RESEARCH MEMORANDUM

A THEORETICAL ANALYSIS OF THE EFFECT OF ENGINE ANGULAR MOMENTUM ON LONGITUDINAL AND DIRECTIONAL STABILITY IN STEADY ROLLING MANEUVERS

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SUMMARY

The effect of engine momentum on the longitudinal and directional stability of aircraft in steady rolling maneuvers has been investigated. The results presented indicate that the gyroscopic moments produced on the aircraft by rotating engine in rolling maneuvers can have an appreciable effect on the range of rolling velocities for which longitudinal or directional instability might occur.

INTRODUCTION

The analysis presented in reference 1 of the effect of steady rolling on the longitudinal and directional stability of aircraft was made for the assumption of zero engine momentum; hence, the results presented were independent of the direction of rolling. Some of the present-day aircraft have exhibited different characteristics in left and right rolls which can be attributed to the asymmetric moments produced on the aircraft by the rotating engine. The purpose of this report is to present the aircraft equations which include these asymmetric engine gyroscopic moments and to demonstrate the effects of these terms on the divergence boundaries presented in reference 1 for the steady rolling case. The divergence boundaries presented in this paper are for aircraft having static stability.

SYMBOLS

\[ W \quad \text{weight, lb} \]
\[ T \quad \text{total aerodynamic moment, lb-ft} \]
rolling moment, lb-ft
pitching moment, lb-ft
yawing moment, lb-ft
angular momentum, slug-ft²/sec
moment of inertia about body X-axis, slug-ft²
moment of inertia about body Y-axis, slug-ft²
moment of inertia about body Z-axis, slug-ft²
product of inertia in X-Z-plane (positive when principal X-axis is below body X-axis at nose), slug-ft²
moment of inertia of engine about body X-axis, slug-ft²
rotational velocity about body X-axis, radians/sec
rotational velocity about body Y-axis, radians/sec
rotational velocity about body Z-axis, radians/sec
engine rotational velocity, radians/sec
aircraft velocity, ft/sec
component of V along X-body axis, ft/sec
component of V along Y-body axis, ft/sec
component of V along Z-body axis, ft/sec
angle of attack of X-body axis, w/u, radians
angle of sideslip, v/u, radians
total aerodynamic force, lb
Components of the aerodynamic force along X-, Y-, and Z-axes, lb
Direction cosines relating aircraft body axes to earth Z-axis
The aircraft equations of motion written in vector form are:

\[
\begin{align*}
\frac{D}{Dt}(\vec{H}) &= \vec{T} \\
\frac{m}{Dt}(\vec{V}) &= \vec{F} + \vec{W}
\end{align*}
\]

(1)

damping ratios in pitch and yaw, respectively
coefficients of characteristic equation
total time derivative

A dot over a symbol indicates differentiation with respect to time.
where \( \frac{D}{Dt} \) refers to total differentiation with respect to time, \( \overline{H} \) is the angular momentum vector, \( \overline{T} \) represents the aerodynamically applied moments, \( \overline{V} \) is the aircraft velocity vector, \( \overline{F} \) represents the aerodynamically applied forces, and \( \overline{W} \) is the weight of the aircraft. A right-handed system of axes is chosen which originates at the center of gravity of the aircraft and which is fixed in the aircraft. The X-axis is assumed to be coincident with the X-axis of the engine and the X,Z-plane is considered to be the plane of symmetry of the aircraft. Also, the mass distribution of the engine is assumed to be symmetrical about the X-axis, and the engine is assumed to be rotating with constant speed. The rotational velocities about the X-, Y-, and Z-axes are \( p \), \( q \), and \( r \), respectively, and the components of \( \overline{V} \) in this system of axes are \( u \), \( v \), and \( w \).

