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Engineering Notes

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Improved Harmonic Large-Angle Fuselage Aerodynamics Model

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Introduction

FLIGHT vehicle simulation, guidance and control law design, and flight performance analysis methods commonly use aerodynamic models based on tabulated force and moment coefficients. Inputs for these models are generally derived from wind-tunnel test data and/or computational fluid dynamics (CFD) results. However, wind-tunnel data are often only available for a limited range of pitch and yaw angles, and CFD computations for a large number of arbitrary attitudes can be expensive. Rotorcraft simulation models require aerodynamic inputs at extreme attitudes and commonly use trigonometric high-angle models to provide smoothly varying data in these regimes.[1,2] Other applications for extreme high-angle aerodynamic models are ground-handling simulations, where the wind may come from any azimuth, flight performance analysis at high angles,[2] and trajectory analysis of tumbling bodies.

This Engineering Note presents a trigonometric, quasi-steady, fuselage aerodynamics model that is valid at all aerodynamic angles with a range of ±180 deg yaw and ±90 deg pitch. This model is based on the C81 high-angle equation (HAE) model found in some rotorcraft simulations[1] but with improvements to the usability of the original model. The HAE model uses aerodynamic coefficient inputs at key values of pitch and yaw angles that may come from wind-tunnel tests, CFD analysis, or other sources. A set of sinusoidal functions is used to estimate the values for all six wind-reference fuselage aerodynamic forces and moments at any combination of pitch angle and yaw angle.

The HAE model is desirable in that the equations are continuous and easily computed, give the proper trends at all attitudes, include some cross-coupling effects, and require relatively few inputs. The quasi-steady nature of the HAE model makes it unsuitable for situations where time-dependent flow characteristics are significant. This model is not suitable where high accuracy is required and is not expected to capture sudden changes in flow characteristics at critical angles such as the onset of stall or slender forebody vortex shedding. To address this issue, a blending scheme is often used to transition between wind tunnel data (or other high-quality data) at low angles and the HAE model at high angles.[1]

This Note addresses three limitations with the Ref. 1 model. First, the original model assumes lateral–directional coefficients are constant as a function of yaw angle for pitch angles of ±90 deg. This assumption causes a blending to occur that shows up as a nonzero lateral–directional coefficient slope with pitch attitude through zero pitch and yaw. For a symmetric fuselage, at angles of 0- and ±180-deg yaw, all lateral–directional forces and moments should be near zero for any pitch angle.

Second, the HAE model provides parameters for setting the angles where peak values occur, such as the pitch angle for maximum lift. However, the original formulation incorrectly adjusts only the peak magnitude, not the angle where the peak occurs.

Third, the original HAE model is symmetric with pitch, giving the same peak values at positive and negative pitch angles. Asymmetric peak values with pitch angle are desirable for modeling many configurations.[3]

Reference System

The HAE model uses a wind-axis reference system, with aerodynamic angles defined in accordance with wind-tunnel data. The orientation of the vehicle with respect to this system is defined by successive rotations of yaw and pitch, where yaw angle ψ_w is defined to be between ±180 deg and pitch angle θ_w to be between ±90 deg. These aerodynamic angles can be defined as functions of the flight-path velocity V and its body reference components (u, forward or X component; v, to the right or Y component; and w, down or Z component) as follows:

$$\psi_w = \sin^{-1}(-v/V) \tag{1}$$

$$\theta_w = \tan^{-1}(w/u) \tag{2}$$

These two variables are the independent variables for the HAE model. The outputs of the model can then be converted to any desired reference system.

Note that if $V = 0$ both ψ_w and θ_w are indeterminate. However, in this case they can both be safely set to 0 because aerodynamic forces and moments are zero at zero velocity. If $u = w = 0$, while $V \neq 0$, that is, $\psi_w = \pm 90$ deg, it may be physically possible to pitch a wind-tunnel model, but the angle cannot be defined by Eq. (2). In this case, care is taken to understand how the data are used in the resulting analysis. Often, the pitch angle is defined as zero when the yaw angle is ±90 deg. If wind-reference data are resolved to the body frame, then a single yaw rotation can be used independent of pitch angle.

