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Influence of Unsteady Aerodynamics on Extracted Aircraft Parameters

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The effect of accounting for unsteady aerodynamics on the parameters extracted from flight data is examined. Longitudinal equations of motion have been modified, and a parameter-extraction program developed to include the effects of unsteady aerodynamics. The approach used was to model and to use that data in two parameter-extraction programs, one including and the other neglecting unsteady effects, to see if the parameters were significantly different. Flight data for a light airplane was also used with the two extraction programs for the same purpose. Results showed that, for the cases considered, including unsteady aerodynamics in the parameter-extraction program did affect the extracted quantities, particularly the damping in pitch. In addition, the parameter variances were lower than when unsteady aerodynamics were included in the extraction program than when the effects were neglected.

Nomenclature

A	= aspect ratio
c	= chord
c_r	= root chord
$\bar{c}$	= mean geometric chord
C_L	= lift coefficient, lift/($\frac{1}{2}\rho U^2 S_w$)
$\Delta C_L(t)$	= indicial lift function
C_{L_α}	= $\partial C_L/\partial\alpha$
$C_{L_{\delta_e}}$	= $\partial C_L/\partial\delta_e$
C_m	= pitching moment coefficient, pitching moment/($\frac{1}{2}\rho U^2 S_w \bar{c}_w$)
C_{m_q}	= $\partial C_m/[\partial(q\bar{c}_w)/(2U)]$
$C_{m_{\delta_e}}$	= $\partial C_m/\partial\delta_e$
i	= $\sqrt{-1}$
I_y	= pitch moment of inertia
l	= distance from quarter chord of wing root chord to point at which downwash is being calculated
l_t	= tail length
m	= mass
q	= pitch rate
S	= area
t	= time
U	= freestream velocity
w	= downwash velocity
α	= angle of attack
δ_e	= elevator deflection
ϵ	= downwash angle
Γ	= circulation strength
ρ	= air density
λ	= taper ratio
Λ	= sweep of quarter-chord line
ω	= frequency
$\Delta\epsilon$	= indicial downwash function

Subscripts

f	= fuselage
w	= wing
t	= horizontal tail
ss	= steady state
l	= at distance l behind wing root quarter chord point

Introduction

EXTRACTION of aerodynamic parameters from flight data is becoming a routine task for numerous organizations, and sophisticated techniques have been developed for this purpose. Although the methods are well developed and work well with computer-generated data, several problems become apparent when the methods are applied to real flight data. These problems include the following: 1) extraction of different numerical values for the same parameter, under similar flight conditions; 2) estimated variances which are too optimistic when compared to ensemble averages; and 3) dependence of extracted parameters on the control input.

One possible factor contributing to these problems is the fact that unsteady aerodynamics associated with load buildup generally have not been modeled. Although there are various methods available[1-3] for calculating unsteady aerodynamic loads on lifting surfaces, the methods are generally too complex for use in equations of motion or for parameter extraction. Reference 4 was a preliminary attempt to develop a method of including unsteady effects in the equations of motion, for use in parameter extraction. In that reference, a simple, single-vortex system was developed for calculating indicial lift. It gave results in agreement with those from more

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accurate and complex vortex systems for unswept wings in incompressible flow. The simple vortex concept was generalized[5] to obtain indicial lift for tapered, swept wings in incompressible flow.

The purposes of the present study were: 1) to develop further the methods of Refs. 4 and 5 to derive an equation for the downwash behind tapered, swept wings; 2) to develop equations of motion including unsteady aerodynamic effects; and 3) to apply an algorithm for parameter extraction which accounts for unsteady aerodynamics[6] to computer-generated and flight data.

Analysis

The longitudinal aerodynamic parameters of an aircraft are determined primarily by the lift forces acting on the wing and tail surfaces. Unsteady aerodynamic forces on these surfaces are estimated through use of the indicial lift (lift response due to unit step increase in effective angle of attack) at each surface.