For the previous conditions, the vector momentum is given by

\[
\overline{H} = \overline{I} \left( I_X p - I_{XZ} r + I_{Xe} \omega_e \right) + \overline{J} q + \overline{K} \left( I_Z r - I_{XZ} p \right)
\]

where \( \overline{I} \), \( \overline{J} \), and \( \overline{K} \) are unit vectors in X-, Y-, and Z-directions; \( I_X \), \( I_Y \), and \( I_Z \) are the moments of inertia; \( I_{XZ} \) is the product of inertia in the XZ-plane; \( I_{Xe} \) is the moment of inertia of the engine about the X-axis; and \( \omega_e \) is the rotational velocity of the engine about this axis, taken positive in the same sense as the rolling velocity \( p \).

Equations (1) become, after differentiation and resolution into X-, Y-, and Z-components:

Rolling:

\[
I_X \dot{p} - I_{XZ} \dot{r} - (I_Y - I_Z) q r - I_{XZ} p q = \sum L
\]  

(2a)

Pitching:

\[
I_Y \dot{q} - (I_Z - I_X) p r + I_{XZ} (p^2 - r^2) + I_{Xe} \omega_e r = \sum M
\]  

(2b)
Yawing:

\[ I_Z \dot{r} - (I_X - I_Y)pq - I_{XZ} \dot{p} + I_{XZ}qr - I_X \omega_e q = \sum N \] (2c)

X-force:

\[ m(\dot{u} + qw - vr) = \sum F_X + Wl_3 \] (2d)

Y-force:

\[ m(\dot{v} - pw + ur) = \sum F_Y + Wm_3 \] (2e)

Z-force:

\[ m(\dot{w} + pv - uq) = \sum F_Z + Wn_3 \] (2f)

The terms \( l_3, m_3, \) and \( n_3 \) are the direction cosines between the earth Z-axis and the axes being used, which are fixed in the body. The equations which relate \( l_3, m_3, \) and \( n_3 \) to the airplane rotational velocities \( p, q, \) and \( r \) are

\[ \dot{l}_3 = m_3r - n_3q \]

\[ \dot{m}_3 = n_3p - l_3r \]

\[ \dot{n}_3 = l_3q - m_3p \]

Certain assumptions beyond that of a constant rolling velocity are necessary in order to linearize these equations. The term \( p^2 - r^2 \) in the pitching equation is taken as approximately equal to \( p^2 \), the term \( I_{XZ}qr \) in the yawing equation is considered negligible, and it is
assumed that no change occurs in the X-component of the forward velocity. Further, it is assumed that

\[
\frac{\dot{y}}{u} \approx \beta \quad \frac{\dot{w}}{u} \approx \alpha
\]

and, for the assumption of small out-of-trim aerodynamic forces, the Y-force and Z-force equations are approximately

\[
\dot{\beta} = p\alpha - r
\]

\[
\dot{\alpha} = q - p\beta
\]

Also, the aerodynamic moments are taken as

\[
M = \frac{\partial M}{\partial q} + \frac{\partial M}{\partial \alpha} \Delta \alpha = M_q q + M_\alpha \Delta \alpha
\]

\[
N = \frac{\partial N}{\partial r} + \frac{\partial N}{\partial \beta} = N_r r + N_\beta \beta
\]

Equations (2), for these assumptions and substitutions, become in determinant form

\[
\begin{vmatrix}
q & \Delta \alpha & \beta & r \\
D - \frac{M_q}{I_Y} & -\frac{M_\alpha}{I_Y} & 0 & \frac{(I_X - I_Z)p_o}{I_Y} + \frac{I_X \omega_e}{I_Y} \\
-\frac{(I_X - I_Y)p_o - I_X \omega_e}{I_Z} & 0 & -\frac{N_\beta}{I_Z} & D - \frac{N_r}{I_Z} \\
0 & -p_o & D & 1 \\
-1 & D & p_o & 0
\end{vmatrix} = 0
\]

where \( p_o \) refers to a constant value of the rolling velocity \( p \) and \( \alpha_0 \), to the initial value of the angle of attack. Expansion of this determinant with the right-hand side set equal to zero yields a characteristic equation of the form
\[ a_4 D^4 + a_3 D^3 + a_2 D^2 + a_1 D + a_0 = 0 \]  

