)

mass moment of rotor blade about flapping hinge in a horizontal position, slug-ft (kg-m)

mass moment of rotor blade segment between the flapping and lag hinge about the inner hinge (flapping or lag hinge depending on a hinge sequence) in a horizontal position, slug-ft (kg-m)

components of aircraft angular velocity in hub-body system, rad/sec (or deg/sec)

components of aircraft angular acceleration in hub-body system, rad/sec² (or deg/sec²)
generalized force associated with lead-lag for L-F-P hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\zeta 1}$

generalized force associated with flapping for L-F-P hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\beta 1}$

generalized force associated with lead-lag for F-P-L hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\zeta 2}$

generalized force associated with flapping for F-P-L hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\beta 2}$

generalized force associated with lead-lag for F-L-P hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\zeta 3}$

generalized force associated with flapping for F-L-P hinge sequence, lb-ft/rad (N-m/rad)

$Q_{\beta 3}$

aerodynamic force contribution to the generalized force associated with lead-lag and flapping, respectively (different expressions for the three hinge sequences), lb-ft/rad

$Q_{\zeta, A}, Q_{\beta, A}$

gravitational force contribution to the generalized force associated with lead-lag and flapping, respectively (different expressions for the three hinge sequences), lb-ft/rad

$Q_{\zeta, G}, Q_{\beta, G}$

contribution of dampers to the generalized force associated with lead-lag and flapping, respectively, lb-ft/rad

$Q_{\zeta, D}, Q_{\beta, D}$

contribution of hub springs to the generalized force associated with lead-lag and flapping, respectively, lb-ft/rad

$Q_{\zeta, S}, Q_{\beta, S}$

radial position of the blade element measured from the lag hinge, ft (m)

$r_{\zeta}$

radial position of the blade element measured from the flapping hinge, ft (m)

$r_{\beta}$

radius of blade root pocket cutout (i.e., radius at which lifting surface of blade begins), ft (m)

$r_{c}$

rotor blade radius measured from the center of rotation, ft (m)

$R$

total kinetic energy of a blade, lb-ft (N-m)

$T$

resultant relative air velocity perpendicular to blade-span axis at blade element, ft/sec (m/sec), $U = (u_T^2 + u_p^2)^{1/2}$

$U$
u_T \text{ component at the blade element of resultant relative air velocity perpendicular to the blade-span axis and on the plane parallel to } x_1-y_1 \text{ plane, ft/sec (m/sec)}

u_P \text{ component at blade element of resultant relative air velocity perpendicular to both the blade-span axis and } u_T, \text{ ft/sec (m/sec)}

u_S \text{ component at blade element of resultant relative air velocity along the blade span, ft/sec (m/sec)}

V_r \text{ total inertial velocity of the blade element, ft/sec (m/sec)}

\delta W_t \text{ total virtual work done on the blade by an external force, lb-ft (N-m)}

x,y,z \text{ hub-body system}

x',y',z' \text{ inertia system}

x_a',y_a',z_a \text{ body-axis system}

\dot{x}_0,\dot{y}_0,\dot{z}_0 \text{ components of velocity at the aircraft center of gravity in hub-body system, ft/sec (m/sec)}

\dot{x},\dot{y},\dot{z} \text{ components of velocity at blade element due to rotation, flapping, pitching, and lagging motion (i.e., isolated rotor) in hub-body system, ft/sec (m/sec)}

\Delta \dot{x},\Delta \dot{y},\Delta \dot{z} \text{ component of velocity at blade element due to aircraft motion in hub-body system, ft/sec (m/sec)}

X_A,Y_A,Z_A \text{ components of the total aerodynamic force on blade element in hub-body system, lb (N)}

X_G,Y_G,Z_G \text{ components of the gravitational force on blade element in hub-body system, lb (N)}

\alpha_r \text{ blade element local angle of attack, rad (or deg)}

\phi_r \text{ tan}^{-1}(u_P/u_T), \text{ rad (or deg)}

\theta \text{ blade pitch angle measured from hub plane, } \theta = \theta_o - A_1 \cos \psi - B_1 \sin \psi + \theta_{t,r} - K_1 \beta - K_2 \zeta, \text{ rad (or deg)}

\theta_o \text{ blade-root collective pitch measured from hub plane, rad (or deg)}

\theta_{t,r} \text{ blade twist at blade element, rad (or deg)}

\beta \text{ blade flapping angle measured from hub plane, rad (or deg)}
\( \dot{\theta}, \ddot{\theta} \) first and second derivative of \( \theta \) with respect to time

\( \zeta \) blade lagging angle (measured positive when opposite to the direction of rotor rotation), rad (or deg)

\( \dot{\zeta}, \ddot{\zeta} \) first and second derivative of \( \zeta \) with respect to time

\( \psi_a, \theta_a, \phi_a \) Euler angles of the body-axis system with respect to the inertia system using the sequence of rotations as indicated

\( \rho \) mass density of air, slug/ft\(^3\) (kg/m\(^3\))

\( \Omega \) rotor system angular velocity, rad/sec

\( \psi \) azimuth angle measured from \(-x\) axis in the sense of rotor rotation, rad (or deg)
SUMMARY

This report documents a derivation of coupled flap-lag equations of motion for a rigid articulated rotor with hinge springs and viscous dampers. Three different flapping-lag-pitch hinge sequences are considered and the Lagrange method is used in deriving the equations. The effects of the complete six degrees-of-freedom aircraft motions are included and all the inertia dynamic terms are retained; no small-angle assumptions are used in the development. Comparisons of the results of this work with those available in the literature are made. Sources of terms missing in previous analyses, especially those of the inertia dynamics, are identified.

INTRODUCTION

Most helicopters in production today utilize articulated main rotors. A recent projection (ref. 1) indicates that, for the transport class of helicopters, future development may still rely heavily on the conventional articulated rotor design, although a trend seems to be set to use hingeless or bearingless rotors in the design of smaller combat helicopters to enhance agility and maintainability.

An articulated rotor uses flapping, lead-lag, and feathering hinges (or elastomeric bearings) in an appropriate sequence. The flapping hinge is employed to relieve the blade-root bending moment arising from the lift and centrifugal forces, the lag hinge to alleviate the in-plane moment at the blade root due to the drag force and the Coriolis force which stems from the flapping motion, and the feathering (or pitch) bearing to change the angle of attack of the blade. Figure 1 shows three widely used hinge sequences, i.e., flap-lag-pitch (F-L-P), flap-pitch-lag (F-P-L), and lag-flap-pitch (L-F-P) hinge arrangements. Use of a specific hinge sequence is often dictated by the past design experience and preference of the helicopter manufacturers. For example, Sikorsky designs tend to use an L-F-P hinge sequence with colocated hinges (refs. 2 and 3) as schematically shown in figure 2. The other two hinge sequences, the F-L-P and F-P-L, are more commonly used by other manufacturers.

The flap-lag equations of motion and the dynamic characteristics of the articulated rotor blades have been under intensive investigations for a long time (refs. 4-11), largely by rotor dynamicists, but it is only relatively recently that the importance of the hinge sequence has been recognized (refs. 8 and 9). The rotor dynamicists tend to place their main emphasis on the stability characteristics of the isolated rotor system and, as a consequence, will tend not to include the effects of aircraft (or shaft) motions (refs. 4-9). Therefore, the flap-lag
HINGES: 1. FLAP  
2. LAG  
3. FEATHERING (PITCH)

![Diagram of Hinges]

**Figure 1.** Three commonly used hinge sequences (ref. 2).

**Figure 2.** Elastomeric-bearing rotor hub system (ref. 2).

Equations of motion developed with this emphasis are not readily usable by the flight dynamicists, who are interested primarily in the stability and control characteristics of the entire vehicle and, as such, the effects of aircraft motions must be included in the development of flap-lag equations of motion. Some effects of aircraft motions were included, notably by the flight dynamicists (refs. 3, 10, and 11), but the effects are for specialized hinge arrangements. Extensions of those flap-lag equations of motion to include other hinge sequences and/or to include the complete effects of aircraft motion for a wider range of applications are not readily apparent, and therefore require a new development.

In the past, most rotor models developed expressly for flight dynamics and control applications, especially those for use in real-time simulation, have considered only the flapping motion (refs. 12-16). Recent studies related to high-bandwidth flight control systems for rotorcraft (refs. 17-21) have shown not only
that the flapping and other higher-order dynamics need to be considered (refs. 17-19), but the lead-lag dynamics must also be included in the rotor math model (refs. 20 and 21). These initial studies, coupled with the dramatically increased computational power that has become available in the past few years, serve as strong motivation to develop a generic rotor model for an articulated rotor system that includes various hinge arrangements for the rotor blades for a wider range of flight dynamics applications. It also permits a detailed investigation into the effects of hinge sequence.

The work reported here represents the first of a series of efforts designed to achieve the above objective. A detailed derivation is provided herein in the development of flap-lag equations of motion for the three commonly used hinge sequences, i.e., L-F-P, F-P-L, and F-L-P for articulated rigid blade with a complete account for the effects of aircraft motion.

COORDINATE SYSTEMS

In this section, the position and velocity of an element of a rotor blade are calculated. To express these vector quantities, the following coordinate systems are used. Different coordinate systems are used for the three hinge sequences considered.

L-F-P Hinge Sequence

Figure 3 shows the coordinate systems that are used for the L-F-P hinge sequence. The blade is assumed to be rigid. The pitch bearing is outboard of the flapping hinge, and the flapping hinge is outboard of the lag hinge.

Figure 3.- Coordinate systems used for the L-F-P hinge sequence.

The flapping hinge is assumed to be perpendicular to the rotor shaft. The lag hinge is assumed to be parallel to the shaft. The feathering axis is assumed to
coincide with the blade span axis, and the center of gravity and aerodynamic pressure center of the blade sections are assumed to be on the blade span axis. With these assumptions in mind, the following coordinate systems are used:

\( x_1, y_1, z_1 \) - With its origin on the flapping hinge \( F \); \( z_1 \) parallel to the shaft and pointing downward; \( y_1 \) parallel to the blade segment between the two hinges (coinciding with the feathering axis when flap angle is equal to zero) and pointing outward; \( z_1, y_1, \) and \( x_1 \) forming an orthogonal set.

\( x_2, y_2, z_2 \) - With origin on the lag hinge \( L \); \( z_2 \) parallel to \( z_1 \); \( y_2 \) parallel to the blade segment between the shaft and \( L \) and pointing outward; \( z_2, y_2, \) and \( x_2 \) forming an orthogonal set.

\( x_3, y_3, z_3 \) - With origin at the hub center, otherwise the same as \( x_2, y_2, z_2 \) system. This coordinate system will be referred to as the rotating shaft system.

\( x, y, z \) - This axis system will be referred to as hub-body system with origin also at the hub center; \( z \) parallel to \( z_3 \); \( x \) pointing forward to the nose of the aircraft; \( y \) toward the right. This system is related to the rotating shaft system through the azimuth angle \( \psi \) as depicted in figure 4.

\[ x \]
\[ z, z_3 \]
\[ H \]
\[ y \]
\[ \psi \]
\[ y_3 \]

Figure 4.- Relationship of the rotating-shaft system and the hub-body system.

It is important to note that the sign convention regarding the flapping and lagging angles as defined in this report is: positive for flapping up and for lagging back. With this sign convention, the component of the position vector \( r \) with respect to the rotating-shaft and the hub-body systems are, respectively,
\[
\begin{bmatrix}
x_3 \\
y_3 \\
z_3
\end{bmatrix} = \begin{bmatrix}
0 \\
e_\zeta \\
0
\end{bmatrix} + \begin{bmatrix}
\cos \zeta & -\sin \zeta & 0 \\
\sin \zeta & \cos \zeta & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
0 \\
\Delta e + r_B \cos \beta \\
-r_B \sin \beta
\end{bmatrix}
\]

\[
=-\left(\Delta e + r_B \cos \beta\right) \sin \zeta
\]

\[
= \begin{bmatrix}
\Delta e + r_B \cos \beta \\
-r_B \sin \beta
\end{bmatrix}
\]

and

\[
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix} = \begin{bmatrix}
\sin \psi & -\cos \psi & 0 \\
\cos \psi & \sin \psi & 0 \\
0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x_3 \\
y_3 \\
z_3
\end{bmatrix}
\]

\[
\begin{bmatrix}
-\left(\Delta e + r_B \cos \beta\right) \sin \zeta \sin \psi - \left[ e_\zeta + \left(\Delta e + r_B \cos \beta\right) \cos \zeta\right] \cos \psi \\
\left[ e_\zeta + \left(\Delta e + r_B \cos \beta\right) \cos \zeta\right] \sin \psi
\end{bmatrix}
\]

\[
= \begin{bmatrix}
-\left(\Delta e + r_B \cos \beta\right) \sin \zeta \cos \psi + \left[ e_\zeta + \left(\Delta e + r_B \cos \beta\right) \cos \zeta\right] \sin \psi \\
-r_B \sin \beta
\end{bmatrix}
\]

The hub-body system is now related to the aircraft body-axis system \((x_a, y_a, z_a)\) and an inertia system \((x', y', z')\). Figure 5 depicts the relationships among the three coordinate systems. Note that we consider a shaft tilt angle \(\iota\), and a general offset of the hub center of the rotor system from the center of gravity of the aircraft \((r_H)\). The center of gravity of the aircraft is translating \((v_0)\), accelerating linearly \((a_0)\), and rotating \((\omega, \dot{\omega})\) with respect to the inertia system. To expedite the development that follows, these vector quantities are now expressed in terms of the hub-body system, i.e.,

\[
r = (x, y, z)^T
\]

\[
r_H = (\dot{x}, \dot{y}, \dot{z})^T
\]

\[
v_0 = (\dot{x}_0, \dot{y}_0, \dot{z}_0)^T
\]

\[
\omega = (p, q, r)^T
\]

Note that when expressed in the hub-body system (also in the aircraft body-axis system), \(a_0 = (d/dt)(v_0) = (\dot{v}_0)(v_0) + \omega \times v_0\), and
(d/dt)\omega = (3/\partial t)\omega + \omega \times \omega = (3/\partial t)\omega, owing to the rotation of the system with respect to the inertia frame x',y',z'. Thus,

$$a_o = (a_x, a_y, a_z)^T = (x_o, y_o, z_o)^T + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} (x, y, z)^T$$

$$\dot{\omega} = (\dot{p}, \dot{q}, \dot{r})^T$$

![Diagram of HUB-BODY SYSTEM, AIRCRAFT, and INERTIA SYSTEM](image)

Figure 5.- Relationships among inertia, body-axis, and hub-body systems.