Indicial Lift

The analysis of Ref. 5 resulted in an expression for indicial lift which can be fitted accurately by the equation

$$\Delta C_L(t) = (C_{L_\alpha})_{ss}\left[1 - y\exp\left(-z\frac{Ut}{c_r/2}\right)\right] \tag{1}$$

The constants $(C_{L_\alpha})_{ss}$, y, and z are functions of the geometry of the lifting surface.

where

$$f_1 = \frac{1}{2\frac{l}{c_r}}\left(\tan\Lambda + \left\{\left[\frac{A(1+\lambda)}{4}s^2\Lambda - \frac{l}{c_r}\tan\Lambda\right]\Big/\sqrt{\left[\frac{A(1+\lambda)}{4\cos\Lambda} - \frac{l}{c_r}\sin\Lambda\right]^2 + \left[\frac{l}{c_r}\cos\Lambda\right]^2}\right\}\right) \tag{3a}$$

$$f_2(t) = \frac{2}{A(1+\lambda)}\left\{\left[\frac{l}{c_r} - \frac{A(1+\lambda)}{4}\tan\Lambda\right]\Big/\sqrt{\left[\frac{l}{c_r} - \frac{A(1+\lambda)}{4}\tan\Lambda\right]^2 + \left[\frac{A(1+\lambda)}{4}\right]^2}\right.$$

$$\left. - \left[\frac{l}{c_r} - 1 - \frac{Ut}{c_r} - \frac{A(1+\lambda)}{4}\tan\Lambda\right]\Big/\sqrt{\left[\frac{l}{c_r} - 1 - \frac{Ut}{c_r} - \frac{A(1+\lambda)}{4}\tan\Lambda\right]^2 + \left[\frac{A(1+\lambda)}{4}\right]^2}\right\} \tag{3b}$$

$$f_3(t) = -\frac{1}{2\left(\frac{l}{c_r} - 1 - \frac{Ut}{c_r}\right)}\left(\tan\Lambda + \left\{\left[\frac{A(1+\lambda)}{4}s^2\Lambda - \left(\frac{1}{c_r} - 1 - \frac{Ut}{c_r}\right)\tan\Lambda\right]\right.\right.$$

$$\left.\left.\Big/\sqrt{\left[\frac{A(1+\lambda)}{4\cos\Lambda} - \left(\frac{l}{c_r} - 1 - \frac{Ut}{c_r}\right)\sin\Lambda\right]^2 + \left[\left(\frac{l}{c_r} - 1 - \frac{Ut}{c_r}\right]^2\right.}\right\}\right) \tag{3c}$$

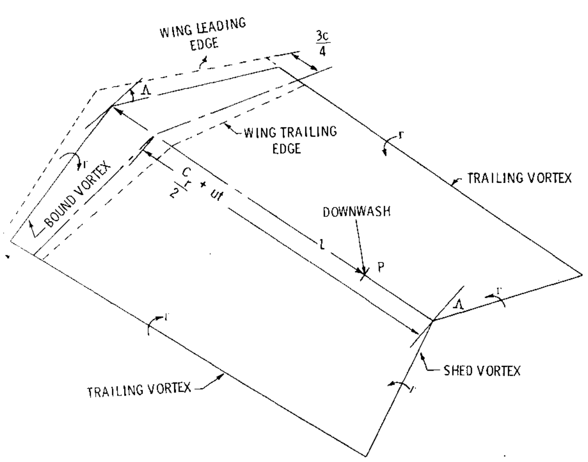

Fig. 1 Vortex system used in computing downwash.

Downwash

In determining the lift of a horizontal tail, it is necessary to compute the downwash at the tail caused by the wing lift. In a physical system, a vortex shed from the wing moves downstream at freestream velocity. The downwash caused by the vortex as it crosses a given point is a discontinuous function since it changes to upwash abruptly. The downwash discontinuity reaches the tail at a time approximately equal to the tail length divided by the freestream velocity. In order to have the simplified vortex model as consistent as possible with this physical fact, it was decided to assume that a single vortex stretched in the downstream direction with freestream velocity when determining downwash behind a wing. The vortex system used for determining downwash is shown in Fig. 1. The time variation of the lift strength for unit step in angle of attack and, consequently, the corresponding circulation strength is determined by use of Eq. (1).