where

\[ a_4 = 1 \]

\[ a_3 = -\frac{N_r}{I_Z} - \frac{M_q}{I_Y} \]

\[ a_2 = p_o^2 + \frac{N_\beta}{I_Z} - \frac{M_\alpha}{I_Y} + \frac{M_q N_r}{I_Y I_Z} - \left[ \frac{(I_Z - I_X)p_o - I_X \omega_e}{I_Y} \right] \left[ \frac{(I_X - I_Y)p_o + I_X \omega_e}{I_Z} \right] \]

\[ a_1 = -\frac{N_r}{I_Z} \cdot p_o^2 - \frac{M_q}{I_Y} \cdot p_o^2 - \frac{M_q N_\beta}{I_Y I_Z} + \frac{M_q N_r}{I_Y I_Z} \]

\[ a_0 = \frac{M_\alpha N_\beta}{I_Y I_Z} \cdot p_o^2 - \frac{N_\beta}{I_Z} \left[ \frac{(I_Z - I_X)p_o - I_X \omega_e}{I_Y} \right] - \frac{M_\alpha N_\beta}{I_Y I_Z} \cdot p_o \frac{M_\alpha}{I_Y} \left[ \frac{(I_X - I_Y)p_o + I_X \omega_e}{I_Z} \right] - p_o^2 \left[ \frac{(I_Z - I_X)p_o - I_X \omega_e}{I_Y} \right] \left[ \frac{(I_X - I_Y)p_o + I_X \omega_e}{I_Z} \right] \]

For the substitutions

\[ \omega_y^2 = \frac{N_\beta}{I_Z p_o^2} \]

\[ \omega_\theta^2 = \frac{-M_\alpha}{I_Y p_o^2} \]

\[ 2s_\theta \omega_\theta = \frac{-M_q}{I_Y p_o} \]
These coefficients become

\[ a_4 = 1 \]

\[ a_3 = p_o \left( 2 \xi \psi \omega_\psi + 2 \xi \theta \omega_\theta \right) \]

\[ a_2 = p_o^2 \left[ 1 + \omega_\psi^2 + \omega_\theta^2 - \frac{(I_Z - I_X - I_{Xe}) \left( I_X - I_Y + I_{Xe} \tau \right)}{I_Y I_Z} + 4 \xi \phi \xi \psi \omega_\theta \omega_\psi \right] \]

\[ a_1 = p_o^3 \left( 2 \xi \psi \omega_\psi + 2 \xi \theta \omega_\theta + 2 \xi \phi \omega_\phi \omega_\psi + 2 \xi \psi \omega_\phi \omega_\psi^2 \right) \]

\[ a_0 = p_o^4 \left[ 4 \xi \phi \xi \psi \omega_\phi \omega_\psi - \omega_\psi^2 \frac{(I_Z - I_X - I_{Xe} \tau)}{I_Y} + \omega_\psi^2 \omega_\theta^2 + \right. \\

\left. \omega_\theta^2 \left( \frac{(I_Z - I_X - I_{Xe} \tau)}{I_Z} \right) - \left( \frac{(I_Z - I_X - I_{Xe} \tau)}{I_Y} \right) \left( \frac{(I_X - I_Y + I_{Xe} \tau)}{I_Z} \right) \right] \]

which are essentially equivalent to the coefficients presented on page 9 of reference 1, with the exception of the engine momentum terms. It will be noted that the \( p_o \) factors which multiply the coefficients shown here do not appear in reference 1. This is attributable to the fact that the differential operator used in this paper is a time operator, whereas in reference 1 the operator has been made a function of rolling velocity.
ANALYSIS AND DISCUSSION

The combinations of $\omega_\psi$ and $\omega_\theta$ which will result in the constant term of equation 3 $a_0$ being negative, for given values of $\xi_\theta$, $\xi_\psi$, and $\tau$, and hence give aperiodic instability are of primary interest. For an airplane with given values of pitch and yaw natural frequencies, these values of $\omega_\psi$ and $\omega_\theta$ define the rolling velocities for which this instability will exist.