It should be noted that, due to the shaft tilt angle \( \alpha \), the components of the vector quantities in equation (3) differ from those which are expressed in the aircraft body-axis system by a transformation \( T_i \),

$$T_i = \begin{bmatrix} \cos i & 0 & \sin i \\ 0 & 1 & 0 \\ -\sin i & 0 & \cos i \end{bmatrix} \quad (4a)$$

For example, if \( v_o = (\dot{x}_a, \dot{y}_a, \dot{z}_a)^T \) and \( \omega = (p_a, q_a, r_a)^T \) are, respectively, the linear velocity and angular velocity of the aircraft c.g. when expressed in the aircraft body-axis system, then in the hub-body system, \( (\dot{x}_o, \dot{y}_o, \dot{z}_o)^T = T_i(x_a, y_a, z_a)^T \) and \( (p, q, r)^T = T_i(p_a, q_a, r_a)^T \). If the shaft has a sideward tilt with an angle \( \beta \), in addition to the forward tilt angle \( \alpha \), then \( T_i \) is to be replaced by \( T_{ji} = T_j T_i \), which is a result of the sequence of rotational transformations.
The aircraft body-axis system, \( x_a, y_a, z_a \), is related to the inertia system, \( x', y', z' \), through the usual sequence of rotation of the Euler's angles, \( \psi_a, \theta_a, \phi_a \). The components of a vector expressed in the two frames are related by the following transformation:

\[
\begin{bmatrix}
  x' \\
  y' \\
  z'
\end{bmatrix} =
\begin{bmatrix}
  \cos \psi_a \cos \theta_a & \cos \psi_a \sin \theta_a & -\sin \psi_a \\
  \sin \psi_a \cos \theta_a & \sin \psi_a \sin \theta_a & \cos \theta_a \\
  \sin \theta_a & -\cos \theta_a & 0
\end{bmatrix}
\begin{bmatrix}
  x_a \\
  y_a \\
  z_a
\end{bmatrix}
\]

From figure 5, it is clear that the sign convention for the components \( l_x, l_y, l_z \) in equation (3) is as follows: \( l_x \) is positive when the hub center \( H \) is forward of aircraft c.g. (along x-axis); \( l_y \) is positive when \( H \) is to the right of c.g. (along y-axis); and \( l_z \) is positive when \( H \) is below aircraft c.g. (along z-axis).

With the above considerations we are now in a position to determine the total velocity of the blade element.

**Total velocity of blade element**—With reference to figure 5, the position vector with respect to the aircraft c.g. is:

\[ r_r = r_H + r \]

Expressed in the hub-body system, \( r_r = (l_x + x, l_y + y, l_z + z)^T \), where \((x, y, z)^T \) are given in equation (2).

The total inertial velocity of the blade element \( V_r \) is (fig. 5):

\[
V_r = \frac{d}{dt}(r'_r) = \frac{d}{dt}(r'_o) + \frac{d}{dt}(r_r)
\]

\[ = v_o + \frac{3}{at}(r_r) + \omega \times r_r \]

Note that \( (a/at)(r_r) = (a/at)(r) \), because \( (a/at)(r_H) = 0 \). When expressed in the hub-body system, \( (a/at)(r) \) can be obtained by a simple differentiation of equation (2) with respect to time to yield
\[
\frac{3}{\partial t} (r) = \begin{cases}
\dot{x} \\
\dot{y} \\
\dot{z}
\end{cases}
\]

\[
\begin{align*}
&\varepsilon_\zeta \sin \psi + r_\beta \dot{\beta} \sin \beta \cos(\psi - \zeta) + (\Delta e + r_\beta \cos \beta)(\dot{\Omega} - \dot{\zeta})\sin(\psi - \zeta) \\
&= \varepsilon_\zeta \cos \psi - r_\beta \dot{\beta} \sin \beta \sin(\psi - \zeta) + (\Delta e + r_\beta \cos \beta)(\dot{\Omega} - \dot{\zeta})\cos(\psi - \zeta) \\
&\quad - r_\beta \dot{\beta} \cos \beta
\end{align*}
\]

(6)

The other terms on the right-hand side of equation (5) are due to aircraft motion

\[
v_o + \omega \times r_r = \begin{cases}
\dot{x}_o \\
\dot{y}_o \\
\dot{z}_o
\end{cases} + \begin{bmatrix}
r & 0 & q \\
0 & -p & 0 \\
-q & p & 0
\end{bmatrix} \begin{bmatrix}
x + x \\
y + y \\
z + z
\end{bmatrix}
\]

(7a)

\[
\begin{cases}
\dot{x}_o + qA - rB \\
\dot{y}_o - pA + rC \\
\dot{z}_o + pB - qC
\end{cases}
\]

(7b)

where from equation (2),

\[
A = l_z - r_\beta \sin \beta \\
B = (l_y + e_\zeta \sin \psi) + (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta) \\
C = (l_x - e_\zeta \cos \psi) - (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)
\]

(7c)

In the subsequent development, the velocity components of the blade element (eq. (7b)), which are due to aircraft motions, will be denoted by \((\Delta x, \Delta y, \Delta z)^T\). Equations (5), (6), and (7) thus completely define the total velocity components, in the hub-body system, of the blade element for the L-F-P hinge sequence. The coordinate systems used for the F-P-L hinge sequence are described next.
F-P-L Hinge Sequence

We now consider the second hinge sequence, F-P-L. With the pitch bearing in board of the lag hinge, the blade pitch motion couples directly to the lead-lag motion of the blade, because the feathering axis no longer passes through the blade-span axis. A sequence of coordinate systems, which differs from that used for the L-F-P hinge sequence previously discussed, is now set up as shown in figure 6. These coordinate systems have been previously used in reference 10 for a comprehensive flap-lag rotor analysis. That analysis was specifically for tandem rotor configurations. In order to apply the results of analysis to other rotorcraft configurations, such as side-by-side dual-rotor or tilt-rotor configurations, a more general analysis must be undertaken.

In figure 6, the x,y,z system is the hub-body system; the x₅,y₅,z₅ system is the rotating-shaft system (shown as x₃,y₃,z₃ in the L-F-P case); and the x₄,y₄,z₄ system is identical to the x₅,y₅,z₅ system except that its origin is now shifted from the hub center H to point F on the flapping hinge line, which is assumed to be in a direction perpendicular to the shaft. The x₃,y₃,z₃ system has its origin also located at F and is obtained by rotating about x₄ (thus x₃ = x₄) a flapping angle θ so that y₃ aligns with FL. The x₂,y₂,z₂ system is obtained from x₃,y₃,z₃ system by shifting its origin from F to L on the lag hinge. Finally, the x₁,y₁,z₁ system is obtained from the x₂,y₂,z₂ system by a rotation θ about the y₂ axis. Now with respect to the x₁,y₁,z₁ system, the blade element dm has the components:
With respect to the other coordinate systems, the components are obtained using the following transformations:

\[
\begin{align*}
\{x_1\} &= \begin{bmatrix} -r_\xi & \sin \xi \\ r_\xi & \cos \xi \\ 0 \end{bmatrix} \\
\{y_1\} &= \begin{bmatrix} -r_\eta & \sin \eta \\ r_\eta & \cos \eta \\ 0 \end{bmatrix} \\
\{z_1\} &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\]

(8)

Combining equations (8) through (13), the components of the position vector \( \mathbf{r} \) from the hub center \( H \) to the blade element \( dr \) (with mass \( dm \) as shown in fig. 6), when expressed in the hub-body system, are obtained:
\[
\begin{align*}
\mathbf{r} &= \begin{pmatrix} x \\ y \\ z \end{pmatrix} \\
&= \begin{pmatrix} -(e_8 + \Delta e \cos \beta + r_\zeta \cos \beta \cos \zeta + r_\zeta \sin \beta \sin \zeta \sin \theta) \cos \psi \\ -r_\zeta \cos \theta \sin \zeta \sin \psi \\ (e_8 + \Delta e \cos \beta + r_\zeta \cos \beta \cos \zeta + r_\zeta \sin \beta \sin \zeta \sin \theta) \sin \psi \\ -r_\zeta \cos \theta \sin \zeta \cos \psi \\ -\Delta e \sin \beta - r_\zeta (\cos \zeta \sin \beta - \cos \theta \sin \zeta \sin \theta) \end{pmatrix}
\end{align*}
\]

Total velocity of the blade element- As in the case of the L-F-P hinge sequence, the total velocity of the blade element \( \mathbf{v} \) is the sum of the relative velocity of the blade element with respect to the hub center and the velocity caused by the aircraft motion as given in equation (5). The relative velocity with respect to the hub center, when expressed in the hub-body system, is obtained as before, that is, by directly taking the derivative of equation (14) with respect to time, yielding

\[
\frac{\partial}{\partial t} (\mathbf{r}) = \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}
\]
where

\[
\dot{x} = \Omega [\sin \psi (e_B + r_{\xi} \sin \beta \sin \zeta \sin \theta + \Delta e \cos \beta + r_{\xi} \cos \beta \cos \zeta)] \\
- r_{\xi} \cos \psi \cos \theta \sin \zeta] + \dot{\psi} \cos \psi (r_{\xi} \sin \beta \cos \zeta + \Delta e \sin \beta) \\
- r_{\xi} \cos \beta \sin \zeta \sin \theta ) + \dot{r}_{\xi} \sin \zeta (\sin \psi \sin \theta - \cos \psi \sin \beta \cos \theta) \\
+ \dot{\psi} \sin \zeta (- \sin \psi \cos \beta \sin \zeta - \cos \psi \cos \zeta \cos \theta - \sin \psi \sin \beta \cos \zeta \sin \theta)
\]

\[
\dot{y} = \Omega [\cos \psi (e_B + r_{\xi} \sin \beta \sin \zeta \sin \theta + \Delta e \cos \beta + r_{\xi} \cos \beta \cos \zeta)] \\
+ r_{\xi} \sin \psi \cos \theta \sin \zeta] + \dot{\psi} \sin \psi (-r_{\xi} \sin \beta \cos \zeta - \Delta e \sin \beta) \\
+ r_{\xi} \cos \beta \sin \zeta \sin \theta ) + \dot{r}_{\xi} \sin \zeta (\cos \psi \sin \theta + \sin \psi \sin \beta \cos \theta) \\
+ \dot{\psi} \sin \zeta (- \sin \psi \cos \beta \sin \zeta - \cos \psi \cos \zeta \cos \theta - \sin \psi \sin \beta \cos \zeta \sin \theta)
\]

\[
\dot{z} = -\dot{\psi} (r_{\xi} \cos \zeta \cos \beta + \Delta e \cos \beta + r_{\xi} \sin \beta \sin \zeta \sin \theta) \\
+ \dot{r}_{\xi} (\cos \beta \sin \zeta \cos \theta) + \dot{\psi} (\sin \zeta \sin \beta + \cos \beta \cos \zeta \sin \theta)
\]

When expressed in the hub-body system, the components of the velocity of the blade element due to the aircraft motion is given in equation (7), in which the components of the position vector, \((x,y,z)^T\), are now given by equation (14) rather than equation (2). Denote these velocity components by \((\Delta \dot{x}, \Delta \dot{y}, \Delta \dot{z})\); then

\[
V_o + \omega \times \mathbf{r}_r = \begin{bmatrix} \Delta \dot{x} \\ \Delta \dot{y} \\ \Delta \dot{z} \end{bmatrix} \quad (17a)
\]
where

\[ \Delta x = \dot{x}_o + q(e_z - \Delta e \sin \theta - r \zeta (\cos \zeta \sin \theta - \cos \theta \sin \zeta \sin \theta)) \]

\[ - r(x + [e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]) \sin \psi \]

\[ - r \zeta \cos \theta \sin \zeta \cos \psi \}

\[ \Delta y = \dot{y}_o + r(x - [e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]) \cos \psi \]

\[ - r \zeta \cos \theta \sin \zeta \sin \psi \}

\[ + p(y + [e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]) \sin \psi - r \zeta \cos \theta \sin \zeta \cos \psi \}

\[ \Delta z = \dot{z}_o - q(x - [e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]) \cos \psi \]

\[ - r \zeta \cos \theta \sin \zeta \sin \psi \}

\[ + p(y + [e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]) \sin \psi - r \zeta \cos \theta \sin \zeta \cos \psi \]

and the components of the total velocity of the blade element are the sum of equations (16) and (17), i.e.,

\[ V_r = \begin{cases} \dot{x} + \Delta x \\ \dot{y} + \Delta y \\ \dot{z} + \Delta z \end{cases} \]

This completes the determination of the position and velocity components of the blade element in the hub-body system for the F-P-L hinge sequence.