Since the indicial lift was computed by use of a model consisting of a single vortex,[5] it was possible to satisfy the condition of flow tangency on the lifting surface at only one point. In keeping with this fact, the effective tail angle of attack (and consequently downwash) is computed at a control point P along the wing root chord line extension and at a distance l from the wing root quarter-chord point (Fig. 1). The downwash at the control point P is given by the Biot-Savart Law[7] as

$$w_l(t) = \frac{\Gamma}{\pi c_r}[f_1 + f_2(t) + f_3(t)] \tag{2}$$

The Kutta-Joukowski equation can be used with Eq. (2) to obtain

$$w_l(t) = \frac{U(1+\lambda)}{4\pi}C_L(t)[f_1 + f_2(t) + f_3(t)] \tag{4}$$

The downwash angle is defined by

$$\epsilon_l(t) = [w_l(t)]/U \tag{5}$$

The downwash following a unit step increase in angle of attack is therefore

$$\Delta\epsilon_l(t) = \frac{1+\lambda}{4\pi}\Delta C_L(t)[f_1 + f_2(t) + f_3(t)] \tag{6}$$

or, using Eq. (1)

$$\Delta\epsilon_l(t) = \frac{1+\lambda}{4\pi}(C_{L_\alpha})_{ss}\left[1-y\exp\left(-z\frac{Ut}{c_r/2}\right)\right]$$
$$\times[f_1+f_2(t)+f_3(t)] \tag{7}$$

Equation (7) is approximate of the simple vortex system used. A means of improving the accuracy of Eq. (7) is to assure correctness at known conditions. There are accurate methods for computing downwash under steady-state conditions. It can be shown that Eq. (7) can be expressed in terms of the steady-state value $(\partial\epsilon/\partial\alpha)_{l,ss}$ according to

$$\Delta\epsilon(t) = \left(\frac{\partial\epsilon}{\partial\alpha}\right)_{l,ss}\left[1-y\exp\left(-z\frac{Ut}{c_r/2}\right)\right]$$
$$\times\left[\frac{f_1+f_2(t)+f_3(t)}{f_1+f_2(\infty)+f_3(\infty)}\right] \tag{8}$$

where

$$f_2(\infty) = \frac{2}{A(1+\lambda)}\left\{\left[\frac{l}{c_r}-\frac{A(1+\lambda)}{4}\tan\Lambda\right]\right.$$
$$\left./\sqrt{\left[\frac{l}{c_r}-\frac{A(1+\lambda)}{4}\tan\Lambda\right]^2+\left[\frac{A(1+\lambda)}{4}\right]^2}\right\}+\frac{2}{A(1+2)}$$

$$f_3(\infty)=0$$

Equation (8) is complicated in form; however, it was found that it could be approximated accurately by the equation

$$\Delta\epsilon_l(t) = \left(\frac{\partial\epsilon}{\partial\alpha}\right)_{l,ss}\left[1-\frac{F_w}{l/c_r-1-Ut/c_r}\right.$$
$$\left.-G_w\exp\left(-H_w\frac{Ut}{c_r/2}\right)\right] \tag{9}$$

Equation (9) is in a convenient form to use in frequency-response calculations since its terms do have Laplace transforms. Transforms are not known to exist for some of the forms which are in Eq. (8). The constants F, G, H are functions of wing geometry and can be determined by curvefitting Eq. (9) to results calculated from Eq. (8).