A sample of these aperiodic divergence boundaries is shown in figure 1 for $\tau = 0(\omega_\psi = 0)$, for $\xi_\theta \xi_\psi = 0$ and $\xi_\theta \xi_\psi = 0.0031$. The mass and aerodynamic characteristics of the airplane for which these boundaries were constructed are presented in table I. It should be noted that boundaries constructed for a constant value of $\xi_\theta \xi_\psi$ do not correspond to a constant value of $\frac{M_y N_r}{I_y I_z}$, but, rather, every point on the curve represents, dimensionally, a different value of this parameter. In this plane, the pitch and yaw frequencies of a given airplane, for all values of $p_0$, lie along a straight line similar to the one shown in the figure. The point shown for $p_0 = 1$ radian/sec defines the frequencies of the airplane chosen for this illustration. The slope of this line is determined from the ratio of the square of the pitch and yaw natural frequencies. For the case shown, the frequency locus of this airplane passes through the divergence boundary constructed for $\xi_\theta \xi_\psi = 0.0031$ for $p_0 = \pm 1.8$ radians/sec and remains on the unstable side of the boundary up to $p_0 = \pm 2.3$ radians/sec. Generally, the characteristic roots of the system in the unstable region of this plane are a pair of stable complex roots, one stable real root, and one unstable real root.

It would be possible to take into account the engine momentum by plotting boundaries for various values of $I_X \tau$, but, as was mentioned for the $\xi_\psi \xi_\theta$ case, these boundaries would not correspond to a constant value of engine momentum. Also, both positive and negative values of $I_X \tau$ would have to be considered in order to cover both the left and right rolling conditions.
The former difficulty can be avoided for both these cases by plotting the boundaries as a function of the dimensional frequency parameters rather than in terms of $\omega_2$ and $\omega_3$. This necessitates the construction of a boundary for each rolling velocity, but this construction is relatively simple. A sample of these boundaries is shown in figure 2 for $\frac{M_ζ N_ζ}{I_Y I_Z} = 0.044$ and $I_x \omega_e = 0$. For this case the boundaries for left and right rolling are identical. The effect of the engine momentum on these boundaries can be seen in figure 3 for the case of $I_x \omega_e = 17,554$ slug-ft$^2$/sec. Boundaries are presented for both right and left rolls, and the critical roll velocities are shown on the figure for both rolling conditions. For positive (right) rolling the unstable range of $p$ is between $p_o = 2.1$ radians/sec and $p_o = 2.5$ radians/sec and for negative (left) rolling this range is between $p_o = -1.7$ radians/sec and $p_o = -2.2$ radians/sec. In order to specify the absolute range of the roll rate which might be critical for a given airplane, it is necessary to know the critical values of $p$ for both the left and right rolls. For the value of $I_x \omega_e$ considered here, this unstable range for the example airplane would be defined as being

$$1.7 < |p_o| < 2.5$$

Curves are plotted in figure 4 which show the effect of engine momentum on this absolute range of critical $p$ for the particular airplane being considered. For $I_x \omega_e = 0$, this band is between $|p|$ of 1.8 and 2.3 radians per second, as mentioned previously, and broadens as the engine momentum increases. Thus, the range of rolling velocities for which a given airplane might experience instability, based on this steady rolling assumption, can increase appreciably with the magnitude of the momentum of the rotating engine; hence, the effect of engine momentum should be considered in the analysis.