**F-L-P Hinge Sequence**

The position and velocity of the blade element for the F-L-P hinge sequence can be obtained directly from those for the F-P-L hinge sequence by omitting the transformation caused by blade pitch rotation. Setting \( \theta = 0 \) in equation (14) yields the position components in the hub-body system:

\[ r = \begin{cases} x \{-(e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta) \cos \psi - r \zeta \sin \zeta \sin \psi \} \\ y \{(e_\beta + \Delta e \cos \theta + r \zeta (\cos \theta \cos \zeta) \sin \psi - r \zeta \sin \zeta \cos \psi \} \\ z \{-(\Delta e + r \zeta (\cos \zeta) \sin \beta \} \end{cases} \]
Likewise, the total velocity of the blade element is obtained by setting \( \theta = \dot{\theta} = 0 \) in equations (16) and (17b) to yield:

\[
V_r = \begin{bmatrix}
\dot{x} + \Delta \dot{x} \\
\dot{y} + \Delta \dot{y} \\
\dot{z} + \Delta \dot{z}
\end{bmatrix}
\]

(20a)

where

\[
\begin{align*}
\dot{x} &= \Omega [\sin \psi (e_\beta + \Delta e \cos \beta + r_\zeta \cos \beta \cos \zeta) - r_\zeta \cos \psi \sin \zeta] \\
&\quad + \dot{\beta} \cos \psi \sin \beta (\Delta e + r_\zeta \cos \zeta) + \dot{\zeta} r_\zeta (\cos \psi \cos \beta \sin \zeta - \sin \psi \cos \zeta)
\end{align*}
\]

\[
\begin{align*}
\dot{y} &= \Omega [\cos \psi (e_\beta + \Delta e \cos \beta + r_\zeta \cos \beta \cos \zeta) + r_\zeta \sin \psi \sin \zeta] \\
&\quad - \dot{\beta} \sin \psi \sin \beta (\Delta e + r_\zeta \cos \zeta) - \dot{\zeta} r_\zeta (\sin \psi \cos \beta \sin \zeta + \cos \psi \cos \zeta)
\end{align*}
\]

\[
\begin{align*}
\dot{z} &= -\dot{\beta} \cos \beta (\Delta e + r_\zeta \cos \zeta) + \dot{\zeta} r_\zeta \sin \zeta \sin \beta.
\end{align*}
\]

This concludes the derivation for the expressions of the position and velocity components of the blade element, in the hub-body system, for the F-L-P hinge sequence.

The total velocity as given in equations (5), (18), and (20), respectively, for L-F-P, F-P-L, and F-L-P hinge sequences is required for developing the coupled flap-lag equations of motion using the Lagrange method. It is also required for the calculation of the aerodynamic forces and moments to be discussed later in this
The development of the flapping and lag equations is given in the next section.

INERTIA DYNAMICS

The Lagrangian procedure is applied to develop the inertia dynamics for the flapping and lag motion. This procedure begins with the determination of the kinetic energy of a single blade. This is obtained by integrating the kinetic energy of the blade element over the entire blade span. The development of flap/lag equations of motion will be given separately for each of the three hinge sequences.

L-F-P Hinge Sequence

The kinetic energy of the single rotor blade is determined by summing up that for each blade element, \((1/2)V_r \cdot V_r \, dm\), over the entire blade span, i.e.,

\[
T = \frac{1}{2} \int_0^R V_r \cdot V_r \, dm
\]

To help identify the contribution of the aircraft motion to the total kinetic energy, the dot product of the total velocity, \(V_r \cdot V_r\), will be expressed in the following manner:

\[
V_r \cdot V_r = (\ddot{x} + \Delta \ddot{x})^2 + (\ddot{y} + \Delta \ddot{y})^2 + (\ddot{z} + \Delta \ddot{z})^2
\]

\[
= (\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + (\ddot{x}^2 + \ddot{y}^2 + \ddot{z}^2) + 2(\dddot{x} \dddot{x} + \dddot{y} \dddot{y} + \dddot{z} \dddot{z})
\]

The first term of the right-hand side of equation (22) involves no effects of aircraft motion and it can be calculated directly from equation (6); the remaining terms involve the effects of aircraft motion and are determined using equations (6) and (7). The result is

\[
V_r \cdot V_r = e_\zeta^2 \dot{u}^2 + r_\beta^2 \dot{\theta}^2 + (\Delta e + r_\beta \cos \beta)^2 (\omega - \dot{\zeta})^2 + 2e_\zeta u [r_\beta \dot{\theta} \sin \beta \sin \zeta
\]

\[
+ (\Delta e + r_\beta \cos \beta) (\omega - \dot{\zeta}) \cos \zeta] + (\dot{x}_o^2 + \dot{y}_o^2 + \dot{z}_o^2)
\]

\[
+ 2(q \dot{x}_o - p \dot{y}_o) (e_\zeta - r_\beta \sin \beta) + 2r \dot{y}_o [(\ell_y - e_\zeta \cos \psi)
\]

\[
- (\Delta e + r_\beta \cos \beta) \cos(\psi - \zeta)] - \dot{x}_o [(\ell_x - e_\zeta \sin \psi)
\]

\[
+ (\Delta e + r_\beta \cos \beta) \sin(\psi - \zeta)] + 2z_o [(\ell_y + e_\zeta \sin \psi)
\]

\[
+ (\Delta e + r_\beta \cos \beta) \sin(\psi - \zeta)] - q [(\ell_x - e_\zeta \cos \psi)
\]
\[
- (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)) + 2(\dot{x}_0[\epsilon_\zeta \Omega \sin \psi + r_\beta \dot{\beta} \sin \beta \cos(\psi - \zeta))
+ (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\sin(\psi - \zeta)) + \dot{y}_0[\epsilon_\zeta \Omega \cos \psi
- r_\beta \dot{\beta} \sin \beta \sin(\psi - \zeta) + (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\cos(\psi - \zeta))
- \dot{z}_0 r_\beta \dot{\beta} \cos \beta) + (p^2 + q^2)(\ell_z - r_\beta \sin \beta)^2
+ (p^2 + r^2)[(\ell_y + e_\zeta \sin \psi) + (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta)]^2
+ (r^2 + q^2)((\ell_x - e_\zeta \cos \psi) - (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)]^2
- 2r(\ell_z - r_\beta \sin \beta)[q[(\ell_y + e_\zeta \sin \psi) + (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta)]
+ p[(\ell_x - e_\zeta \cos \psi) - (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)]
- 2pq[(\ell_y + e_\zeta \sin \psi) + (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta)][(\ell_x - e_\zeta \cos \psi)
- (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)] + 2(\ell_z - r_\beta \sin \beta)[q[\epsilon_\zeta \Omega \sin \psi
+ r_\beta \dot{\beta} \sin \beta \cos(\psi - \zeta) + (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\sin(\psi - \zeta))
- p[\epsilon_\zeta \Omega \cos \psi - r_\beta \dot{\beta} \sin \beta \sin(\psi - \zeta)
+ (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\cos(\psi - \zeta))] - 2r_\beta \dot{\beta} \cos \beta(p[(\ell_y + e_\zeta \sin \psi)
+ (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta)] - q[(\ell_x - e_\zeta \cos \psi)
- (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta))] + 2r[[(\ell_x - e_\zeta \cos \psi)
- (\Delta e + r_\beta \cos \beta)\cos(\psi - \zeta)][e_\zeta \Omega \cos \psi - r_\beta \dot{\beta} \sin \beta \sin(\psi - \zeta)
+ (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\cos(\psi - \zeta)] - [(\ell_y + e_\zeta \sin \psi)
+ (\Delta e + r_\beta \cos \beta)\sin(\psi - \zeta)][e_\zeta \Omega \sin \psi + r_\beta \dot{\beta} \sin \beta \cos(\psi - \zeta)
+ (\Delta e + r_\beta \cos \beta)(\Delta - \zeta)\sin(\psi - \zeta))] \tag{23}
\]

The zeroth, first, and second mass moments of the blade segment outside the flapping hinge are denoted by

\[
I_\beta = \int_0^R r_\beta^2 \, dm, \quad M_\beta = \int_0^R r_\beta \, dm, \quad \text{and} \quad m_\beta = \int_0^R \, dm
\]
in which the limits of integration are from the flapping hinge to the tip of the blade. Consideration of the kinetic energy associated with the blade segment inboard of the flapping hinge introduces additional terms. Appendix A discusses the impact of this on the inertia dynamics for the three hinge sequences considered.

The kinetic energy associated with a single rotor blade, $T$, is determined to be

$$T = \frac{1}{2} \left( \beta^2 I_B + \zeta^2 (\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_B \cos^2 \beta) + \alpha^2 [(e^2_\zeta + \Delta e^2)m_B$$

$$+ 2\Delta e M_B \cos \beta + I_B \cos^2 \beta] + 2\hat{\omega}_N (\Delta e m_B + M_B \cos \beta) \cos \zeta$$

$$- 2\hat{\omega}_N (e (\Delta e m_B + M_B \cos \beta) \cos \zeta + (\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_B \cos^2 \beta))$$

$$+ 2\hat{\omega}_N M_B \sin \beta \sin \zeta) + \frac{1}{2} (\dot{x}_O^2 + \dot{y}_O^2 + \dot{z}_O^2)m_B + (q \dot{x}_O - p \dot{y}_O) (\dot{z}_B - M_B \sin \beta$$

$$+ r \dot{y}_O [(\dot{L}_x - e \cos \psi)m_B - (\Delta e m_B + M_B \cos \beta) \cos (\psi - \zeta)]$$

$$- \dot{x}_O [(\dot{L}_y + e \sin \psi)m_B + (\Delta e m_B + M_B \cos \beta) \sin (\psi - \zeta)]$$

$$+ \dot{z}_O (p [\dot{L}_y + e \sin \psi] m_B + (\Delta e m_B + M_B \cos \beta) \sin (\psi - \zeta) - q [\dot{L}_x - e \cos \psi] m_B$$

$$- (\Delta e m_B + M_B \cos \beta) \cos (\psi - \zeta))] + \dot{\chi}_O [e m_B \omega \sin \psi + M_B \dot{\beta} \sin \beta \cos (\psi - \zeta)$$

$$+ (\Delta e m_B + M_B \cos \beta) (\Omega - \dot{\zeta}) \sin (\psi - \zeta)] + \dot{y}_O [e m_B \Omega \cos \psi$$

$$- M_B \dot{\beta} \sin \beta \sin (\psi - \zeta) + (\Delta e m_B + M_B \cos \beta) (\Omega - \dot{\zeta}) \cos (\psi - \zeta)] - \dot{z}_B M_B \dot{\beta} \cos \beta$$

$$+ \frac{1}{2} (p^2 + q^2) (\dot{z}_B^2 m_B - 2L \dot{z}_B \sin \beta + I_B \sin^2 \beta)$$

$$+ \frac{1}{2} (p^2 + r^2) [(\dot{L}_y + e \sin \psi)^2 m_B$$

$$+ 2(\dot{L}_y + e \sin \psi) (\Delta e m_B + M_B \cos \beta) \sin (\psi - \zeta)$$

$$+ (\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_B \cos^2 \beta) \sin^2 (\psi - \zeta))$$

$$+ \frac{1}{2} (q^2 + r^2) [(\dot{L}_x - e \cos \psi)^2 m_B$$

$$- 2(\dot{L}_x - e \cos \psi) (\Delta e m_B + M_B \cos \beta) \cos (\psi - \zeta)$$

$$+ (\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_B \cos^2 \beta) \cos^2 (\psi - \zeta))$$

$$- pq [(\dot{L}_y + e \sin \psi) (\dot{L}_x - e \cos \psi) m_B$$

$$- (\dot{L}_y + e \sin \psi) (\Delta e m_B + M_B \cos \beta) \cos (\psi - \zeta)$$

$$+ (\dot{L}_x - e \cos \psi) (\Delta e m_B + M_B \cos \beta) \sin (\psi - \zeta)$$

$$- (\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_B \cos^2 \beta) \sin (\psi - \zeta) \cos (\psi - \zeta)]$$

17
\[-p d\left( t + e \cos \psi \right) (t_B - M_e \sin \beta) - [t (\Delta M_e + M_e \cos \beta)

\[-\Delta M_e \sin \beta - I \sin \beta \cos \beta \cos (\psi - \zeta)]

\[-q r (t + e \sin \psi) (t_B - M_e \sin \beta)

\[+ [t (\Delta M_e + M_e \cos \beta) - \Delta M_e \sin \beta - I \sin \beta \cos \beta \sin (\psi - \zeta)]

\[+ (t_B - M_e \sin \beta) \{q \left[ e \Omega \sin \psi + \Delta e (\Omega - \zeta) \sin (\psi - \zeta) \right]

\[-p \left[ e \Omega \cos \psi + \Delta e (\Omega - \zeta) \cos (\psi - \zeta) \right]

\[+ (t_B - I \sin \beta) \{q \left[ e \sin \beta \cos (\psi - \zeta) + (\Omega - \zeta) \cos \beta \sin (\psi - \zeta) \right]

\[-e \cos \beta \{p [(t + e \cos \psi) M_e + (\Delta M_e + I \cos \beta) \sin (\psi - \zeta)

\[-q [(t - e \cos \psi) M_e - (\Delta M_e + I \cos \beta) \cos (\psi - \zeta)]

\[+ r [(t - e \sin \psi) [M_e e \cos \psi - M_e \hat{\gamma} \sin \beta \sin (\psi - \zeta)]

\[+ (\Delta M_e + M_e \cos \beta) (\Omega - \zeta) \cos (\psi - \zeta)]

\[+ (\Delta M_e + M_e \cos \beta) (\Omega - \zeta) \sin (\psi - \zeta)] - (\Delta M_e + M_e \cos \beta) e \Omega \cos \zeta

\[-(\Delta e^2 M_e + 2 \Delta e M_e \cos \beta + I \cos^2 \beta) (\Omega - \zeta)] \right] \}

(24)

It can be seen from equation (24) that the aircraft motion greatly complicates the expression for the kinetic energy of the rotor blade. It also complicates, as can be expected, the equations of motion of the blade.

The coupled flap-lag equations of motion are now derived using the Lagrange procedure (refs. 22 and 23). They are calculated using

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\zeta}} \right) - \frac{\partial T}{\partial \zeta} = Q_\zeta \quad (25a)
\]

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\beta}} \right) - \frac{\partial T}{\partial \beta} = Q_\beta \quad (25b)
\]

In equations (25a) and (25b), \(Q_\zeta\) and \(Q_\beta\) are the generalized forces (moments in the present case). They consist of the effects due to gravity, aerodynamic forces, and
the forces due to lag dampers and hinge springs. These will be discussed later in this report.