Lift and Downwash for Arbitrary Variation of Angle of Attack

The lift and downwash for arbitrary variation in angle of attack are determined by using the indicial responses [Eqs. (1) and (9)] with Duhamel's integral. The results are

$$C_L(t) = (C_{L_\alpha})_{ss}\int_0^t\left\{1-y\exp\left[-z\left(\frac{t-\tau}{c_r/2}\right)U\right]\right\}\dot\alpha(\tau)\,d\tau \tag{10}$$

and

$$\epsilon_l(t) = \left(\frac{\partial\epsilon}{\partial\alpha}\right)_{l,ss}\int_0^t\left\{1-\frac{F_w}{l/c_r-1-[U(t-\tau)]/c_r}\right.$$
$$\left.-G_w\exp\left[-H_w\frac{U(t-\tau)}{c_r/2}\right]\right\}\dot\alpha(\tau)\,d\tau \tag{11}$$

Lift on a Horizontal Tail Behind a Wing

The lift on a horizontal tail behind a wing is proportional to the effective angle of attack of the tail, which is given by

$$\alpha_t=\alpha-\epsilon_l+l_tq/U$$

or since l_tq/U is generally small

$$\alpha_t=\alpha-\epsilon_l \tag{12}$$

The lift on the tail surface, therefore, is

$$C_{L_t}(t)=\int_0^t\Delta C_{L_t}(t-\tau)[\dot\alpha(t)-\dot\epsilon_l(t)]\,d\tau \tag{13}$$

Equations of Motion With Unsteady Aerodynamics

The assumed longitudinal equations of motion are

$$\dot\alpha(t)=q(t)-(\rho US_w/2m)C_L(t) \tag{14}$$

and

$$\dot q(t)=[(\rho U^2S_w\bar c_w)/(2I_y)]C_m(t) \tag{15}$$

The unsteady aerodynamic effects are modeled in the $C_L(t)$ and $C_m(t)$ terms as

$$C_L(t)=C_{L_w}(t)+\frac{S_t}{S_w}C_{L_t}(t)+C_{L_{\delta_e}}\delta_e(t) \tag{16}$$

and

$$C_m(t)=-\frac{l_t}{\bar c_w}\frac{S_t}{S_w}C_{L_t}(t)+C_{m_q}\frac{\bar c_wq(t)}{2U}+C_{m_{\delta_e}}\delta_e(t) \tag{17}$$

It is apparent that when Eqs. (10, 11, and 13) are substituted into Eqs. (16) and (17), and the results used in Eqs. (14) and (15), the consequence is a pair of complicated equations involving convolution integrals. The solution of the equations is very time consuming, even in a high-speed digital computer. The equations, therefore, were transformed into the frequency domain to simplify them and make them more practical for use in parameter extraction. It can be shown that, by transforming to the frequency domain, the equations of motion become

$$i\omega\alpha(i\omega)=q(i\omega)-\frac{\rho US_w}{2m}\left\{\left[\bar C_{L_w}(i\omega)+\frac{S_t}{S_w}\bar C_{L_t}(i\omega)\right]\right.$$
$$\left.\times\alpha(i\omega)+C_{L_{\delta_e}}\delta_e(i\omega)\right\} \tag{18}$$

and

$$i\omega q(i\omega)=\frac{\rho U^2S_w\bar c_w}{2I_y}\left[-\frac{l_t}{\bar c_w}\frac{S_t}{S_w}\bar C_{L_t}(i\omega)\alpha(i\omega)\right.$$
$$\left.+C_{m_q}\frac{\bar c_wq(i\omega)}{2U}+C_{m_{\delta_e}}\delta_e(i\omega)\right] \tag{19}$$

where

$$\bar C_{L_w}(i\omega)=(C_{L_\alpha})_{w,ss}\left(1-\frac{i\omega y_w}{i\omega+(z_wU)/(c_{r_w}/2)}\right) \tag{20}$$

and

$$\bar C_{L_t}(i\omega)=(C_{L_\alpha})_{t,ss}\left[1-\frac{i\omega y_t}{i\omega+(z_tU)/(c_{r_t}/2)}\right]$$
$$\times\left\{1-\left(\frac{\partial\epsilon}{\partial\alpha}\right)_{l,ss}\left[1-\frac{i\omega F_w}{U/c_{r_w}}\exp\left(-\frac{l-c_{r_w}}{U}i\omega\right)\right.\right.$$
$$\left.\left.\times E_i\left(\frac{l-c_{r_w}}{U}i\omega\right)-\frac{i\omega G_w}{i\omega+(H_wU)/(c_{r_w}/2)}\right]\right\} \tag{21}$$