Also, note that ψ_w is not the conventional sideslip angle β. Sideslip is defined as

$$\beta = \tan^{-1}(v/u) \tag{3}$$

It can be shown[1] that for small pitch angles

$$\beta \approx -\psi_w \tag{4}$$

but at large values of θ_w the magnitudes of β and ψ_w are not interchangeable.

Developing the Improved Model

The original HAE equation for side force Y is written as[1]

$$Y = Y_1 \cos^2\theta_w - L(90, 0)\sin^2\theta_w \tag{5}$$

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where Y_1 is a sinusoidal function of yaw angle. $L(90, 0)$ is the input lift at a yaw angle of 90 deg and a pitch angle of 0 deg. Equation (5) incorrectly results in constant side force at pitch angles of ± 90 deg. This is resolved by adding a $\sin^2\psi_w \operatorname{sign}(\theta_w) \operatorname{sign}(\psi_w)$ factor to the second term of Eq. (5). The modified side force equation then becomes

$$Y = Y_1 \cos^2\theta_w - L(90, 0)\sin^2\theta_w \sin^2\psi_w \operatorname{sign}\theta_w \operatorname{sign}\psi_w \tag{6}$$

This causes the side force to remain equal to $-L(90, 0)$ at $\theta_w = \psi_w = 90$ deg and causes it to fade to zero at zero and ±180 deg yaw for all pitch angles. Multiplying by the sign of ψ_w and the sign of θ_w are required due to the assumption that $L(90, 180) = -L(90, 0)$. This same modification is also made to the yawing moment equations. The rolling moment equation is very similar, but with only the sign ψ_w factor because $R(90, \text{any angle}) = R(90, 0)$.

The problems of setting the peak angle and the asymmetry with pitch are more difficult to solve. Consider the original HAE model formulation for the lift force[1]:

$$L = L_1\cos^2\psi_w + L_2\sin^2\psi_w \tag{7}$$

where

$$L_1 = \begin{cases} L(0,0) + L_3\sin^2\theta_w + L_4\sin(2\theta_w) & \text{if} \quad |\psi_w| \le 90 \\ L(180,0) - L_5\cos^2\theta_w - L_4\sin(2\theta_w) & \text{if} \quad |\psi_w| > 90 \end{cases} \tag{8}$$

$$L_2 = L(90, 0)\cos\theta_w + Y(90, 0)\sin\theta_w \tag{9}$$

$$L_3 = L(0, 90) - L(0, 0) \tag{10}$$

$$L_4 = \left[L(0, \theta_{wpL}) - L(0, 0) - L_3\sin^2\theta_{wpL}\right]\Big/\sin(2\theta_{wpL}) \tag{11}$$

$$L_5 = L(0, 90) - L(180, 0) \tag{12}$$

where

θ_{wpL} = pitch angle at which peak value of lift is achieved
$L(\psi, \theta)$ = input lift force or coefficient at corresponding yaw and pitch angles
$Y(\psi, \theta)$ = input side force or coefficient at corresponding yaw and pitch angles

Equation (8) uses a constant magnitude L_4 times a $\sin(2\theta_w)$ term plus other terms that can be considered zero for this discussion. The $\sin(2\theta_w)$ factor results in the peak value always occurring at ±45 deg no matter what peak angle θ_{wpL} is input. Also, if $L(0, 0)$ is zero, the peak value of lift will be symmetric with a value of $\pm L(0, \theta_{wpL})$.