**Coupled flap-lag equations of motion** - With some algebraic manipulations of equations (24) and (25a) the lag equation of motion becomes:

\[
\ddot{\zeta}(\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_\beta \cos^2 \beta)
\]

\[
= \hat{\dot{u}}(\Delta e^2 m_B + 2\Delta e M_B \cos \beta + I_\beta \cos^2 \beta) + (\Delta e m_B + M_B \cos \beta)(a_x \sin(\psi - \zeta)
\]

\[
+ a_y \cos(\psi - \zeta) + e[(\hat{\dot{u}} - \dot{r})\cos \zeta - (\Omega - r)^2 \sin \zeta - pq \cos(2\psi - \zeta)
\]

\[
- p^2 \sin \psi \cos(\psi - \zeta) + q^2 \cos \psi \sin(\psi - \zeta) - \Delta e[\dot{r} + pq \cos 2(\psi - \zeta)
\]

\[
+ \frac{1}{2}(p^2 - q^2)\sin 2(\psi - \zeta)] + I_x[(\dot{r} + pq)\cos(\psi - \zeta) - (q^2 + r^2)\sin(\psi - \zeta)]
\]

\[
+ I_y[(pq - r)\sin(\psi - \zeta) - (p^2 + r^2)\cos(\psi - \zeta)]
\]

\[
- I_z[(\dot{r} - qr)\cos(\psi - \zeta) - (q + pr)\sin(\psi - \zeta)]
\]

\[
+ (\Delta e M_B + I_\beta \cos \beta)[\sin \beta[2\dot{\beta}(\dot{r} - \Omega + \dot{\zeta}) + (\dot{p} - qr)\cos(\psi - \zeta)
\]

\[
- (\dot{q} + pr)\sin(\psi - \zeta)] - \cos \beta(\dot{r} + pq \cos 2(\psi - \zeta) + \frac{1}{2}(p^2 - q^2)\sin 2(\psi - \zeta)
\]

\[
- 2\dot{\beta}[p \cos(\psi - \zeta) - q \sin(\psi - \zeta)] + \Omega_1 Q_1
\]

(26)

Similarly, from equations (24) and (25b), the flapping equation of motion is obtained:

\[
\ddot{\beta} = \frac{M_B}{I_\beta} [\sin \beta(a_y \sin(\psi - \zeta) - a_x \cos(\psi - \zeta) - e[\hat{\dot{u}} \sin \zeta + (\Omega^2 - 2\Omega)\cos \zeta]
\]

\[
- \Delta e[(\Omega - \dot{\zeta})^2 - 2r(\Omega - \dot{\zeta})]
\]

\[
+ [I_x - e_\zeta \cos \psi - \Delta e \cos(\psi - \zeta)][(\dot{r} + pq)\sin(\psi - \zeta) + (q^2 + r^2)\cos(\psi - \zeta)]
\]

\[
+ [I_y + e_\zeta \sin \psi + \Delta e \sin(\psi - \zeta)][(\dot{r} - pq)\cos(\psi - \zeta) - (p^2 + r^2)\sin(\psi - \zeta)]
\]

\[
- I_z[(\dot{r} - qr)\sin(\psi - \zeta) + (\dot{q} + pr)\cos(\psi - \zeta)]
\]

\[
+ \cos \beta(a_z + 2p[\Delta e \cos \psi + \Delta e(\Omega - \dot{\zeta})\cos(\psi - \zeta)]
\]

\[
- 2q[\Delta e \sin \psi + \Delta e(\Omega - \dot{\zeta})\sin(\psi - \zeta)]
\]

\[
- (\dot{q} - pr)[I_x - e_\zeta \cos \psi - \Delta e \cos(\psi - \zeta)]
\]

\[
+ (\dot{p} + qr)[I_y + e_\zeta \sin \psi + \Delta e \sin(\psi - \zeta)] - (p^2 + q^2)I_z]
\]
In equations (26) and (27), \( a_x, a_y, \) and \( a_z \) are, respectively, the components of the total linear acceleration at the aircraft c.g. when projected along the \( x, y, z \) axes of the hub-body system. It is important to recognize that these components are different from \( \dot{x}_o, \dot{y}_o, \) and \( \dot{z}_o, \) which are obtained by differentiating \( \dot{x}_o, \dot{y}_o, \) and \( \dot{z}_o, \) with respect to time, without considering the fact that the hub-body system is rotating about the inertia system, \( x', y', z'. \) In fact, from equation (3),

\[
\begin{align*}
\dot{a}_x &= \ddot{x}_o - r\dot{y}_o + q\dot{z}_o \\
\dot{a}_y &= \ddot{y}_o + r\ddot{x}_o - p\ddot{z}_o \\
\dot{a}_z &= \ddot{z}_o + p\dot{y}_o - q\dot{x}_o
\end{align*}
\]

(28a) \hspace{1cm} (28b) \hspace{1cm} (28c)

This distinction becomes particularly important when combining the flap-lag equations with the rigid-body aircraft equations of motion to calculate the dynamics and responses of the complete rotorcraft.

Equations (26) and (27) are the coupled flap-lag equations of motion for the L-F-P hinge sequence. It should be noted that in deriving these equations, the inertial effects of the blade segment inboard of the flapping hinge were neglected. When these effects are included, the inertia dynamic terms in the lag equation (26) must be expanded to include additional terms given by equation (A2) in appendix A. However, the flapping equation (27) remains unchanged, because they have no direct effect on the flapping motion.

**F-P-L Hinge Sequence**

The coupled flap-lag equations of motion for the F-P-L hinge sequence are developed in the same manner as for the L-F-P hinge sequence discussed previously. Using equations (16), (17b), (21), (22), (25a), and (25b), the coupled flap-lag equations of motion are obtained:
\[I_\zeta = \tilde{e} \sin \theta (I_\zeta + \Delta e \cos \zeta) + \hat{\omega} \cos \theta (I_\zeta \cos \beta + M_\zeta \cos \zeta (e_\beta + \Delta e \cos \beta))
\]
\[+ 2 \tilde{e} \hat{e} I_\zeta \cos \theta \sin^2 \zeta
\]
\[- 2 \tilde{e} \hat{e} \cos \theta \cos \zeta (I_\zeta (\sin \beta \cos \zeta - \cos \theta \sin \zeta \sin \theta) + \Delta e M_\zeta \sin \beta)
\]
\[+ 2 \tilde{e} \hat{e} \sin \zeta I_\zeta (\sin \beta \cos \zeta - \cos \theta \sin \zeta \sin \theta) + \hat{\omega}^2 I_\zeta \sin \zeta \cos \zeta
\]
\[- \hat{\omega}^2 \sin \zeta (I_\zeta \cos \zeta \cos^2 \theta + \Delta e M_\zeta)
\]
\[+ \hat{\omega}^2 \left[ I_\zeta \left( \frac{1}{2} \sin 2 \zeta (\sin^2 \beta - \cos^2 \beta \sin^2 \theta) + \cos 2 \zeta \sin \beta \cos \beta \sin \theta \right)
\]
\[+ (e_\beta M_\zeta + \Delta e M_\zeta \cos \beta) (\sin \beta \cos \zeta \sin \theta - \cos \zeta \sin \phi)
\]
\[+ M_\zeta [a_x (\cos \zeta \sin \psi \cos \phi + \cos \zeta \cos \psi \sin \theta \sin \beta - \sin \zeta \cos \psi \cos \beta)
\]
\[+ a_y (\cos \zeta \cos \phi \cos \theta - \cos \zeta \sin \psi \sin \theta \sin \beta + \sin \zeta \sin \phi \cos \beta)
\]
\[+ a_z (\cos \zeta \sin \phi \cos \theta + \sin \zeta \sin \phi \sin \beta)]
\]
\[+ 2 \tilde{e} I_\zeta (\sin \zeta \cos \zeta (q \sin \psi \cos \phi - p \cos \phi \cos \beta - r \sin \beta)
\]
\[+ \sin^2 \zeta (\sin \theta (q \sin \psi \sin \phi - p \cos \phi \sin \beta + r \cos \beta)
\]
\[- \cos \theta (q \cos \psi + p \sin \psi)]
\]
\[+ 2 \tilde{e} ([I_\zeta \cos \zeta \cos^2 \theta + \Delta e M_\zeta]) \sin \zeta (q \cos \psi + p \sin \psi)
\]
\[+ (I_\zeta \cos \zeta + \Delta e M_\zeta) \cos \zeta \cos \theta (q \sin \psi \cos \phi - p \cos \psi \cos \beta - r \sin \beta)
\]
\[- I_\zeta \cos \theta \sin \zeta \cos \zeta \sin \zeta (q \sin \psi \sin \phi - p \cos \psi \sin \beta + r \cos \beta)]
\]
\[+ 2 \tilde{e} ([(e_\phi M_\zeta + \Delta e M_\zeta \cos \beta) + I_\zeta (\cos \theta \cos \zeta + \sin \beta \sin \zeta \sin \theta)]
\]
\[\times [\sin \theta \cos \zeta (q \sin \psi \cos \phi - p \cos \psi \cos \beta - r \sin \beta)
\]
\[+ \sin \zeta (q \sin \psi \sin \theta - p \cos \psi \sin \beta + r \cos \beta)]
\]
\[- I_\zeta \cos \theta \sin \zeta ([\sin \theta \cos \zeta \cos \beta + \sin \zeta \sin \beta] \times (q \cos \psi + p \sin \psi)
\]
\[+ r \cos \zeta \cos \theta) + (M_\zeta [-\xi \chi + (e_\beta + \Delta e \cos \beta) \cos \psi]
\]
\[+ I_\zeta [\sin \psi \cos \phi \sin \zeta + \cos \psi (\cos \beta \cos \zeta + \sin \theta \sin \zeta \sin \theta)]
\]
\[\times [\sin \theta \cos \zeta ((q^2 + r^2) \cos \psi \sin \beta + (pq + r) \sin \psi \sin \beta - (q - pr) \cos \beta)
\]
\[+ \sin \zeta ((q^2 + r^2) \cos \psi \cos \theta + (pq + r) \sin \psi \cos \theta + (q - pr) \sin \beta)]
\]
\[ + \cos \xi \cos \theta \{(q^2 + r^2)\sin \psi - (pq + r)\cos \psi\} \]
\[ + \{M_\zeta [I_y + (e_\theta + Ae \cos \theta)\sin \psi] \]
\[ + I_\zeta \{-\cos \theta \sin \xi \cos \psi + \sin \psi (\cos \theta \cos \xi + \sin \theta \sin \xi \sin \theta)\} \]
\[ \times \{\sin \theta \cos \xi[(pq - \hat{r}) \cos \psi \sin \theta + (p^2 + r^2) \sin \psi \sin \theta - (\hat{p} + qr) \cos \theta] \]
\[ - \sin \xi[(pq - \hat{r}) \cos \psi \cos \theta + (p^2 + r^2) \sin \psi \cos \theta + (\hat{p} + qr) \sin \theta] \]
\[ + \cos \theta \cos \xi[(pq - \hat{r}) \sin \psi - (p^2 + r^2) \cos \psi] \}
\[ + \{M_\zeta (-I_z + \Delta e \sin \theta) + I_\zeta (\sin \theta \cos \xi - \cos \theta \sin \xi \sin \theta)\} \]
\[ \times \{\sin \theta \cos \xi[(-\hat{q} + pr) \cos \psi \sin \theta - (\hat{p} - qr) \sin \psi \sin \theta \}
\[ - (p^2 + q^2) \cos \theta - \sin \xi[(-\hat{q} + pr) \cos \psi \cos \theta - (\hat{p} - qr) \sin \psi \cos \theta \]
\[ + (p^2 + q^2) \sin \theta \}
\[ + \cos \theta \cos \xi[(-\hat{q} + pr) \sin \psi + (\hat{p} - qr) \cos \psi] \} + Q_{\zeta 2} \]

\[ \ddot{\theta} [\Delta e^2 m_\zeta + 2 \Delta e M_\zeta \cos \xi + I_\zeta (\cos^2 \xi + \sin^2 \xi \sin^2 \theta)] \]
\[ = \ddot{\xi} \sin \theta (I_\zeta + \Delta e M_\zeta \cos \xi) + (\ddot{\theta} \cos \theta \sin \xi + 2 \ddot{\xi} \theta \cos \theta \cos \xi - \ddot{\xi}^2 \sin \theta \sin \xi) \]
\[ \times (I_\zeta \cos \xi + \Delta e M_\zeta) + (2 \ddot{\theta} \dot{\theta} \sin \theta \sin \xi - 2 \ddot{\xi} \theta \cos \theta \cos \xi - \ddot{\xi} \cos \theta \sin \xi) \]
\[ \times [I_\zeta (\sin \theta \cos \xi \sin \theta - \sin \theta \cos \xi) - \Delta e M_\zeta \sin \theta] \]
\[ + 2 \ddot{\theta} \dot{\theta} \sin \xi (I_\zeta \cos \xi \cos^2 \theta + \Delta e M_\zeta) \]
\[ - 2 \ddot{\theta} \dot{\theta} I_\zeta \sin \theta \cos \theta \sin^2 \xi - \ddot{\xi}^2 \Delta e M_\zeta \sin \theta \sin \xi \]
\[ + \Omega^2 \left\{ - \frac{1}{2} \sin 2 \theta [\Delta e^2 m_\zeta + 2 \Delta e M_\zeta \cos \xi + I_\zeta (\cos^2 \xi - \sin^2 \theta \sin^2 \xi)] \right\} \]
\[ + \frac{1}{2} I_\zeta \sin 2 \xi \cos 2 \theta \sin \theta + \Delta e M_\zeta \sin \theta \sin \xi \cos 2 \theta \]
\[ + e_\theta M_\zeta (\cos \theta \sin \xi \sin \theta - \sin \theta \cos \xi) - \Delta e e_\theta M_\zeta \sin \theta \]
\[- a_x \cos \phi [m_\zeta \Delta e \sin \theta - M_\zeta (\sin \theta \cos \phi \sin \xi - \sin \theta \cos \xi)] \]
\[- a_y \sin \phi [-m_\zeta \Delta e \sin \theta + M_\zeta (\sin \theta \cos \phi \sin \xi - \sin \theta \cos \xi)] \]
\[ + a_z \{ -m_\zeta \Delta e \cos \phi + M_\zeta (\sin \theta \phi \sin \xi + \cos \theta \cos \xi)] \]
\[- 2 \ddot{\xi}[-(q \sin \psi \sin \theta + \hat{p} \cos \psi \sin \theta + r \cos \theta)] I_\zeta \sin \theta \cos \theta \sin \xi \cos \xi}$