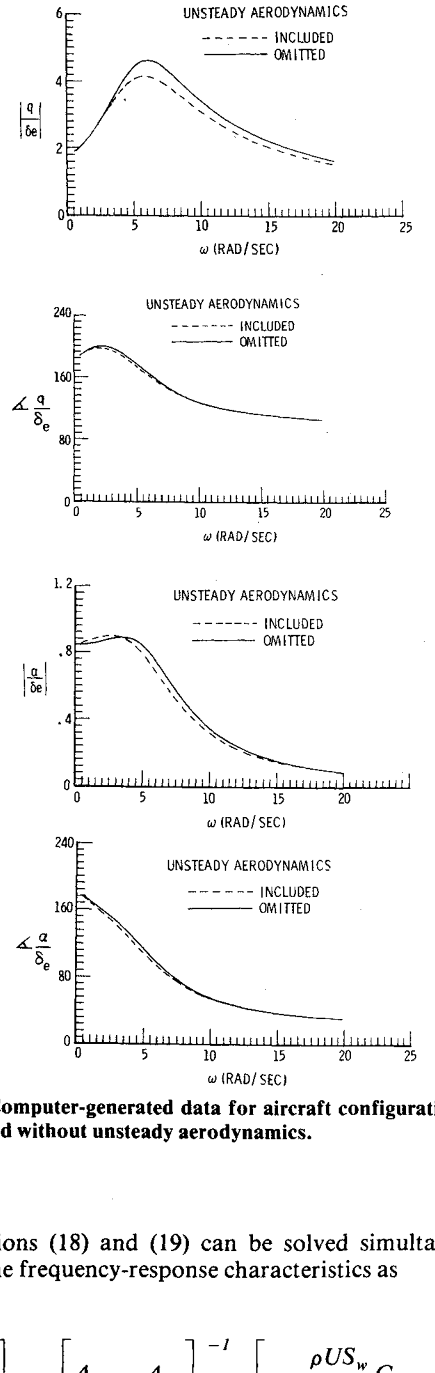

Fig. 2 Computer-generated data for aircraft configuration of Table 1, with and without unsteady aerodynamics.

Equations (18) and (19) can be solved simultaneously to obtain the frequency-response characteristics as

$$\begin{bmatrix} \dfrac{\alpha(i\omega)}{\delta_e(i\omega)} \\ \\ \dfrac{q(i\omega)}{\delta_e(i\omega)} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ \\ A_{21} & A_{22} \end{bmatrix}^{-1} \begin{bmatrix} -\dfrac{\rho U S_w}{2m} C_{L_{\delta_e}} \\ \\ \dfrac{\rho U^2 S_w \bar{c}_w C_{m_{\delta_e}}}{2I_y} \end{bmatrix} \tag{22}$$

where

$$A_{11} = i\omega + \frac{\rho U S_w}{2m}\left[\bar{C}_{L_t}(i\omega) + \frac{S_t}{S_w}\bar{C}_{L_t}(i\omega)\right]$$

$$A_{12} = -1$$

$$A_{21} = \frac{\rho U^2 S_w \bar{c}_w}{2I_y}\,\frac{l_t}{\bar{c}_w}\,\frac{S_t}{S_w}\bar{C}_{L_t}(i\omega)$$

$$A_{22} = i\omega - \frac{\rho U^2 S_w \bar{c}_w}{2I_y} C_{m_q}\frac{\bar{c}_w}{2U}$$

Table 1 Characteristics used in calculating simulated data in the frequency domain[a]

	Wing	Horizontal tail
Aspect ratio	6.00	4.00
Taper ratio	1.00	1.00
Sweep, deg	0	0
Root chord, m	1.74	1.00
Area, m^2	17.11	4.0
y	0.418	0.379
z	0.339	0.380
F	1.0894	–
G	0.5023	–
H	0.0856	–
$(C_{L_\alpha})_{ss}$	4.529	3.883

[a] Weight = 13090 N, I_y = 3762.4 Kg m^2; U = 73.2 m/s; ρ = 1.056 Kg/m^3; $C_{m_{\delta_e}} = -1.420$; $C_{L_{\delta_e}} = 0.511$; and $(\partial\epsilon/\partial\alpha)_{t,ss} = 0.49$.