The solution is to use multiple sine waves to model the data on either side of the peak values on both the positive and negative side of zero pitch. The first sine wave, on the positive side of zero pitch, has the frequency adjusted so that the peak of the wave occurs at the positive peak value θ_{wpL+}. The second sine wave has both frequency and phase adjusted so that the peak occurs at θ_{wpL+} and the wave passes through zero at 90 deg. The same procedure is repeated for the peak on the negative side of zero pitch angle using θ_{wpL-} as the peak angle. This is implemented using a phase angle ϕ and a frequency factor f. For the lift force, Eqs. (8) and (10–12) are modified as follows:

$$L_1 = \begin{cases} L(0,0) + L_3\sin^2\theta_w \\ \quad + L_4\sin[f_L(\theta_w + \phi_L)] & \text{if} \quad |\psi_w| \le 90 \\ L(180,0) + L_5\sin^2\theta_w \\ \quad + L_6\sin[f_L(\theta_w + \phi_L)] & \text{if} \quad |\psi_w| > 90 \end{cases} \tag{13}$$

$$L_3 = \begin{cases} L(0,90) - L(0,0) & \text{if} \quad \theta_w \ge 0 \\ L(0,-90) - L(0,0) & \text{if} \quad \theta_w < 0 \end{cases} \tag{14}$$

$$L_4 = \begin{cases} L(0,\theta_{wpL+}) - L(0,0) - L_3\sin^2\theta_{wpL+} & \text{if} \quad \theta_w \ge 0 \\ -L(0,\theta_{wpL-}) + L(0,0) + L_3\sin^2\theta_{wpL-} & \text{if} \quad \theta_w < 0 \end{cases} \tag{15}$$

$$L_5 = \begin{cases} L(0,90) - L(180,0) & \text{if} \quad \theta_w \ge 0 \\ L(0,-90) - L(180,0) & \text{if} \quad \theta_w < 0 \end{cases} \tag{16}$$

In addition, a new equation has been added, L_6, which is very similar to L_4 and accounts for the lift at $\psi = 180$ deg being different than at $\psi = 0$,

$$L_6 = \begin{cases} -L(0,\theta_{wpL+}) - L(180,0) - L_5\sin^2\theta_{wpL+} & \text{if} \quad \theta_w \ge 0 \\ L(0,\theta_{wpL-}) + L(180,0) + L_5\sin^2\theta_{wpL-} & \text{if} \quad \theta_w < 0 \end{cases} \tag{17}$$

The frequency factor f_L may be computed using

$$f_L = \begin{cases} 90/(90 - \theta_{wpL+}) & \text{if} \quad \theta_w \ge \theta_{wpL+} \\ 90/\theta_{wpL+} & \text{if} \quad 0 \le \theta_w < \theta_{wpL+} \\ -90/\theta_{wpL-} & \text{if} \quad \theta_{wpL-} < \theta_w < 0 \\ 90/(90 + \theta_{wpL-}) & \text{if} \quad \theta_w \le \theta_{wpL-} \end{cases} \tag{18}$$

and the phase shift (ϕ_L) is computed using

$$\phi_L = \begin{cases} 0 & \text{if} \quad \theta_{wpL-} < \theta_w < \theta_{wpL+} \\ (90 - 2\theta_{wpL+}) & \text{if} \quad \theta_w \ge \theta_{wpL+} \\ (90 + 2\theta_{wpL-}) & \text{if} \quad \theta_w \le \theta_{wpL-} \end{cases} \tag{19}$$

The complete set of the improved HAE model lift equations is as follows:

$$L = L_1\cos^2\psi_w + L_2\sin^2\psi_w \tag{20}$$

$$L_1 = \begin{cases} L(0,0) + L_3\sin^2\theta_w \\ \quad + L_4\sin[f_L(\theta_w + \phi_L)] & \text{if} \quad |\psi_w| \le 90 \\ L(180,0) + L_5\sin^2\theta_w \\ \quad + L_6\sin[f_L(\theta_w + \phi_L)] & \text{if} \quad |\psi_w| > 90 \end{cases} \tag{21}$$