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+ (q \sin \psi \cos \beta - p \cos \psi \cos \beta) \cos \theta \cos \xi (M_{\zeta} \Delta e - I_{\zeta} \cos \xi) \\
+ r \sin \beta \cos \theta \cos \xi (M_{\zeta} \Delta e + I_{\zeta} \cos \xi) + (q \cos \psi + p \sin \psi) \\
\times [M_{\zeta} \Delta e \sin \xi (1 - 2 \cos^2 \beta) + 2M_{\zeta} \Delta e \sin \beta \cos \beta \cos \xi \sin \theta \\
+ I_{\zeta} \sin \xi \cos \xi \cos^2 \theta)] \\
- 2\dot{\theta}((q \sin \psi \sin \beta - p \cos \psi \sin \beta + r \cos \beta)I_{\zeta} \sin^2 \theta \sin^2 \xi \\
+ (q \sin \psi \cos \beta - p \cos \psi \cos \beta) \sin \theta \sin \xi (-M_{\zeta} \Delta e + I_{\zeta} \cos \xi) \\
- r \sin \theta \sin \xi \sin \beta (M_{\zeta} \Delta e + I_{\zeta} \cos \xi) \\
+ (q \cos \psi + p \sin \psi) \sin \xi \cos \theta (2M_{\zeta} \Delta e \sin \beta \cos \beta - I_{\zeta} \sin \xi \sin \theta)) \\
- 2\dot{\psi}(q \cos \psi + p \sin \psi)[2M_{\zeta} \Delta e \sin \theta \sin \xi \cos^2 \beta \\
- 2 \Delta e \sin \beta \cos \beta (M_{\zeta} \cos \xi + M_{\zeta} \Delta e)] \\
- 2\xi \sin \theta \sin \xi (-p \cos \psi \sin \beta + q \sin \psi \sin \beta + r \cos \beta) \\
\times [M_{\zeta} \Delta e + I_{\zeta} \sin \beta \sin \xi \sin \theta + \cos \beta \cos \xi] \\
- \sin \theta \sin \xi \cos \beta M_{\zeta} \Delta e (-p \cos \psi \sin \beta + q \sin \psi \sin \beta - r \cos \beta) \\
- (p \cos \psi \cos \beta - q \sin \psi \cos \beta + r \sin \beta)[M_{\zeta} \cos \xi (e_\beta + \Delta e \cos \beta) \\
+ M_{\zeta} \Delta e \sin \beta \sin \theta \sin \xi + I_{\zeta} \cos \xi \cos \beta \cos \xi \sin \theta \sin \xi \sin \theta) \\
+ (p \cos \psi \cos \beta - q \sin \psi \cos \beta - r \sin \beta)[M_{\zeta} \Delta e (e_\beta + \Delta e \cos \beta) \\
+ M_{\zeta} \Delta e \cos \beta \cos \xi] - \cos \theta \sin \xi (p \sin \psi + q \cos \psi) \\
\times [-M_{\zeta} \Delta e \cos \beta + I_{\zeta} (\sin \theta \sin \xi \sin \beta + \cos \xi \cos \beta)]] \\
+ [(q + pr) \cos \psi \sin \beta + (\dot{p} - qr) \sin \psi \sin \beta - (p^2 + q^2) \cos \beta] \\
\times (m_{\zeta} \Delta e (-z + \Delta e \sin \beta) - M_{\zeta} \Delta e (\cos \beta \sin \xi \sin \theta - \cos \xi \sin \theta)) \\
+ [(\dot{q} + pr) \cos \psi \sin \beta + (\dot{p} - qr) \sin \psi \sin \beta + (p^2 + q^2) \cos \beta] \\
\times (M_{\zeta} \cos \xi (-z + \Delta e \sin \beta) + I_{\zeta} \cos \xi (\cos \xi \sin \beta - \sin \xi \sin \theta \cos \beta) \\
- [(\dot{q} + pr) \cos \psi \cos \beta + (\dot{p} - qr) \sin \psi \cos \beta - (p^2 + q^2) \sin \beta] \\
\times (M_{\zeta} \sin \theta \sin \xi (-z + \Delta e \sin \beta))
\[ I_\zeta \sin \zeta \sin \theta (\sin \beta \cos \zeta - \cos \beta \sin \zeta \sin \theta) \]
\[- [(\ddot{r} - pq) \cos \psi \sin \beta - (p^2 + r^2) \sin \psi \sin \beta - (\dot{p} + qr) \cos \beta \]
\[ \times (M_\zeta \Delta e \cos \psi \cos \theta \sin \zeta - \sin \psi (\cos \beta \cos \zeta + \sin \beta \sin \theta \sin \zeta)) \]
\[- m_\zeta \Delta e (e_\beta + \Delta e \cos \beta) \sin \theta \]
\[- [(\ddot{r} - pq) \cos \psi \sin \beta - (p^2 + r^2) \sin \psi \sin \beta + (\ddot{p} + qr) \cos \beta \]
\[ \times (-l_y m_\zeta \Delta e - M_\zeta \cos \zeta [l_y + (e_\beta + \Delta e \cos \beta) \sin \psi] \]
\[ + I_\zeta \cos \zeta [\cos \psi \cos \theta \sin \zeta - \sin \psi (\cos \beta \cos \zeta + \sin \beta \sin \theta \sin \zeta)] \]
\[- [(\ddot{r} - pq) \cos \psi \cos \beta - (p^2 + r^2) \sin \psi \cos \beta - (\ddot{p} + qr) \sin \beta \]
\[ \times (M_\zeta \sin \theta \sin \zeta [l_y + (e_\beta + \Delta e \cos \beta) \sin \psi] - I_\zeta \sin \zeta \sin \theta \]
\[ + \cos \psi \cos \theta \sin \zeta - \sin \psi (\cos \beta \cos \zeta + \sin \beta \sin \theta \sin \zeta))] \]
\[ + [(q^2 + r^2) \cos \psi \sin \beta + (pq + \dot{r}) \sin \psi \sin \beta + (\dot{q} - pr) \cos \beta \]
\[ \times (M_\zeta \Delta e [l_x - (e_\beta + \Delta e \cos \beta) \cos \psi] - I_\zeta \cos \zeta \]
\[ + \cos \psi \cos \theta \sin \zeta + \cos \psi (\cos \beta \cos \zeta + \sin \beta \sin \theta \sin \zeta))] \]
\[ + [(q^2 + r^2) \cos \psi \cos \beta + (pq + \dot{r}) \sin \psi \cos \beta + (\dot{q} - pr) \sin \beta \]
\[ \times - M_\zeta \sin \theta \sin \zeta [l_x - (e_\beta + \Delta e \cos \beta) \cos \psi] + I_\zeta \sin \theta \sin \zeta \]
\[ + \sin \psi \cos \theta \sin \zeta + \cos \psi (\cos \beta \cos \zeta + \sin \beta \sin \theta \sin \zeta)] \]
\[ + Q_2 \]

In equations (29) and (30), \( m_\zeta \), \( M_\zeta \), and \( I_\zeta \) are the zeroth, first, and second
mass moments of the blade segment outboard of the lag hinge, i.e.,
\[ m_\zeta = \int_0^R dm \]
\[ M_\zeta = \int_0^R r_\zeta dm \]
\[ I_\zeta = \int_0^R r_\zeta^2 dm \]
The limits of integration for these quantities are from the lag hinge to the tip of
the blade. When the effect of the inertia dynamics of the blade segment inboard of
the lag hinge is considered, additional terms as given by equation (A4) must be added to the right-hand side of the flapping equation (30) as discussed in detail in appendix A.

F-L-P Hinge Sequence

Now with the pitch bearing outboard of the lag hinge, the motion of the blade pitch no longer couples to the flap and lag motion. The coupled flap-lag equations of motion for the F-L-P hinge sequence can therefore be obtained directly from equations (29) and (30) by setting $\theta = \dot{\theta} = \ddot{\theta} = 0$. Alternatively, they can also be obtained using equations (20a), (20b), (21), (22), (25a), and (25b). The results are:

\[
\begin{align*}
I_{\zeta} \ddot{\zeta} &= \dot{\alpha}[I_{\zeta} \cos \beta + M_{\zeta} \cos \zeta(e_{\beta} + \Delta e \cos \beta)] - 2\Delta \beta \cos \zeta \sin \beta(I_{\zeta} \cos \zeta + \Delta e M_{\zeta}) \\
&- \beta^2 \sin \zeta(I_{\zeta} \cos \zeta + \Delta e M_{\zeta}) + \alpha^2 \left[\frac{1}{2} I_{\zeta} \sin^2 \beta \sin 2\zeta \right] \\
&- M_{\zeta}(e_{\beta} + \Delta e \cos \beta) \cos \beta \sin \zeta + M_{\zeta}[a_x(\cos \zeta \sin \psi - \sin \zeta \cos \psi \cos \beta) \\
&+ a_y(\cos \zeta \cos \psi + \sin \zeta \sin \psi \cos \beta) - a_z \sin \zeta \sin \beta] \\
&+ 2\Delta \dot{\beta}(I_{\zeta} \cos \zeta + \Delta e M_{\zeta})[\sin \zeta(q \cos \psi + p \sin \psi) \\
&- \cos \zeta(q \sin \psi \cos \beta - p \cos \psi \cos \beta - r \sin \beta)] \\
&+ 2\alpha([M_{\zeta}(e_{\beta} + \Delta e \cos \beta) + I_{\zeta} \cos \beta \cos \zeta] \sin \zeta \\
&\times (q \sin \psi \sin \beta - p \cos \psi \sin \beta + r \cos \beta) \\
&- I_{\zeta} \sin \zeta[(q \cos \psi + p \sin \psi) \sin \zeta \sin \beta + r \cos \zeta]) \\
&+ [M_{\zeta}[-2x + (e_{\beta} + \Delta e \cos \beta) \cos \psi] + I_{\zeta} [\sin \psi \sin \zeta + \cos \psi \cos \beta \cos \zeta] \\
&\times (-\sin \zeta[(q^2 + r^2) \cos \psi \cos \beta + (pq + \dot{r}) \sin \psi \cos \beta + (\dot{q} - pr) \sin \beta] \\
&+ \cos \zeta[(q^2 + r^2) \sin \psi - (pq + \dot{r}) \cos \psi]) \\
&+ [M_{\zeta}[-2y + (e_{\beta} + \Delta e \cos \beta) \sin \psi] - I_{\zeta} [\cos \psi \sin \zeta - \sin \psi \cos \beta \cos \zeta] \\
&\times (-\sin \zeta[(pq - \dot{r}) \cos \psi \cos \beta + (p^2 + r^2) \sin \psi \cos \beta + (\dot{p} + qr) \sin \beta] \\
&+ \cos \zeta[(pq - \dot{r}) \sin \psi - (p^2 + r^2) \cos \psi]) \\
&+ [M_{\zeta}[-2z + \Delta e \sin \beta] + I_{\zeta} \sin \beta \cos \zeta] \\
\end{align*}
\]
x (-sin ψ[-(q + pr)cos ψ cos β - (p - qr)sin ψ cos β + (p^2 + q^2)sin β] + cos ψ[-(q + pr)sin ψ + (p - qr)cos ψ]) + Q \zeta

\beta[\Delta^2 \mathbf{m}_\zeta + 2 \Delta \mathbf{m}_\zeta \cos \zeta + I'' \cos^2 \zeta]

= (2\Delta \cos \zeta + \hat{\Delta} \sin \zeta)(I' \cos \zeta + \Delta \mathbf{m}_\zeta) \sin \theta + 2\Delta \cos \zeta (I'' \cos \zeta + \Delta \mathbf{m}_\zeta)

\zeta = \frac{1}{2}(\Delta^2 \mathbf{m}_\zeta + 2 \Delta \mathbf{m}_\zeta \cos \zeta + I'' \cos^2 \zeta) \sin 2\theta

- e_\beta \sin \beta(M \cos \theta + \Delta \mathbf{m}_\zeta) - \sin \beta(M \cos \theta + \Delta \mathbf{m}_\zeta) (a_x \cos \psi - a_y \sin \psi)

+ \cos \beta(M \cos \theta - \Delta \mathbf{m}_\zeta) a_z - 2\Delta \cos \zeta[\cos \beta(q \sin \psi - p \cos \psi)]

x (M \Delta \theta - I'' \cos \zeta) + r \sin \beta(M \Delta \theta + I'' \cos \zeta)]

+ \sin \zeta(q \cos \psi + p \sin \psi)(M \cos \theta + \Delta \mathbf{m}_\zeta \Delta \theta \sin 2\theta)

+ 2\Delta(q \cos \psi + p \sin \psi)(M \cos \theta + \Delta \mathbf{m}_\zeta) \Delta \theta \sin 2\theta

+ 2\Delta \cos \zeta(p \cos \psi \cos \beta - q \sin \psi \cos \beta + r \sin \beta)

x [M \cos \theta + \Delta \theta \cos \beta] + \sin \zeta(p \sin \psi + q \cos \psi)

x [-M \cos \theta - \Delta \theta \cos \beta]

- (p \cos \psi \cos \beta - q \sin \psi \cos \beta - r \sin \beta)

x [m \Delta \theta (e_\beta + \Delta \theta \cos \beta) + M \Delta \theta \cos \beta \cos \zeta)]

