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Lift and Pitching Moment Characteristics of Stores Determined from Flight Drop Tests

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An accurate estimation of the aerodynamic characteristics of externally carried stores, like bombs, drop tanks, missiles in the presence of the interference flowfield of the aircraft is essential for prediciton of reliable separation trajectories. The currently available theoretical methods are restricted to steady-state conditions of the flowfield around the model. Wind-tunnel methods such as the captive model, drop model and flow field survey techniques can be used to generate aerodynamic data for pre-flight simulation studies. But they are incapable of simulating the pronounced dynamic conditions of the stores encountered during the free fall which give rise to considerable aerodynamic forces and moments of noncirculatory origin. The present paper describes a simple parameter identification procedure employed to estimate the lift and pitching moment coefficients of a family of droppable fuel tanks using photographic data obtained from full-scale drop tests. Results are presented for the stores showing the combined effect of store incidence and pitch rate.

Nomenclature

C_L, C_D, C_M	= aerodynamic coefficients referred to maximum cross-sectional area
d	= distance of the c.g. from tail
F_N	= frame number
g	= acceleration due to gravity
K_{yy}	= (k_{yy}/l) nondimensional radius of gyration of the store about pitch axis through the c.g.
l	= store length
m	= store mass
N	= number of frames/s
R	= Reynolds number based on store length
S	= maximum cross-sectional area of the store
t	= time
U	= aircraft true airspeed
x,z	= coordinates
α	= store angle of attack, deg
$\dot{\alpha}$	= store pitch rate, rad/s
γ	= angle made by the tangent to the flight path with X axis
δ	= (l/U) aerodynamic time
θ	= store pitch attitude, deg
u	= (m/ρ_{ls})
ρ	= ambient density
τ	= nondimensional time
ξ,ζ	= nondimensional coordinates

Subscripts and Superscripts

$(\hat{\ })$	= measurements made in frame
l	= rear end of the store
o	= time $t=0$

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Introduction

A RELIABLE prediction of the release trajectories of externally carried stores like bombs, fuel tanks, and other ordnances dropped from aircraft is governed by the possibility of the accurate determination of their aerodynamic coefficients in the presence of the complex interference flowfields from the aircraft and other external stores present in the vicinity. In addition, the stores also very often experience somewhat large random pitching and yawing motions during their general forward and downward motion. Consequently, it is necessary to estimate their aerodynamic coefficients as functions of the angle of pitch, yaw, pitch rate, and yaw rate. However, estimation methods for aerodynamic coefficients for these complex body shapes including complicated interference flowfield effects are not available.

Present analytical techniques are restricted to only small angles of attack and yaw and steady flow conditions, whereas the estimates are required up to high angles of attack and yaw including pronounced dynamic flowfield conditions. The observations of the present tests showed the particularly high pitching velocities of the order of 4 rad/s and higher, attained by the store so very early during its free fall and completely at variance with the values expected using the aerodynamic coefficients from the current literature.[4,7] This order of angular velocities may be somewhat altered in the case of powered stores like missiles or power-ejected stores. Nevertheless, strong interference field effects on the store aerodynamic characteristics seem to demand closer investigation. A comparison of the predicted flight trajectories with those observed during flight tests has been reported[9] by one of the authors elsewhere.

The prevailing wind-tunnel methods, like the captive model testing reported by Roberts and Myers,[10] Furey and Martin,[3] Christopher and Costs,[2] Landers et al.,[6] and the drop model technique besides being affected by Reynolds number effects and a number of other limitations, appear to be unable to simulate these unsteady conditions. In this resepct, the wind-tunnel drop model technique appears to be closer to the real situation than the captive model testing. The importance of theoretical and experimental investigations into the strong noncirculatory lift from dynamic flow conditions up to high angles of attack is thus highlighted. Whereas some theoretical work[5] is available on the unsteady motion of arbitrary bodies and bodies of revolution in an infinite unbounded fluid, results on such bodies in the complex aircraft flowfield are not available.

The objective of this paper is to show the possibility of obtaining reliable aerodynamic characteristics of stores at full-scale and flight Mach numbers up to high incidence with large incidence change rates, in general, as a byproduct of routine flight clearance drop tests, with little or no special instrumentation.

A series of flight drop tests on a family of drop tanks was performed in 1973 from a strike aircraft, a fighter bomber, and a jet trainer. During these tests, a chase aircraft was used for formation flying to observe and photograph the store motion in a vertical plane. As a result, no yawing motion of the store in the horizontal plane could be studied during these drop tests. For identification of the aerodynamic characteristics of the drop tanks from the motion picture photographs of these flight tests, the trajectory of a well-defined point on the store, like the aftmost point of the drop tank relative to some point on the aircraft and the orientation of the store axis relative to the airplane axis, can be measured. From the enlarged frames of the movie photographs taken at a speed of 64 frames/s (Fig. 6) in the present studies, the center of the roundel painted on the side of the aircraft was chosen as a reference point on the aircraft.