$$L_2 = L(90, 0)\cos\theta_w + Y(90, 0)\sin\theta_w \tag{22}$$

$$L_3 = \begin{cases} L(0,90) - L(0,0) & \text{if} \quad \theta_w \ge 0 \\ L(0,-90) - L(0,0) & \text{if} \quad \theta_w < 0 \end{cases} \tag{23}$$

$$L_4 = \begin{cases} L(0,\theta_{wpL+}) - L(0,0) - L_3\sin^2\theta_{wpL+} & \text{if} \quad \theta_w \ge 0 \\ -L(0,\theta_{wpL-}) + L(0,0) + L_3\sin^2\theta_{wpL-} & \text{if} \quad \theta_w < 0 \end{cases} \tag{24}$$

$$L_5 = \begin{cases} L(0,90) - L(180,0) & \text{if} \quad \theta_w \ge 0 \\ L(0,-90) - L(180,0) & \text{if} \quad \theta_w < 0 \end{cases} \tag{25}$$

$$L_6 = \begin{cases} -L(0,\theta_{wpL+}) - L(180,0) - L_5\sin^2\theta_{wpL+} & \text{if} \quad \theta_w \ge 0 \\ L(0,\theta_{wpL-}) + L(180,0) + L_5\sin^2\theta_{wpL-} & \text{if} \quad \theta_w < 0 \end{cases} \tag{26}$$

$$f_L = \begin{cases} 90/(90 - \theta_{wpL+}) & \text{if} \quad \theta_w \ge \theta_{wpL+} \\ 90/\theta_{wpL+} & \text{if} \quad 0 \le \theta_w < \theta_{wpL+} \\ -90/\theta_{wpL-} & \text{if} \quad \theta_{wpL-} < \theta_w < 0 \\ 90/(90 + \theta_{wpL-}) & \text{if} \quad \theta_w \le \theta_{wpL-} \end{cases} \tag{27}$$

$$\phi_L = \begin{cases} 0 & \text{if} \quad \theta_{wpL-} < \theta_w < \theta_{wpL+} \\ (90 - 2\theta_{wpL+}) & \text{if} \quad \theta_w \ge \theta_{wpL+} \\ (90 + 2\theta_{wpL-}) & \text{if} \quad \theta_w \le \theta_{wpL-} \end{cases} \tag{28}$$

The pitching moment equations are identical to the lift equations but with M substituted for L and with $N(90, 0)$ (the yawing moment at $\psi_w = 90$ deg and $\theta_w = 0$) substituted for $Y(90, 0)$ in Eq. (9).

The improved HAE model drag equations are unchanged from the original HAE model:

$$D = D_1 \cos^2 \psi_w + D(90, 0) \sin^2 \psi_w \tag{29}$$

$$D_1 = D_2 \cos^2 \theta_w + D_v \sin^2 \theta_w \tag{30}$$

$$D_2 = \begin{cases} D(0, 0) & \text{if} \quad |\psi_w| \le 90 \\ D(180, 0) & \text{if} \quad |\psi_w| > 90 \end{cases} \tag{31}$$

$$D_v = \begin{cases} D(0, 90) & \text{if} \quad \theta_w \ge 0 \\ D(0, -90) & \text{if} \quad \theta_w < 0 \end{cases} \tag{32}$$

The lateral–directional equations are modified in a similar fashion to the longitudinal equations. The only significant differences are that asymmetric peaks are not required and care is taken to use the proper frequency and phase for the region on either side of ±180-deg yaw. Side force was already modified in Eq. (6) to give the right trends at high-pitch attitudes. The remaining original side force equations are

$$Y_1 = Y(90, 0) \sin \psi_w + Y_2 \sin(2\psi_w) \tag{33}$$

$$Y_2 = \lfloor Y(\psi_{wpY}, 0) - Y(90, 0) \sin \psi_{wpY} \rfloor / \sin(2\psi_{wpY}) \tag{34}$$