+ ([q + pr] \cos \psi \sin \theta + (p - qr) \sin \psi \sin \theta - (p^2 + q^2) \cos \theta) \Delta \theta

x [m \Delta \theta (e_\beta + \Delta \theta \cos \beta) + M \cos \theta \sin \beta]

+ ([q + pr] \cos \psi \sin \theta + (p - qr) \sin \psi \sin \theta + (p^2 + q^2) \cos \theta) \cos \zeta

x [M \Delta \theta (e_\beta + \Delta \theta \cos \beta) + I'' \cos \theta \sin \theta]

- [(r - qp) \cos \psi \sin \theta - (p^2 + q^2) \sin \psi \sin \theta - (p + qr) \cos \theta] \Delta \theta

x [M \Delta \theta (\cos \psi \sin \theta - \sin \psi \cos \beta \cos \zeta) - m \Delta \theta (e_\beta + \Delta \theta \cos \beta) \sin \psi]

- [(r - qp) \cos \psi \sin \theta - (p^2 + q^2) \sin \psi \sin \theta + (p + qr) \cos \theta]

x [-m \Delta \theta \Delta \theta - m \Delta \theta \cos \zeta (e_\beta + \Delta \theta \cos \beta) \sin \psi]

+ I'' \cos \theta \cos \zeta [\cos \psi \sin \theta - \sin \psi \cos \beta \cos \zeta]]
+ [(q² + r²)cos ψ sin β + (pq + r)sin ψ sin β + (q − pr)cos β]Δε
× [m_ζ [l_x - (e_β + Δε cos β)cos ζ] - M_ξ [sin ψ sin ζ + cos ψ cos β cos ζ]]
+ [(q² + r²)cos ψ sin β + (pq + r)sin ψ sin β - (q − pr)cos β]cos ζ
× [M_ζ [l_x - (e_β + Δε cos β)cos ζ] - I_ζ [sin ψ sin ζ + cos ψ cos β cos ζ]]
+ Q_β_3

Equation (31) provides the complete inertia dynamics for the lead-lag equation of motion. However, as with the F-P-L hinge sequence, additional terms, as given by equation (A4), must be included in the right-hand side of the flapping equation (32), when the effect of the inertia dynamics associated with the blade segment inboard of the lag hinge is considered.

COMPARISON OF THE RESULTS WITH PREVIOUS WORK

The inertia dynamics in the coupled flap-lag equations of motion for the three hinge sequences, as shown in equations (26) through (32), are now compared with available results in the literature. In general, the previous results have tended to be only for one specific hinge sequence or with limited considerations for the effects of aircraft motions.

L-F-P Hinge Sequence

A complete derivation of the inertia dynamics for the coupled flap-lag equations of motion, including some effects of aircraft motions, is given in reference 11 for an L-F-P hinge sequence with co-located flap and lag hinges. Reference 3 also provides an approximation for the same configuration. This specific hub configuration can be obtained by setting Δε = 0 in equations (26) and (27) to yield:

[Equation for L-F-P hinge sequence]

\[ \zeta = \frac{M_B}{I_β cos β} (a_x sin(ψ - ζ) + a_y cos(ψ - ζ)) \]

[Additional terms for L-F-P hinge sequence]
Note that the underlined quantities in equations (33) and (34) are not included in reference 11 because the effects of the displacement between the hub center and the aircraft c.g. have not been considered. These effects are considered in the present development, allowing applications to tandem or side-by-side dual-rotor configurations where the offset between the hub center and aircraft c.g. are generally large and therefore cannot be neglected. Note also that the sign convention used in this report for the lead-lag angle is positive for lagging (roughly, measured positive when opposite to the direction of rotor rotation). Several other reports (e.g., refs. 3, 5, 9, and 11) use different sign convention.
F-P-L Hinge Sequence

A comprehensive flap-lag rotor analysis was reported in reference 10 for the F-P-L hinge sequence for tandem-rotor applications. The present work expands the effects due to aircraft motion to account for lateral offset \( l_y \), which is necessary for modeling tilt-rotor or side-by-side dual-rotor configurations. The inertia moment for the blade segment inboard of the lag hinge, which was neglected in reference 10, is also included in the present work for completeness (appendix A).

F-L-P Hinge Sequence

This hinge sequence (as well as the L-F-P hinge sequence) was considered in reference 9 for centrally co-located flap and lag hinges; no hinge offsets were included. Nor were the effects of aircraft motions considered in that work. Reference 5 provides a list of the inertia dynamic terms for this hinge sequence. Unfortunately, neither the effects of the variation in the angular velocity of the rotor system nor the effects of aircraft motion were included. As discussed earlier, the effects of aircraft motions, which need to be considered for flight dynamics and control applications, drastically complicates the coupled flap-lag equations of motion as evident from equations (31) and (32). When these effects are neglected, equations (31), (32), and (A4) in appendix A reduce to simply

\[
\begin{align*}
\ddot{\xi} &= \ddot{\alpha} [I_\zeta \cos \beta + M_\zeta (e_\beta + \Delta e \cos \beta) \cos \zeta] - 2\Omega^2 \sin \beta \cos \zeta (I_\zeta \cos \zeta + \Delta e M_\zeta) \\
&\quad - \dot{\beta}^2 \sin \zeta (I_\zeta \cos \zeta + \Delta e M_\zeta) + \ddot{\alpha}^2 \\
&\quad \times \left[ \frac{1}{2} I_\zeta \sin^2 \beta \sin 2\zeta - M_\zeta (e_\beta + \Delta e \cos \beta) \cos \beta \sin \zeta \right] + Q_{\xi 3} \\
&+ \Delta e M_\zeta \cos \zeta + I_\zeta \cos^2 \zeta + I_\Delta e \beta \\
&= (2\dot{\zeta} \cos \zeta + \dot{\alpha} \sin \zeta)(I_\zeta \cos \zeta + \Delta e M_\zeta) \sin \beta + 2\dot{\alpha} \sin \zeta (I_\zeta \cos \zeta + \Delta e M_\zeta) \\
&\quad - \dot{\alpha}^2 \left[ \frac{1}{2} (\Delta e^2 M_\zeta + 2 \Delta e M_\zeta \cos \zeta + I_\zeta \cos^2 \zeta) \sin 2\beta + e_\beta \sin \beta (M_\zeta \cos \zeta + \Delta e M_\zeta) \\
&\quad + (I_\Delta e \cos \beta + e_\beta M_\Delta e) \sin \beta \right] + Q_{\beta 3}
\end{align*}
\]

When the effects of the variation in rotor rpm, as indicated by the underlined terms in equations (35) and (36), are neglected, these equations reduce to those shown in reference 5.

We now turn to examine two special cases: (1) co-located hinges with another hinge sequence, F-L-P, and (2) elimination of the lead-lag degree of freedom.

When the flapping and lag hinges are co-located, the inertia dynamics for the coupled flap-lag equations can also be readily obtained by simply setting \( \Delta e = 0 \) in equations (31) and (32). It is important to note, however, that the resulting
expressions will be different from equations (33) and (34) for the L-F-P hinge sequence, because the sequence of rotation associated with flapping and lag angles is different, thereby resulting in a different definition associated with these two angles (similar to the situation when the sequence of rotation is changed, the definition of Euler angles must change accordingly). It is for this reason that equations (26) and (27) were used as the basis for equations (33) and (34).

Finally, in the absence of the lead-lag degree of freedom, it can be seen from equations (26) through (32) that the inertia dynamics for all three hinge sequences collapse to the same identical flapping dynamics as shown in equation (37).
where

\[
\delta x = \frac{3x}{\partial \beta} \delta \beta + \frac{3x}{\partial \zeta} \delta \zeta \\
\delta y = \frac{3y}{\partial \beta} \delta \beta + \frac{3y}{\partial \zeta} \delta \zeta \\
\delta z = \frac{3z}{\partial \beta} \delta \beta + \frac{3z}{\partial \zeta} \delta \zeta 
\]

and \(x, y, z\) are the coordinates of the blade element as given by equations (2), (14), and (19) for the three hinge sequences being considered. Now, summing up the elemental virtual work over the appropriate blade span results in the total virtual work \(\delta W_t\):

\[
\delta W_t = \int \left( X_i \frac{3x}{\partial \beta} + Y_i \frac{3y}{\partial \beta} + Z_i \frac{3z}{\partial \beta} \right) \delta \beta + \int \left( X_i \frac{3x}{\partial \zeta} + Y_i \frac{3y}{\partial \zeta} + Z_i \frac{3z}{\partial \zeta} \right) \delta \zeta 
\]

By equating the total virtual work \(\delta W_t\) to the virtual work of the generalized forces along the virtual displacement in the generalized coordinates, i.e., \(\delta W_t = Q_\beta \delta \beta + Q_\zeta \delta \zeta\), the generalized forces associated with that external force \(F_i\) are determined:

\[
Q_{\beta, i} = \int \left( X_i \frac{3x}{\partial \beta} + Y_i \frac{3y}{\partial \beta} + Z_i \frac{3z}{\partial \beta} \right) \\
Q_{\zeta, i} = \int \left( X_i \frac{3x}{\partial \zeta} + Y_i \frac{3y}{\partial \zeta} + Z_i \frac{3z}{\partial \zeta} \right) 
\]

As an example, the generalized forces \(Q_{\zeta}^3\) and \(Q_{\beta}^3\) in equations (31) and (32) for the F-L-P hinge sequence will be derived in detail below to illustrate the procedure. Let

\[
Q_{\zeta}^3 = Q_{\zeta}, G + Q_{\zeta}, A + Q_{\zeta}, D + Q_{\zeta}, S \\
Q_{\beta}^3 = Q_{\beta}, G + Q_{\beta}, A + Q_{\beta}, D + Q_{\beta}, S 
\]

representing the contributions from the gravity force, aerodynamic forces, and the forces due to dampers and hinge springs. We will consider each of these forces separately.
Gravity Force Contribution, $Q_{G, C}$ and $Q_{G, B}$

The gravity force acting on a blade element with mass $dm$ can be expressed in the hub-body system of reference using a sequence of transformation, equations (4b) and (4a), from inertia to aircraft body to hub-body systems. The result is

\[
\begin{align*}
X_G &= gdm A_1 \\
Y_G &= gdm A_2 \\
Z_G &= gdm A_3 
\end{align*}
\]

where

\[
\begin{align*}
A_1 &= \sin i \cos \phi_a \cos \theta_a - \cos i \sin \theta_a \\
A_2 &= \sin \phi_a \cos \theta_a \\
A_3 &= \cos i \cos \phi_a \cos \theta_a + \sin i \sin \theta_a 
\end{align*}
\]

From equation (19), the virtual displacement, in the hub-body system, of the blade element outboard of the lag hinge is obtained.

\[
\begin{align*}
\delta x &= (\Delta e \sin \beta + r_\zeta \sin \beta \cos \zeta) \cos \psi \delta \zeta + r_\zeta (\cos \beta \sin \zeta \cos \psi - \cos \zeta \sin \psi) \delta \zeta \\
\delta y &= -(\Delta e \sin \beta + r_\zeta \sin \beta \cos \zeta) \sin \psi \delta \zeta - r_\zeta (\cos \beta \sin \zeta \sin \psi + \cos \zeta \cos \psi) \delta \zeta \\
\delta z &= -(\Delta e + r_\zeta \cos \zeta) \cos \beta \delta \beta + r_\zeta \sin \zeta \sin \beta \delta \beta
\end{align*}
\]

The coordinates for a blade element between the two hinges, measured $r_\beta$ from the flapping hinge, are

\[
\begin{align*}
x &= -(e_\beta + r_\beta \cos \beta) \cos \psi \\
y &= (e_\beta + r_\beta \cos \beta) \sin \psi \\
z &= -r_\beta \sin \beta 
\end{align*}
\]
and therefore,

\[ \delta x = r_\beta \sin \beta \cos \psi \delta \psi \]
\[ \delta y = -r_\beta \sin \beta \sin \psi \delta \psi \]
\[ \delta z = -r_\beta \cos \beta \delta \psi \]

which are independent of the virtual displacement in the lead-lag motion.

Substituting equations (41)-(43) and (45) into equation (39), the desired generalized forces due to gravity are obtained.

\[ Q_{\zeta,G} = -gM_\zeta[(A_1 \sin \psi + A_2 \cos \psi) \cos \zeta + (A_2 \sin \psi - A_1 \cos \psi) \cos \beta \sin \zeta - A_3 \sin \beta \sin \zeta] \]

\[ Q_{\beta,G} = g(\Delta e_m + M_\zeta \cos \zeta + M_{\Delta e})[(A_1 \cos \psi - A_2 \sin \psi) \sin \beta - A_3 \cos \beta] \]

Equations (46) and (47) represent a generalization of the results given previously in references 5 and 10 by including in \( Q_{\beta,G} \) both the effects of shaft tilt angle and the weight moment inboard of the lag hinge. Note that equations (46) and (47) can alternatively be obtained using appropriate coordinate transformations listed in appendix B, and by considering the blade weight moment about the lag and flapping hinges as were done in references 5 and 10.

Aerodynamic Force Contribution, \( Q_{\beta,A} \) and \( Q_{\zeta,A} \)

The elementary aerodynamic forces acting on the blade element, \( dL \) and \( dD \), are resolved first in the plane perpendicular to the blade span in a manner as illustrated in figures 7(a) and 7(b).

\[ dD_1 = dD \cos \phi_r - dL \sin \phi_r \]  
\[ dL_1 = dL \cos \phi_r + dD \sin \phi_r \]

where

\[ dD = 1/2 \rho U^2 c_\zeta c \, dr_\zeta \]
\[ dL = 1/2 \rho U^2 c_\zeta c \, dr_\zeta \]
\[ U^2 = u_T^2 + u_p^2 \]
\[ \phi_r = \tan^{-1}(u_p/u_T) \]
Figure 7.- Elemental aerodynamic forces. (a) Force diagram in \( x_1-y_1 \) plane; (b) resolution of elementary lift and drag forces.