Table 2 Parameters extracted from computer-generated data of Fig. 2, including unsteady aerodynamics

Parameter	Correct value[a]	Extracted values: Unsteady aerodynamics omitted	Extracted values: Unsteady aerodynamics retained
$(C_{L_\alpha})_{t,ss}$	3.883	3.588(0.068)[b]	3.883
C_{m_q}	−18.1	−21.4(0.405)	−18.1
$C_{m_{\delta_e}}$	− 1.420	−1.419(0.004)	−1.420
$C_{L_{\delta_e}}$	0.511	0.611(0.008)	0.511

[a] Values used in generating data. [b] Numbers in parentheses are variances.

In the parameter-extraction mode, flight data in the form of time histories of α, q, and δ_e are converted to the frequency domain, and Eq. (18) and (19) are used in a parameter-extraction algorithm[6] to extract parameters to best fit the frequency-domain data.

Results and Discussion

To assess the effects of excluding unsteady aerodynamics in the force and moment models used in the present estimation algorithms, an example using numerically simulated data was used. After this step, real flight data was analyzed for the same purpose.

Numerically Simulated Data

Equation (22), in combination with Eqs. (20) and (21), were used to generate simulated data for the aircraft and flight conditions of Table 1. The results are shown in Fig. 2. Equation (22), with unsteady aerodynamics omitted ($y = F = G = 0$), were also used to generate data for the same flight condition. These results are also shown in Fig. 2. It is apparent that including the unsteady aerodynamic terms affects the dynamic response of the aircraft.

The response generated with the unsteady aerodynamic model were used as "measured" data. In the parameter-extraction process, two cases were considered: 1) estimation of parameters using the extraction algorithm with unsteady aerodynamic terms retained and 2) estimation using the algorithm with unsteady terms omitted. The results of these two cases are given in Table 2. It is apparent that including unsteady aerodynamics in the extraction algorithm has a noticeable effect on the extracted parameters; in particular, it showed a decrease in the extracted value of C_{m_q}. As expected, the parameters extracted using the algorithm which included unsteady aerodynamics were precisely those used in generating the data; that is, the variances were zero.

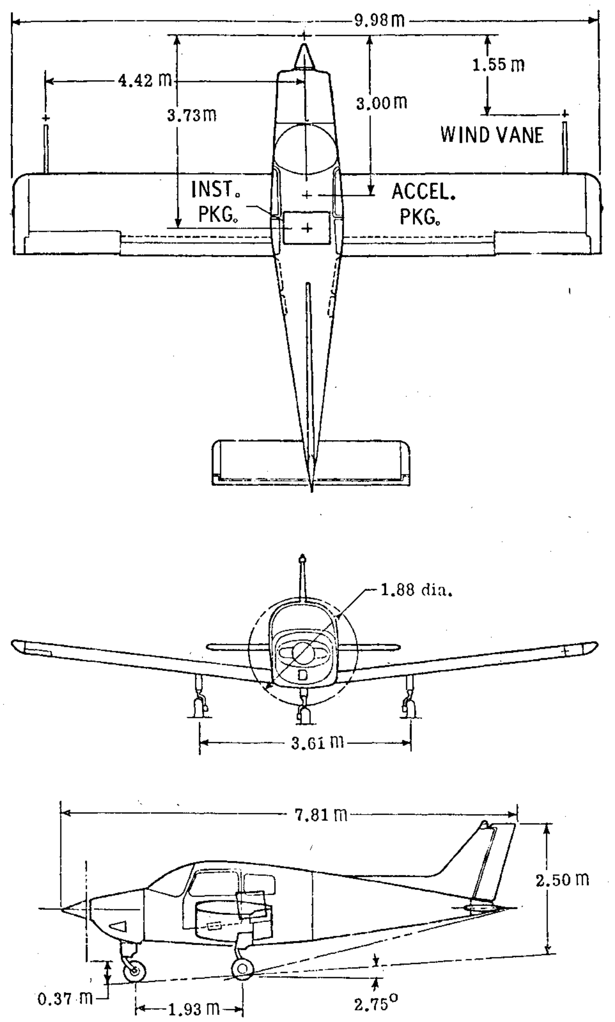

Fig. 3 Sketch of aircraft used for obtaining flight data.