Equation (33) is modified by adding a frequency factor and phase shift to adjust the peak values and the yaw angles where those peaks occur,

$$Y_1 = Y(90, 0) \sin \psi_w + Y_2 \sin[f_Y(\psi_w + \phi_Y)] \tag{35}$$

where

$$f_Y = \begin{cases} 90/\psi_{wpY} & \text{if} \quad (|\psi_w| < \psi_{wpY}) \\ & \text{or} \quad (\psi_w < \psi_{wpY} - 180) \\ & \text{or} \quad (\psi_w > 180 - \psi_{wpY}) \\ 90/(90 - \psi_{wpY}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{36}$$

$$\phi_Y = \begin{cases} 0 & \text{if} \quad |\psi_w| < \psi_{wpY} \\ 90 & \text{if} \quad (\psi_w < \psi_{wpY} - 180) \\ -90 & \text{if} \quad (\psi_w > 180 - \psi_{wpY}) \\ (\text{sign of } \psi_w)(90 - 2\psi_{wpY}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{37}$$

Equation (34) is also modified in accordance with how Eq. (11) was modified for the lift force. The resulting equation is

$$Y_2 = Y(\psi_{wpY}, 0) - Y(90, 0) \sin \psi_{wpY} \tag{38}$$

The final set of the improved HAE model side force equations is

$$Y = Y_1 \cos^2 \theta_w - L(90, 0) \sin^2 \theta_w \sin^2 \psi_w \operatorname{sign} \theta_w \operatorname{sign} \psi_w \tag{39}$$

$$Y_1 = Y(90, 0) \sin \psi_w + Y_2 \sin[f_Y(\psi_w + \phi_Y)] \tag{40}$$

$$Y_2 = Y(\psi_{wpY}, 0) - Y(90, 0) \sin \psi_{wpY} \tag{41}$$

$$f_Y = \begin{cases} 90/\psi_{wpY} & \text{if} \quad (|\psi_w| < \psi_{wpY}) \\ & \text{or} \quad (\psi_w < \psi_{wpY} - 180) \\ & \text{or} \quad (\psi_w > 180 - \psi_{wpY}) \\ 90/(90 - \psi_{wpY}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{42}$$

$$\phi_Y = \begin{cases} 0 & \text{if} \quad (|\psi_w| < \psi_{wpY}) \\ 90 & \text{if} \quad (\psi_w < \psi_{wpY} - 180) \\ -90 & \text{if} \quad (\psi_w > 180 - \psi_{wpY}) \\ (\text{sign of} \psi_w)(90 - 2\psi_{wpY}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{43}$$

The yawing moment equations are identical to the side force equations but with Y replaced with N and $M(90, 0)$ substituted for $L(90, 0)$.

The rolling moment equations are almost identical to the side force equations with Y replaced with R and $R(90, 0)$ substituted for $L(90, 0)$. The only difference is that the rolling moment equation deletes the sign θ_w factor in Eq. (6). The complete set of rolling moment equations is

$$R = R_1 \cos^2 \theta_w + R(90, 0) \sin^2 \theta_w \sin^2 \psi_w \operatorname{sign} \psi_w \tag{44}$$

$$R_1 = R(90, 0) \sin \psi_w + R_2 \sin[f_Y(\psi_w + \phi_Y)] \tag{45}$$

$$R_2 = R(\psi_{wpY}, 0) - R(90, 0) \sin \psi_{wpY} \tag{46}$$

$$f_R = \begin{cases} 90/\psi_{wpR} & \text{if} \quad (|\psi_w| < \psi_{wpR}) \\ & \text{or} \quad (\psi_w < \psi_{wpR} - 180) \\ & \text{or} \quad (\psi_w > 180 - \psi_{wpR}) \\ 90/(90 - \psi_{wpR}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{47}$$

$$\phi_R = \begin{cases} 0 & \text{if} \quad (|\psi_w| < \psi_{wpR}) \\ 90 & \text{if} \quad (\psi_w < \psi_{wpR} - 180) \\ -90 & \text{if} \quad (\psi_w > 180 - \psi_{wpR}) \\ (\text{sign of} \psi_w)(90 - 2\psi_{wpR}) & \text{if} \quad \text{preceding not true} \end{cases} \tag{48}$$