A point of interest with respect to the construction of the divergence boundaries in the dimensional frequency plane is that it is possible to obtain mathematically the envelope of these boundaries by plotting the locus of the points of maximum curvature of the respective curves. The mathematical expression for the curvature of a given function can be found in any calculus book (for example, ref. 2) and in order to obtain the desired envelope it is necessary only to maximize this expression in the proper manner. From this envelope and the zero and asymptotic values of $\frac{N_ζ}{I_Z}$ and $\frac{-M_ζ}{I_Y}$ which are rather easy to calculate, one can approximately
draw the divergence boundaries for any given value of roll rate for specified inertia characteristics. In any event, the envelopes of the branches of the curves will define, for the steady rolling case, the combinations of pitch and yaw frequency for which there will be no roll-induced instability. The equations from which the envelopes can be calculated, and expressions for the previously mentioned asymptotic values of \( \frac{N_\beta}{I_Z} \) and \( \frac{-M_\alpha}{I_Y} \) are:

(a) Equations for determination of zero and asymptotic values of \( \frac{N_\beta}{I_Z} \) and \( \frac{M_\alpha}{I_Y} \):

\[
\frac{M_\alpha}{I_Y} = \frac{M_\alpha}{I_Y} \frac{I_Z}{I_Y} = \frac{p_0 I_X e \omega_e - (I_Z - I_X) p_0}{I_Y} \]

\[
\frac{M_\alpha}{I_Y} \Bigg|_{N_\beta \to \infty} = \frac{M_\alpha}{I_Y} \frac{I_X - I_Y}{I_Y} p_0^2 + \frac{I_X e \omega_e p_0}{I_Y} + \frac{I_X e \omega_e p_0}{I_Y} - \frac{(I_Z - I_X) p_0^2}{I_Y} \]

\[
\frac{N_\beta}{I_Z} = -\frac{(I_X - I_Y) p_0^2 + I_X e \omega_e p_0}{I_Z} \]

\[
\frac{N_\beta}{I_Z} \Bigg|_{M_\alpha \to \infty} = \frac{-M_\alpha}{I_Y} \frac{I_Z}{I_Y} = \frac{M_\alpha}{I_Y} \frac{I_Z}{I_Y} = \frac{M_\alpha}{I_Y} \frac{I_X - I_Y}{I_Y} p_0^2 - \frac{(I_Z - I_X) p_0^2}{I_Z} - \frac{I_X e \omega_e p_0}{I_Z} \]
(b) Equations for determination of envelope of divergence boundaries:

\[
\frac{N_B}{I_Z} = - \left[ \frac{(I_X - I_Y)p_0^2 + I_X \omega e p_0}{I_Z} \right] \pm \frac{M q N_r}{I_Y I_Z} p_0^2 = a \pm b
\]

\[
-\frac{M_{\alpha}}{I_Y} = - \left[ \frac{I_X \omega e p_0 - (I_Z - I_X)p_0^2}{I_Y} \right] \pm \frac{M q N_r}{I_Y I_Z} p_0^2 = c \pm b
\]

The equations presented for determination of the envelopes of the divergence boundaries require some further explanation. The combinations of \( \frac{N_B}{I_Z} \) and \( -\frac{M_{\alpha}}{I_Y} \) which define the envelopes are

\[
\frac{N_B}{I_Z} = a + b
\]

\[
-\frac{M_{\alpha}}{I_Y} = c - b
\]

and

\[
\frac{N_B}{I_Z} = a - b
\]

\[
-\frac{M_{\alpha}}{I_Y} = c + b
\]

The branch of the family of divergence boundaries to which each combination applies depends on the sign of the rolling velocity. A sample of the envelopes calculated for the boundaries of figures 2 and 3 is shown in figure 5.
CONCLUDING REMARKS

From the analysis presented in this paper it appears that the momentum of the rotating engine of an aircraft can increase appreciably the ranges of rolling velocity for which the aircraft might experience a roll-induced aperiodic divergence in steady rolling maneuvers. For the aircraft discussed herein, the range of critical rolling velocities $p$ was calculated to be

$$1.8 < |p| < 2.3$$

when engine momentum was assumed zero, and

$$1.7 < |p| < 2.5$$

when engine momentum was considered. For higher values of engine momentum than that assumed for this illustrative example, this band would, of course, be further expanded.