Note that the section lift and drag coefficients \( c_L \) and \( c_D \) in equations (49a) and (49b) are functions of the local angle of attack \( \alpha_r \) and Mach number \( M_r \) (ref. 24).¹ The calculation of \( \alpha_r \) and the airspeed components \( u_p \) and \( u_T \) will be discussed later.

When expressed in the \( x_1,y_1,z_1 \) frame of reference, the components of the aerodynamic force are

\[
\begin{align*}
X_1 &= -dD_1 \cos \zeta \\
Y_1 &= -dD_1 \sin \zeta \\
Z_1 &= -dL_1
\end{align*}
\]  

(50)

From equations (B7) and (B8), these components can be transformed into those in the hub-body system

\[
\begin{align*}
X_A &= -dD_1(\cos \zeta \sin \psi - \sin \zeta \cos \beta \cos \psi) + dL_1 \sin \beta \cos \psi \\
Y_A &= -dD_1(\cos \zeta \cos \psi + \sin \zeta \cos \beta \sin \psi) - dL_1 \sin \beta \sin \psi \\
Z_A &= dD_1 \sin \zeta \sin \beta - dL_1 \cos \beta
\end{align*}
\]  

(51)

Using equations (51), (43), (39b), and (39c), the aerodynamic force contributions to the generalized forces in equations (40a) and (40b) are obtained.

¹Extensions of the two-dimensional airfoil data may be made to include the spanwise flow effect (refs. 25 and 26), unsteady effects (refs. 26-29), and dynamic inflow (ref. 30).
\[
Q_{B,A} = \int_{r_c}^{R} \frac{1}{2} \rho U^2 c_d c \sin \phi_r (\Delta e + r \cos \zeta) \, d\zeta
+ \int_{r_c}^{BR} \frac{1}{2} \rho U^2 c_d c \cos \phi_r (\Delta e + r \cos \zeta) \, d\zeta \\
Q_{C_A} = \int_{r_c}^{R} \frac{1}{2} \rho U^2 c_d c \cos \phi_r r \zeta \, d\zeta
- \int_{r_c}^{BR} \frac{1}{2} \rho U^2 c_d c \sin \phi_r r \zeta \, d\zeta
\]

(52) (53)

Note that in setting up the limits of integration in equations (52) and (53), the blade cutoff is assumed to extend beyond the blade segment outboard of the lag hinge. Note also that in calculating the total blade lift, a tip loss factor \( B \) is used, thereby effectively limiting the lift of the blade beyond \( BR \).

The calculation of the components of the velocity (with respect to the air mass), \( u_p \) and \( u_T \), and the local angle of attack, \( \alpha_r \), is now addressed. The velocity of the blade element due to blade and aircraft motions has been obtained previously as shown in equation (20). Additional contributions to the total local airspeed components in the hub-body system are due to rotor-induced velocity and wind and turbulence. The resultant airspeed components in the hub-body system are then transformed into \( x_1, y_1, z_1 \) frame of reference using equation (B9). Let the resultant local airspeed components be denoted by \( \dot{x}_1, \dot{y}_1, \dot{z}_1 \). Then, \( u_p, u_T, \) and \( u_S \) (the spanwise component) are given by

\[
\begin{align*}
\dot{u}_p &= \dot{z}_1 \\
\dot{u}_T &= \dot{x}_1 \cos \zeta + \dot{y}_1 \sin \zeta \\
\dot{u}_S &= -\dot{x}_1 \sin \zeta + \dot{y}_1 \cos \zeta
\end{align*}
\]

(54a) (54b) (54c)

The local angle of attack of the blade element consists of \( \phi_r \) and the blade pitch setting, which includes, for generality, collective and cyclic pitch, blade twist, and pitch-flap and pitch-lag couplings, \( K_1 \) and \( K_2 \), as shown in equation (55).

\[
\alpha_r = \phi_r + \theta_o - A_{1s} \cos \psi - B_{1s} \sin \psi + \theta_{t,r} - K_1 \beta - K_2 \zeta
\]

(55)

This concludes the formulation of quantities that are necessary to compute the aerodynamic contribution to the generalized forces.
Contributions from Spring Restraints and Dampers

The generalized forces corresponding to the spring restraints and dampers can be obtained directly (ref. 23) from the potential energy for the hub springs, 

\[(1/2)K_\theta \dot{\theta}^2 + (1/2)K_\zeta \dot{\zeta}^2,\]

and the dissipation functions for the dampers,

\[(1/2)C_\theta \dot{\theta}^2 + (1/2)C_\zeta \dot{\zeta}^2,\]

respectively. For generality, a provision is made, permitting either the representation of the actual springs/viscous dampers or the simulation of the structural stiffness/damping. These generalized forces are:

\[Q_{\zeta,S} = -K_\zeta \dot{\zeta} \]
\[Q_{\zeta,D} = -C_\zeta \dot{\zeta} \]
\[Q_{\theta,S} = -K_\theta \dot{\theta} \]
\[Q_{\theta,D} = -C_\theta \dot{\theta} \]

This concludes the development of all the factors contributing to the generalized forces in equations (40a) and (40b) for the F-L-P hinge sequence. The generalized forces for the other two hinge sequences considered can be developed in a similar fashion. Results are shown in appendix C.

CONCLUDING REMARKS

Flap-lag equations of motion for a rigid articulated rotor blade have been developed for three widely used flap, lag, and pitch hinge sequences. The effects of the complete six degrees-of-freedom of aircraft motions were included and all the inertia dynamic terms were retained. Comparisons of the results of this development, which uses the Lagrangian method, with those available in the literature were made to identify, with special emphasis on the inertia dynamics, the source of terms missing in previous analyses.

This effort represents the first step toward developing a generic blade-element rotor model suitable for full-flight envelope, real-time, flight dynamic simulation of various rotorcraft. Subsequent steps will involve the development of detailed equations for the calculation of the rotor forces and moments, and the development of appropriate approximate models for specific applications. To permit comparisons with flexible blade analysis planned for a later date, a provision is made in the present analysis to allow for representation of the actual hub springs and viscous dampers or simulation of the structural stiffness and damping in both the flapping and lead-lag degrees of freedom. In addition, kinematic feedback couplings in pitch-flap and pitch-lag have also been included.
APPENDIX A

INERTIA DYNAMICS OF THE BLADE SEGMENT BETWEEN THE FLAPPING AND LAG HINGES

In the development of the coupled flap-lag equations of motion, the inertia dynamics associated with the blade segment between the flapping and lag hinges were neglected. For completeness, additional terms due to this blade segment are developed here for the three hinge sequences considered.

L-F-P Hinge Sequence

For this hinge sequence, the portion of the rotor blade inboard of the flapping hinge involves only the lead-lag motion. As a result, the inertia dynamics associated with this segment contribute only to the lead-lag equation of motion (26); however, they have no effects on the flapping equation of motion (27).

The total velocity of a blade element between the flapping and lag hinges, a distance \( r_\zeta \) from the lag hinge, can readily be obtained from equations (6) and (7) by setting \( \beta = \dot{\xi} = 0, r_\beta = 0 \), and by replacing \( \Delta e \) with \( r_\zeta \). The results are:

\[
V_r = \begin{bmatrix}
\dot{x} + \Delta \dot{x} \\
\dot{y} + \Delta \dot{y} \\
\dot{z} + \Delta \dot{z}
\end{bmatrix}
\]  \hspace{1cm} (A1a)

where

\[
\begin{align*}
\dot{x} &= e_\zeta \Omega \sin \psi + r_\zeta (\Omega - \dot{\zeta}) \sin (\psi - \tau) \\
\dot{y} &= e_\zeta \Omega \cos \psi + r_\zeta (\Omega - \dot{\zeta}) \cos (\psi - \tau) \\
\dot{z} &= 0
\end{align*}
\]  \hspace{1cm} (A1b)

and

\[
\begin{align*}
\Delta \dot{x} &= \dot{x}_o + q \dot{z}_x - r[(\dot{y}_x + e_\zeta \sin \psi) + r_\zeta \sin (\psi - \tau)] \\
\Delta \dot{y} &= \dot{y}_o - p \dot{z}_x + r[(\dot{z}_y + e_\zeta \cos \psi) - r_\zeta \cos (\psi - \tau)] \\
\Delta \dot{z} &= \dot{z}_o + p[(\dot{z}_y + e_\zeta \sin \psi) + r_\zeta \sin (\psi - \tau)] - q[(\dot{z}_y + e_\zeta \cos \psi) - r_\zeta \cos (\psi - \tau)]
\end{align*}
\]  \hspace{1cm} (A1c)

37
Using equations (21) through (25a), the inertia dynamics associated with the blade segment can be obtained as shown in equation (A2). These additional terms are to be added to the right-hand side of equation (26) to provide the complete set of inertia dynamics for the single rotor blade. Note that equation (A2) can also be directly obtained from equation (33) by setting $\beta = 0 = \zeta$ and by replacing $M_\beta$ and $I_\beta$ with $M_{\Delta e}$ and $I_{\Delta e}$, respectively.

$$
-I_{\Delta e} \ddot{\zeta} + I_{\Delta e} \left[ (\dot{\alpha} - \dot{r}) - \frac{1}{2} (p^2 - q^2) \sin 2(\psi - \zeta) - pq \cos 2(\psi - \zeta) \right] \\
+ M_{\Delta e} \left[ a_x \sin(\psi - \zeta) + a_y \cos(\psi - \zeta) + e_\zeta [(\dot{\alpha} - \dot{r}) \cos \zeta - (\alpha - r)^2 \sin \zeta] \\
- pq \cos(2\psi - \zeta) - p^2 \sin \psi \cos(\psi - \zeta) + q^2 \cos \psi \sin(\psi - \zeta) \right] \\
+ I_{\zeta} [(\dot{r} + pq) \cos(\psi - \zeta) - (q^2 + r^2) \sin(\psi - \zeta)] \\
+ I_{\zeta} [(pq - r) \sin(\psi - \zeta) - (p^2 + r^2) \cos(\psi - \zeta)] \\
- I_{\zeta} [(\dot{p} - qr) \cos(\psi - \zeta) - (\dot{q} + pr) \sin(\psi - \zeta)] \tag{A2}
$$

where

$$M_{\Delta e} = \int_{0}^{\Delta e} r_\zeta \, dm$$

$$I_{\Delta e} = \int_{0}^{\Delta e} r_\zeta^2 \, dm$$

F-P-L and F-L-P Hinge Sequences

The effect of the inertia dynamics of the blade segment inboard of the lag hinge on the flapping equation of motion is identical for the F-P-L and the F-L-P hinge sequences. This blade segment involves only flapping motion and therefore its inertia dynamics have no effects on the lead-lag equation of motion, equation (29) or (31).

The total velocity of a blade element between the flapping and lag hinges, measured $\dot{r}_\beta$ from the flapping hinge, can be obtained from equations (20a) and (20b) by setting $\zeta = \zeta = 0$ and by replacing $\Delta e$ with $\beta$ to yield equations (A1a), (A3a), and (A3b).

$$\dot{x} = (e_\beta + r_\beta \cos \beta) \Omega \sin \psi + r_\beta \dot{\beta} \cos \psi \sin \beta$$

$$\dot{y} = (e_\beta + r_\beta \cos \beta) \Omega \cos \psi - r_\beta \dot{\beta} \sin \psi \sin \beta \tag{A3a}$$

$$\dot{z} = -r_\beta \dot{\beta} \cos \beta$$
\[
\Delta x = \dot{x}_0 + q(l_z - r_\beta \sin \beta) - r[l_y + (e_\beta + r_\beta \cos \beta) \sin \psi]
\]
\[
\Delta y = \dot{y}_0 + r[l_x - (e_\beta + r_\beta \cos \beta) \cos \psi] - p[l_z - r_\beta \sin \beta]
\]
\[
\Delta z = \dot{z}_0 - q[l_x - (e_\beta + r_\beta \cos \beta) \cos \psi] + p[l_y + (e_\beta + r_\beta \cos \beta) \sin \psi]
\]

Using equations (21) through (24) and (25b), the inertia dynamics associated with the blade segment are determined as shown in equation (A4). The same expression can also be obtained from equation (37) by simply replacing \( M_\beta \) with \( M_{\Delta \psi} \), and \( I_\beta \) with \( I_{\Delta \psi} \). Adding these additional terms to the right-hand side of equations (30) and (32) provides the complete set of inertia dynamic terms for these two hinge sequences.

\[
-\frac{1}{2} I_{\Delta \psi} = -\frac{1}{2} \left( \frac{1}{2} I_{\Delta \psi} \sin \beta + \frac{1}{2} I_{\Delta \psi} \sin \beta \right)
\]

\[
\frac{1}{2} \left( \frac{1}{2} I_{\Delta \psi} \sin \beta + \frac{1}{2} I_{\Delta \psi} \sin \beta \right)
\]

Using equations (21) through (24) and (25b), the inertia dynamics associated with the blade segment are determined as shown in equation (A4). The same expression can also be obtained from equation (37) by simply replacing \( M_\beta \) with \( M_{\Delta \psi} \), and \( I_\beta \) with \( I_{\Delta \psi} \). Adding these additional terms to the right-hand side of equations (30) and (32) provides the complete set of inertia dynamic terms for these two hinge sequences.
APPENDIX B

USEFUL TRANSFORMATION MATRICES

A list of useful transformation matrices is given in this appendix to facilitate the determination of the generalized forces in the Lagrange equations of motion, (25a) and (25b). Specific transformations of interest vary with the hinge sequences considered.