Numerical Example

Aerodynamic data for the UH-60A Black Hawk[3] are used to illustrate how the HAE model is applied to a helicopter fuselage. Table 1 shows the list of inputs, defined as dimensional units of force or moment divided by dynamic pressure, used for this example. Figure 1 shows a comparison of the HAE model predictions (using the inputs given in Table 1) with lift data from Ref. 3. Similarly, Fig. 2 shows a comparison of Ref. 3 yawing moment data with HAE model predictions. Figures 1 and 2 show that the HAE model gives an acceptable approximation of fuselage lift force and

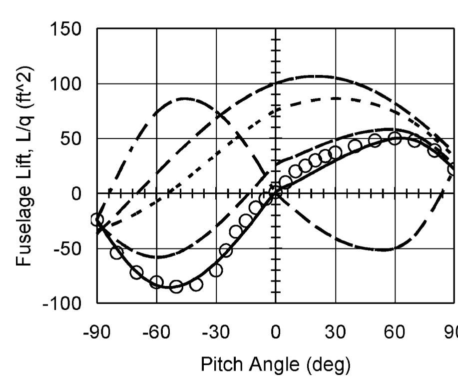

Fig. 1 HAE lift model: ○, Ref. 3; ——, yaw = 0 deg; — —, yaw = 30 deg; - -, yaw = 60 deg; —, yaw = 90 deg; and · · · ·, yaw = 180 deg.

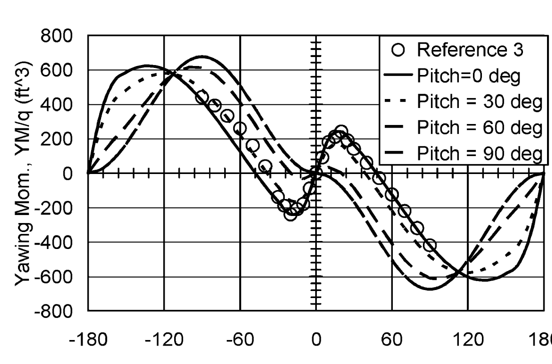

Fig. 2 HAE yawing moment model.

Table 1 HAE model inputs for UH-60A example

Description	Symbol	Value	Unit
Lift at yaw and pitch = 0	L (0,0)	1	ft^2
Lift at yaw = 0, pitch = +90 deg	L (0, 90)	22	ft^2
Lift at yaw = 0, pitch = −90 deg	L (0, −90)	−24	ft^2
Peak lift at yaw = 0, positive pitch	$L\ (0, \theta_{wpL+})$	50	ft^2
Peak lift at yaw = 0, negative pitch	$L\ (0, \theta_{wpL-})$	−85	ft^2
Pitch angle for positive peak lift	θ_{wpL+}	60	deg
Pitch angle for negative peak lift	θ_{wpL-}	−50	deg
Lift at yaw = 180 deg, pitch = 0	L (180, 0)	1	ft^2
Lift at yaw = +90 deg, pitch = 0	L (90, 0)	100	ft^2
Drag at yaw and pitch = 0	D (0, 0)	23.58	ft^2
Drag at yaw = 0, pitch = +90 deg	D (0, 90)	150	ft^2
Drag at yaw = 0, pitch = −90 deg	D (0, −90)	150	ft^2
Drag at yaw = 180 deg, pitch = 0	D (180, 0)	23.58	ft^2
Drag at yaw = +90 deg, pitch = 0	D (90, 0)	194.08	ft^2
Side force at yaw = +90, pitch = 0	Y (90, 0)	37	ft^2
Peak side force at pitch = 0	$Y(\psi_{wpY}, 0)$	103	ft^2
Yaw angle for peak side force	ψ_{wpY}	50	deg
Pitching moment at yaw and pitch = 0	M (0, 0)	−90	ft^3
Pitching moment at yaw = 0, pitch = +90	M (0, 90)	200	ft^3
Pitching moment at yaw = 0, pitch = −90	M (0, −90)	−200	ft^3
Peak pitching moment at yaw = 0, positive pitch	$M\ (0, \theta_{wpM+})$	825	ft^3
Peak pitching moment at yaw = 0, negative pitch	$M\ (0, \theta_{wpM-})$	−760	ft^3
Pitch angle for positive peak pitching moment	θ_{wpM+}	50	deg
Pitch angle for negative peak pitching moment	θ_{wpM-}	−50	deg
Pitching moment at yaw = +90 deg, pitch = 0	M (90, 0)	675	ft^3
Pitching moment at yaw = 180 deg, pitch = 0	M (180, 0)	−90	ft^3
Yawing moment at yaw = +90, pitch = 0	N (90, 0)	−420	ft^3
Peak yawing moment at pitch = 0	$N(\psi_{wpN}, 0)$	240	ft^3
Yaw angle for peak yawing moment	ψ_{wpN}	20	deg
Rolling moment at yaw = +90, pitch = 0	R (90, 0)	−100	ft^3
Peak rolling moment at pitch = 0	$R\ (\psi_{wpR}, 0)$	−150	ft^3
Yaw angle for peak rolling moment	ψ_{wpR}	50	deg