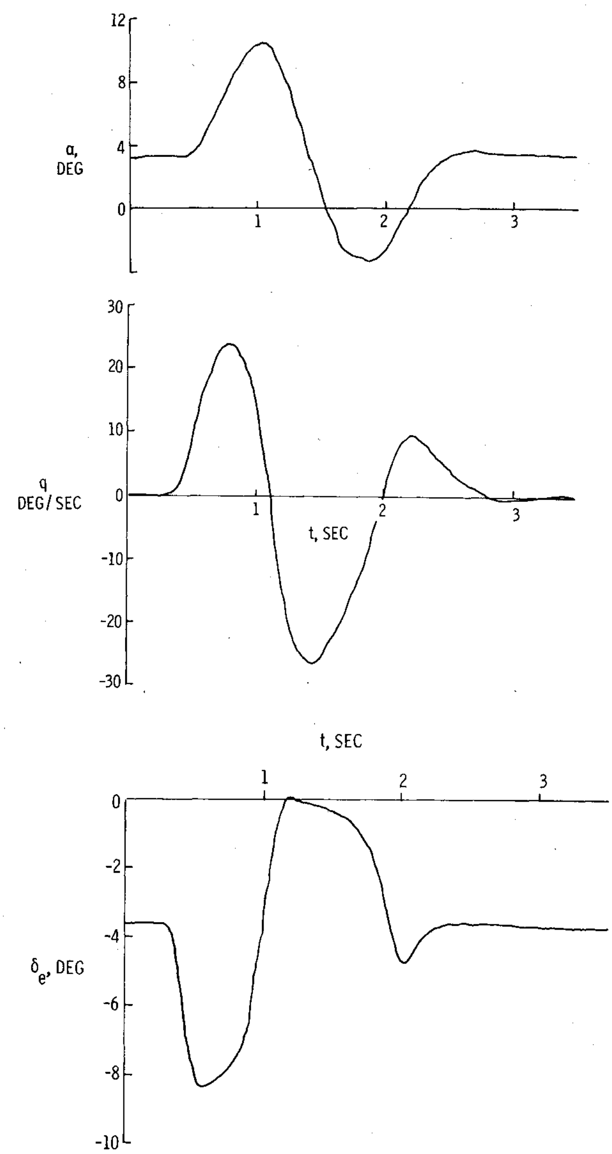

Fig. 4 Time history of data from aircraft of Fig. 3.

Table 3 Characteristics of aircraft and flight conditions used to obtain flight data of Fig. 4[a]

	Wing	Horizontal tail
Aspect ratio	7.35	4.21
Taper ratio	1.00	1.00
Sweep, deg	0	0
Root chord, m	1.34	0.77
Area, m^2	13.56	2.51

[a] Weight = 9230 N, I_y = 2135 Kg m^2; U = 47.5 m/s; and ρ = 1.076 Kg/m^3.

Table 4 Parameters extracted from data of Fig. 5[a]

Parameter	Extracted values	
	Unsteady aerodynamics omitted	Unsteady aerodynamics retained
$(C_{L_\alpha})_{t,ss}$	2.68(0.0115)[b]	2.98(0.0078)
C_{m_q}	−20.64(2.48)	−18.42(1.36)
$C_{m_{\delta_e}}$	−2.93(0.020)	−2.93(0.010)
$C_{L_{\delta_e}}$	0.94(0.25)	0.71(0.12)

[a] Characteristics and constants used in the parameter extraction programs, where applicable: $(C_{L_\alpha})_{w,ss} = 4.795$; $(\partial\epsilon/\partial\alpha)_{t,ss} = 0.44$; $y_w = 0.432$; $z_w = 0.322$; $y_t = 0.380$; $z_t = 0.371$; $F_w = 1.358$; $G_w = 0.513$; and $H_w = 0.065$.
[b] Values in parentheses are variances.