L-F-P Hinge Sequence

The frames of reference of particular interest for this hinge sequence are: $x_1, y_1, z_1; x_3, y_3, z_3$; and $x, y, z$. The components of an arbitrary vector $a$ in these frames are related by

$$\begin{bmatrix} a_{x_3} \\ a_{y_3} \\ a_{z_3} \end{bmatrix} = \begin{bmatrix} \cos \zeta & -\sin \zeta & 0 \\ \sin \zeta & \cos \zeta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_{x_1} \\ a_{x_1} \\ a_{x_1} \end{bmatrix}$$ (B1)

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \sin \psi & -\cos \psi & 0 \\ \cos \psi & \sin \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_{x_3} \\ a_{y_3} \\ a_{z_3} \end{bmatrix}$$ (B2)

$$\begin{bmatrix} a_{x_1} \\ a_{y_1} \\ a_{z_1} \end{bmatrix} = \begin{bmatrix} \sin \psi \cos \zeta - \cos \psi \sin \zeta & \cos \psi \cos \zeta + \sin \psi \sin \zeta & 0 \\ \sin \psi \sin \zeta - \cos \psi \cos \zeta & -\cos \psi \sin \zeta + \sin \psi \cos \zeta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$ (B3)
Since these transformations are orthogonal, the inverse transformations are obtained by a simple transposition of the transformation matrices.

F-P-L Hinge Sequence

The frames of interest are: \( x_1, y_1, z_1; x_3, y_3, z_3 \); and \( x, y, z \). However, these are defined differently from the L-F-P hinge sequence (fig. 6). The components of a vector \( \mathbf{a} \) in these three frames are related by the following transformation.

\[
\begin{bmatrix}
\mathbf{a}_x \\
\mathbf{a}_y \\
\mathbf{a}_z
\end{bmatrix}
= \begin{bmatrix}
\cos \theta & 0 & \sin \theta \\
0 & 1 & 0 \\
-\sin \theta & 0 & \cos \theta
\end{bmatrix}
\begin{bmatrix}
\mathbf{a}_x' \\
\mathbf{a}_y' \\
\mathbf{a}_z'
\end{bmatrix}
\] (B4)

\[
\begin{bmatrix}
\mathbf{a}_x \\
\mathbf{a}_y \\
\mathbf{a}_z
\end{bmatrix}
= \begin{bmatrix}
\sin \psi & -\cos \psi \cos \beta & -\cos \psi \sin \beta \\
\cos \psi & \sin \psi \cos \beta & \sin \psi \sin \beta \\
0 & -\sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
\mathbf{a}_x' \\
\mathbf{a}_y' \\
\mathbf{a}_z'
\end{bmatrix}
\] (B5)

\[
\begin{bmatrix}
\mathbf{a}_x \\
\mathbf{a}_y \\
\mathbf{a}_z
\end{bmatrix}
= \begin{bmatrix}
\sin \psi \cos \theta & \cos \psi \cos \theta & -\cos \beta \sin \theta \\
+ \cos \psi \sin \beta \sin \theta & -\sin \psi \sin \beta \sin \theta \\
-\cos \psi \cos \beta & \sin \psi \cos \beta & -\sin \beta
\end{bmatrix}
\begin{bmatrix}
\mathbf{a}_x' \\
\mathbf{a}_y' \\
\mathbf{a}_z'
\end{bmatrix}
\] (B6)

F-L-P Hinge Sequence

The frames of interest are the same as those for F-P-L hinge sequence. However, with the pitch bearing now outboard of the lag hinge, the transformations reduce to:
\[
\begin{align*}
\begin{bmatrix}
a_{x_3} \\
a_{y_3} \\
a_{z_3}
\end{bmatrix}
&= \begin{bmatrix}
a_{x_1} \\
a_{y_1} \\
a_{z_1}
\end{bmatrix} \\
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
&= \begin{bmatrix}
sin \psi & -\cos \psi \cos \beta & -\cos \psi \sin \beta \\
\cos \psi & \sin \psi \cos \beta & \sin \psi \sin \beta \\
0 & -\sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
a_{x_3} \\
a_{y_3} \\
a_{z_3}
\end{bmatrix} \\
\begin{bmatrix}
a_{x_1} \\
a_{y_1} \\
a_{z_1}
\end{bmatrix}
&= \begin{bmatrix}
sin \psi & \cos \psi & 0 \\
-\cos \psi \cos \beta & \sin \psi \cos \beta & -\sin \beta \\
-\cos \psi \sin \beta & \sin \psi \sin \beta & \cos \beta
\end{bmatrix}
\begin{bmatrix}
a_x \\
a_y \\
a_z
\end{bmatrix}
\end{align*}
\]
APPENDIX C

GENERALIZED FORCES FOR L-F-P AND F-P-L HINGE SEQUENCES

A detailed derivation for the generalized forces in the coupled flap-lag equations of motion for the F-L-P hinge sequence has been given earlier in the report. This appendix provides a summary of the results for the other two hinge sequences, i.e., L-F-P and F-P-L, using the same procedure for the F-L-P case.

L-F-P Hinge Sequence

Similar to equations (40a) and (40b) for the case of F-L-P hinge sequence, the generalized forces $Q_1$ and $Q_6$ in equations (26) and (27) also consist of four contributing sources, i.e., gravity force, aerodynamic forces, and forces from lag dampers and hub springs. The last two sources are the same as equation (56) for the case of F-L-P. The first two sources differ markedly from equations (46), (47), (52), and (53) as shown below.

Gravity force contribution- The virtual displacement is developed from equation (2) to yield

$$\delta x = r_6 \sin \beta \cos(\psi - \zeta) \delta \beta - (\Delta e + r_6 \cos \beta) \sin(\psi - \zeta) \delta \zeta$$

$$\delta y = -r_6 \sin \beta \sin(\psi - \zeta) \delta \beta - (\Delta e + r_6 \cos \beta) \cos(\psi - \zeta) \delta \zeta$$

$$\delta z = -r_6 \cos \beta \delta \beta$$

for a blade element outboard of the flapping hinge, and

$$\delta x = -r_\zeta \sin(\psi - \zeta) \delta \zeta$$

$$\delta y = -r_\zeta \cos(\psi - \zeta) \delta \zeta$$

$$\delta z = 0$$

for inboard of the flapping hinge. Substituting equations (41), (42), (C1), and (C2) into (39), the gravity force contribution to the generalized forces $Q_6$ and $Q_\zeta$ is obtained.

$$Q_6, G = g M_6 [(A_1 \cos(\psi - \zeta) - A_2 \sin(\psi - \zeta)) \sin \beta - A_3 \cos \beta]$$

$$Q_\zeta, G = -g (\Delta e M_6 + M_6 \cos \beta + M_\Delta e) [A_1 \sin(\psi - \zeta) + A_2 \cos (\psi - \zeta)]$$
Contribution of the aerodynamic forces—With reference to figure C1, the elementary lift and drag, dL and dD, as given by equation (C5),

\[ dD = (1/2)\rho U^2 c_y \, d\gamma \]
\[ dL = (1/2)\rho U^2 c_x \, d\gamma \]
\[ U^2 = u_T^2 + u_p^2 \]
\[ \phi_r = \tan^{-1}(u_p/u_T) \]

are first resolved in the plane perpendicular to the blade span,

\[ dD_1 = dD \cos \phi_r - dL \sin \phi_r \]
\[ dL_1 = dL \cos \phi_r + dD \sin \phi_r \]

and then in the \( x_1, y_1, z_1 \) frame of reference as shown in equation (C7)

\[
\begin{bmatrix}
X_1 \\
Y_1 \\
Z_1
\end{bmatrix}
= A
\begin{bmatrix}
dD_1 \\
dL_1 \sin\beta \\
dL_1 \cos\beta
\end{bmatrix}
\]

Figure C1.—Elemental lift and drag forces.

These aerodynamic force components are further resolved into the hub-body system to yield
\[
\begin{align*}
\{X_A\} &= \begin{cases}
-dD_1 \sin(\psi - \zeta) + dL_1 \cos(\psi - \zeta) \sin \beta \\
-dD_1 \cos(\psi - \zeta) - dL_1 \sin(\psi - \zeta) \sin \beta \\
-dL_1 \cos \beta
\end{cases} \\
\{Y_A\} &= \\
\{Z_A\} &= 
\end{align*}
\] (C8)

Using equations (C8), (C1), (39b), and (39c), the aerodynamic force contributions to the generalized forces \(Q_{\phi_1}\) and \(Q_{\zeta_1}\) are obtained.

\[
Q_{\phi_1} = \int_{r_c}^{R} \frac{1}{2} \rho U^2 c_d c \sin \phi_r r_\phi \, dr_\beta \\
+ \int_{r_c}^{BR} \frac{1}{2} \rho U^2 c_k c \cos \phi_r r_\beta \, dr_\beta 
\] (C9)

\[
Q_{\zeta_1} = \int_{r_c}^{R} \frac{1}{2} \rho U^2 c_d c \cos \phi_r (\Delta e + r_\beta \cos \beta) \, dr_\beta \\
- \int_{r_c}^{BR} \frac{1}{2} \rho U^2 c_k c \sin \phi_r (\Delta e + r_\beta \cos \beta) \, dr_\beta 
\] (C10)

We note in passing that the transformation of the local airspeed at the blade element to \(u_T\), \(u_S\), and \(u_P\), shown previously in equation (54) for the F-L-P case is now replaced by

\[
\begin{align*}
\{u_T\} &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{bmatrix} \\
\{u_S\} &= \begin{bmatrix} 0 & \cos \beta & -\sin \beta \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{bmatrix} \\
\{u_P\} &= \begin{bmatrix} 0 & \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} \dot{x}_1 \\ \dot{y}_1 \\ \dot{z}_1 \end{bmatrix}
\end{align*}
\] (C11)

The computation for the local angle of attack remains the same as that for the F-L-P hinge sequence using equations (55) and (49d).

**F-P-L Hinge Sequence**

The contributions due to the lag dampers and the hub springs are the same as equation (56), but the other two factors become somewhat more complicated than equations (46), (47), (52), and (53) as shown below.
Gravity force contribution- The virtual displacement is obtained from equation (14) for both outboard and inboard segments of the lag hinge. Proceeding in the same manner as before for the F-L-P hinge sequence results in equations (C12) and (C13).

\[ Q_{B,G} = g[(\Delta e + M_c \cos \zeta + M_{\Delta e}) \sin \beta - M_c \sin \zeta \cos \beta \sin \theta] \]

\[ \times (A_1 \cos \psi - A_2 \sin \psi) \]

\[-g[(\Delta e + M_c \cos \zeta + M_{\Delta e}) \cos \beta + M_c \sin \zeta \sin \beta \sin \theta] A_3 \]  

(C12)

\[ Q_{C,G} = gM_c \{(\cos \theta \sin \zeta - \sin \beta \cos \zeta \sin \theta)(A_1 \cos \psi - A_2 \sin \psi) \]

\[- \cos \theta \cos \zeta(A_1 \sin \psi + A_2 \cos \psi) + (\sin \beta \sin \zeta + \cos \beta \cos \zeta \sin \theta) A_3 \} \]

(C13)

Aerodynamic force contributions- Using the same procedure as before for the F-L-P case, the aerodynamic force contributions to \( Q_{B,2} \) and \( Q_{C,2} \) are found to be

\[ Q_{B,A} = \int_{r_c}^{BR} \frac{1}{2} \rho U_c^2 c [\cos \phi_r \cos \theta(\Delta e + r_c \cos \zeta)] dr \]

\[ + \sin \phi_r \sin \theta(r_c + \Delta e \cos \zeta)] dr \]

\[- \int_{r_c}^{R} \frac{1}{2} \rho U_c^2 c [\cos \phi_r \sin \theta(r_c + \Delta e \cos \zeta)] dr \]

\[- \sin \phi_r \cos \theta(\Delta e + r_c \cos \zeta)] dr \]  

(C14)

\[ Q_{C,A} = \int_{r_c}^{R} \frac{1}{2} \rho U_c^2 c \cos \phi_r r_c dr \]

\[- \int_{r_c}^{BR} \frac{1}{2} \rho U_c^2 c \sin \phi_r r_c dr \]  

(C15)

The transformation (54) remains valid for computing the \( u_p, u_T, \) and \( u_S \) from the local airspeed at the blade element in \( x_1, y_1, z_1 \) frame of reference. Equation (B6) in turn provides the necessary transformation of the local airspeed components from the hub-body system to \( x_1, y_1, z_1 \) system.

The computation of the local angle of attack requires a special treatment for the F-P-L hinge sequence, because in this case \( \phi_r \) specifically contains the blade pitch \( \theta \) and its time derivative \( \dot{\theta} \), as evident from equations (16) and (17). It should be noted also that the inertia dynamics for this hinge sequence require
values of $\theta$ and $\dot{\theta}$ as input quantities. Let $\theta_{\text{vpo}}$ be the root collective pitch when the lag hinge is parallel to the $z$ axis. Then $\theta$ is given by (ref. 10)

$$\theta = \theta_o - \theta_{\text{vpo}} - A_{1s} \cos \psi - B_{1s} \sin \psi - K_1 \beta - K_2 \zeta$$  \hspace{1cm} (C16)

Thus, in general,

$$\dot{\theta} = \dot{\theta}_o - (\dot{A}_{1s} + B_{1s} \Omega) \cos \psi - (\dot{B}_{1s} - A_{1s} \Omega) \sin \psi - K_1 \dot{\beta} - K_2 \dot{\zeta}$$  \hspace{1cm} (C17)

Finally, the local angle of attack is:

$$\alpha_r = \phi_r + \theta_{\text{vpo}} + \theta_{t,r}$$  \hspace{1cm} (C18)
REFERENCES


Flap-Lag Equations of Motion of Rigid, Articulated Rotor Blades with Three Hinge Sequences

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This report documents a derivation of coupled flap-lag equations of motion for a rigid articulated rotor with hinge springs and viscous dampers. Three different flapping-lag-pitch hinge sequences are considered and the Lagrange method is used in deriving the equations. The effects of the complete six degrees-of-freedom aircraft motions are included and all the inertia dynamic terms are retained; no small-angle assumptions are used in the development. Comparisons of the results of this work with those available in the literature are made. Sources of terms missing in previous analyses, especially those of the inertia dynamics, are identified.

Flapping, Lead-lag, Feathering, Equation of motion, Inertia dynamics Aerodynamic forces, Hinge sequences Lagrangian