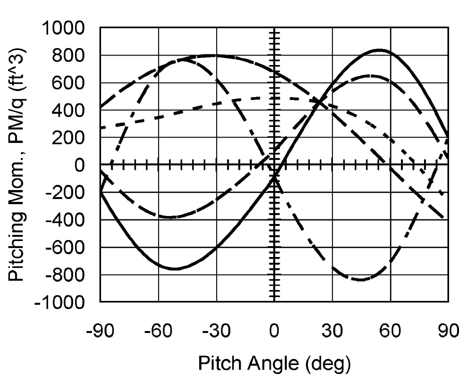

Fig. 3 HAE pitching moment model: ——, yaw = 0 deg; — —, yaw = 30 deg; - -, yaw = 60 deg; —, yaw = 90 deg; and · · · ·, yaw = 180 deg.

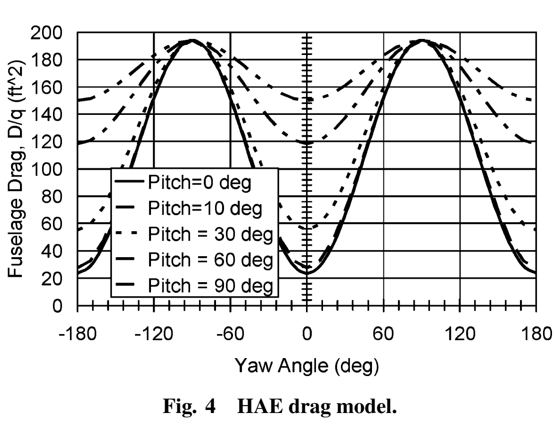

Fig. 4 HAE drag model.

yawing moment at angles greater than approximately 30 deg, but misses details in the data at small angles. Figure 1 also shows the feature of asymmetric peak lift values on either side of zero pitch angle.

The HAE model provides an advantage over the Ref. 3 data because it can generate data at any combination of pitch angle and yaw angle (Figs. 1–4). The data from Ref. 3 are only available for either yaw = 0 or pitch = 0, and the data for pitch = 0 cover a limited range of yaw angle.

Conclusions

A complete set of quasi-steady fuselage aerodynamic force and moment data at any aerodynamic angle may be generated using the harmonic HAE model presented. This model gives proper trends in lateral–directional forces and moments at high pitch angles, allows selection of peak angles, and provides for asymmetric data with pitch angle. The resulting forces and moments are useful for simulation modeling, for developing guidance laws, and for prediction of vehicle performance at large aerodynamic angles.

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