Flight Data

The flight data used in this part of the study were for the aircraft configuration shown in Fig. 3. The aircraft geometric and mass characteristics and flight conditions are given in Table 3, and the measured flight data are shown in Fig. 4. As noted previously, it is convenient, when including unsteady aerodynamics in the aircraft math model, to perform parameter extraction in the frequency domain. The data of Fig. 4 were converted to the frequency domain by use of the Fourier transform. The results were used to generate the data shown in Fig. 5, which were then in a form to be used in the parameter-extraction process.

The flight data were used in two different parameter-extraction cases: 1) in the frequency domain, using an algorithm with unsteady aerodynamics omitted and 2) in the frequency domain, using an algorithm with unsteady effects retained. Results for each of the two cases are given in Table 4.

As in the case with computer-generated data, the inclusion of unsteady aerodynamic parameters in the extraction algorithm did affect the values of the extracted parameters, particularly the damping-in-pitch parameter C_{m_q}. It is interesting to note that the variances obtained when unsteady aerodynamics are included are smaller than when unsteady aerodynamics are neglected.

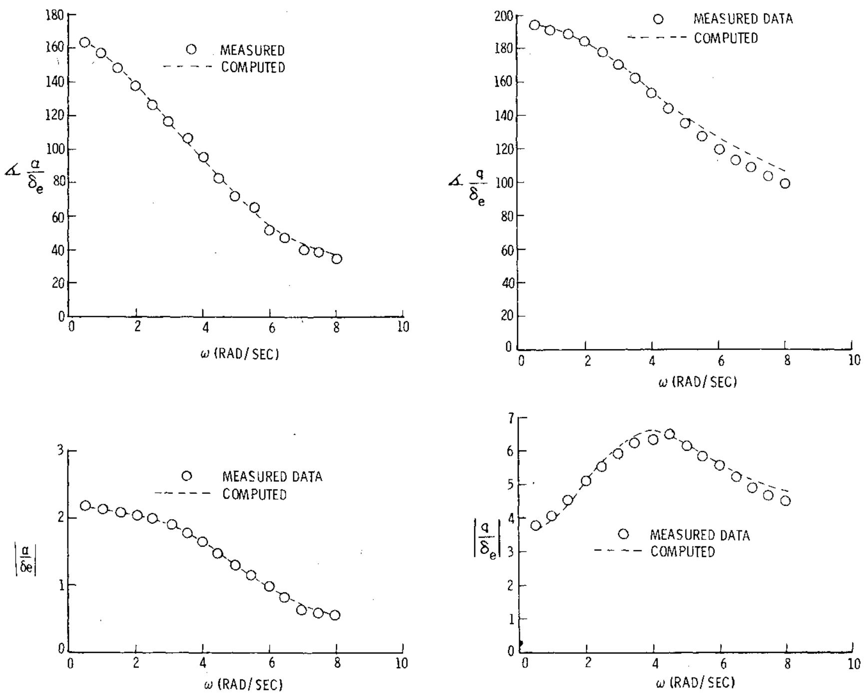

Fig. 5 Frequency-response curves obtained from the time history of Fig. 4.

Concluding Remarks

The effect of including unsteady aerodynamics on the parameters extracted from flight data is examined. Longitudinal equations of motion have been modified, and a parameter extraction program developed to include the effects of unsteady aerodynamics. The presence of convolution integrals in the modified equations of motion led to the idea of transforming these into the frequency domain using Laplace transforms which reduced the integro-differential equations to simple algebraic equations, thereby reducing the computation time significantly. The approach used is to generate pseudodata using the unsteady model, and use that data in two parameter-extraction programs, one including and the other neglecting unsteady effects. In the case of real flight data, transformation of time histories to the frequency domain was achieved by Fourier transformation. The preliminary results indicate that, for the case considered, inclusion of unsteady aerodynamics in the extraction model shows significant difference in some of the parameters, particularly in the damping in pitch.

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