It was also shown how the construction of the divergence boundaries was affected by inclusion of engine momentum, and an alternate method of construction to that presented in NACA TN 1627 was discussed.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,

REFERENCES


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<th>Characteristic</th>
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<td>$I_X$, slug-ft$^2$</td>
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Figure 1.- Boundaries in the $\omega_\psi^2$, $\omega_\theta^2$ plane which define regions of aperiodic divergence for example aircraft. $I_x \omega_e = 0$. 

$p_0 = 1$ radian/sec

$\zeta_\theta \zeta_\psi = 0$

$\zeta_\theta \zeta_\psi = 0.0031$
Figure 2.- Boundaries in the $N_{\beta}/I_Z$, $M_{\alpha}/I_Y$ plane for example aircraft which define regions of aperiodic divergence as a function of rolling velocity. $I_{Xe}e_{ae} = 0.$
Figure 3. - Boundaries in the $\frac{N_\beta}{I_Z}$, $\frac{M_a}{I_Y}$ plane for example aircraft which define regions of aperiodic divergence as a function of rolling velocity. $I_x \omega_e = 17,554$ slug-ft²/sec.
(b) Left rolls.

Figure 3. - Concluded.
Figure 4.- Effect of engine momentum $I_{Xe} \omega_e$ on rolling-velocity range for which example aircraft is unstable.
Figure 5.- Envelopes of divergence boundaries presented in figures 2 and 3.
Let (x = W = e):

\[ 0.6732 \rho_i^4 - 5.9688 \rho_i^3 + 12.614 \rho_i^2 - 9.8911 \rho_i + 18.790 = 0 \]
\[ \rho_i^4 = 4.44555 \pm 98636 \]
\[ \rho_i = 3.4592 \quad \text{or} \quad 5.4314 \]
\[ \rho_i = \pm 1.85989 \quad \text{or} \quad 2.33054 \]

Let (x = W = e):

\[ 0.6732 \rho_i^4 - 26.977 \rho_i^3 - 5.9419 \rho_i^2 + 12.325 \rho_i + 12.614 = 0 \]
\[ \rho_i^4 = 4.0222 \rho_i^3 - 8.8511 \rho_i^2 + 15359 \rho_i + 18.790 \]
\[ \text{Roots:} \quad 1.7506, 1.9763, 2.4203, -2.1440 \]

Let (x = W = e):

\[ 0.6732 \rho_i^4 - 5.3974 \rho_i^3 - 5.7610 \rho_i^2 + 12.614 \rho_i = 0 \]
\[ \rho_i^4 - 24.040 \rho_i^3 - 8.7306 \rho_i^2 + 3.6719 \rho_i + 18.790 \]
\[ \text{Roots:} \quad -1.6483, 2.10, 2.5127, -2.1604 \]

Let (x = W = e):

\[ 0.6732 \rho_i^4 - 8.0961 \rho_i^3 - 5.7262 \rho_i^2 + 3.6975 \rho_i + 12.614 = 0 \]
\[ \rho_i^4 - 20.60 \rho_i^3 - 8.5298 \rho_i^2 + 5.5078 \rho_i + 18.790 \]
\[ \text{Roots:} \quad 1.8529, 2.2321, +2.5867, -2.0999 \]

Let (x = W = e):

\[ 0.6732 \rho_i^4 - 1.6795 \rho_i^3 - 5.5375 \rho_i^2 + 4.9300 \rho_i + 12.614 \]
\[ \rho_i^4 - 1.680 \rho_i^3 - 5.1437 \rho_i^2 + 7.3437 \rho_i + 18.790 \]
\[ \text{Roots:} \quad -1.4639, 2.3711, 2.7033, -2.0625 \]
Let \((I x \omega W e) = 17554\)

\[
0.67132 \rho_0^4 - 47873 \rho_0^3 - 58337 \rho_0^2 + 21635 \rho_0 - 12614 \\
0.70567 \rho_0^3 - 57674 \rho_0^2 + 32228 \rho_0 + 19790
\]

\(\text{Roots:} \quad -0.673, \quad 2.07, \quad 2.4890, \quad -2.1866\)