The geometry of the drop tanks during these tests (Fig. 1) generally consists of an elliptic nose and tail section with a cylindrical centerpiece joining the two ellipses. Further, a fin with a small initial pitch setting was provided at the aft of some of the fuel tanks. A schematic diagram of the external store installation is shown in Figs. 2 and 3. The geometric and inertia characteristics of the drop tanks for which the aerodynamic parameters are identified and the geometric characteristics of the aircraft used during these tests and their installation details are also given.

Mathematical Formulation

The position of the store trailing edge and the store angle are uniquely determined with reference to the parent aircraft at a time t after jettison by the coordinates (x_t, Z_t, θ) obtained from the picture frames (Fig. 4). The coordinates $(\hat{x}, \hat{z})$ of the store center of gravity with respect to the aircraft roundel are given by the simple transformation

$$\hat{x}=\hat{x}_t+\hat{d}\cos\hat{\theta} \tag{1a}$$

$$\hat{z}=\hat{z}_t+\hat{d}\sin\hat{\theta} \tag{1b}$$

$$\hat{d}=d\hat{l}/l \tag{1c}$$

The steady level flight conditions of the parent aircraft before a store jettison is assumed to continue unaffected for the small time interval of interest in these studies even after the store release. The linear and angular accelerations of the aircraft consequent to store jettison have been neglected for the sake of simplicity and their implications are indicated later.

If U is the true airspeed of the parent aircraft at the instant of jettison, the absolute coordinates of the drop tank trajectory (x, z, θ) in an inertial reference frame fixed to the Earth may be written as

$$x=Ut+(\hat{x}-\hat{x}_o)(l/\hat{l}) \tag{2a}$$

$$z=(\hat{z}-\hat{z}_o)(l/\hat{l}), \theta=\hat{\theta} \tag{2b}$$

where the distances measured in the photographs have been scaled up to full scale (Fig. 5). Equations (2) may be written in the dimensionless form

$$\xi=\tau+(\hat{\xi}-\hat{\xi}_o),\ \zeta=\hat{\zeta}-\hat{\zeta}_o, \theta=\hat{\theta} \tag{3}$$

where

$$\tau=t/\delta=(U/l)(F_N-1)N$$

$$\hat{\xi}=\hat{x}/\hat{l}, \hat{\zeta}=\hat{Z}/\hat{l}$$

$$\xi=x/l, \zeta=Z/l \tag{4}$$

	EMPTY	FULL
WEIGHT Kg.	22.0	199.5
DISTANCE OF CG FROM NOSE M	1.259	1.185
MOMENT OF INERTIA Kg.f. M.S.² IN PITCH.	0.923	5.667

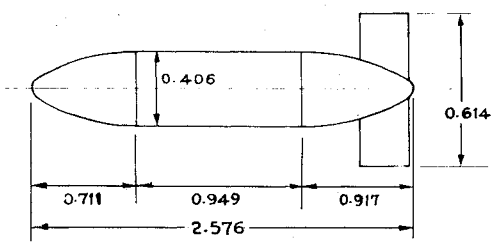


Fig. 1 Schematic of drop tank geometry.

SPAN M	10.7
MEAN CHORD M	1.891
TAPER RATIO	0.401
ASPECT RATIO	6.11
Λ C/4	7.3°
AREA SQ.M	19.06

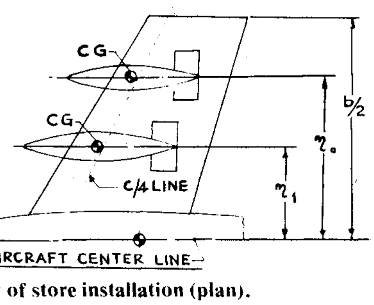


Fig. 2 Geometry of store installation (plan).

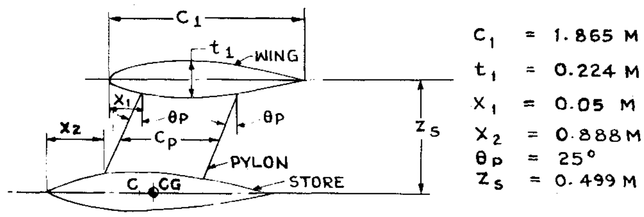


Fig. 3 Geometry of store installation (side view).

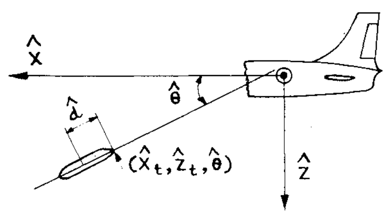


Fig. 4 Measurements made in each frame.

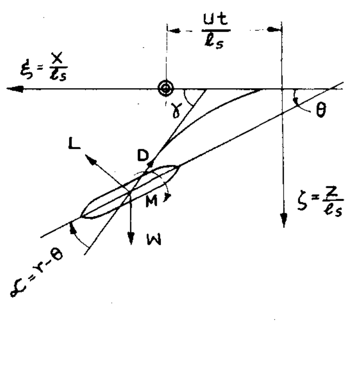


Fig. 5 Coordinate system.

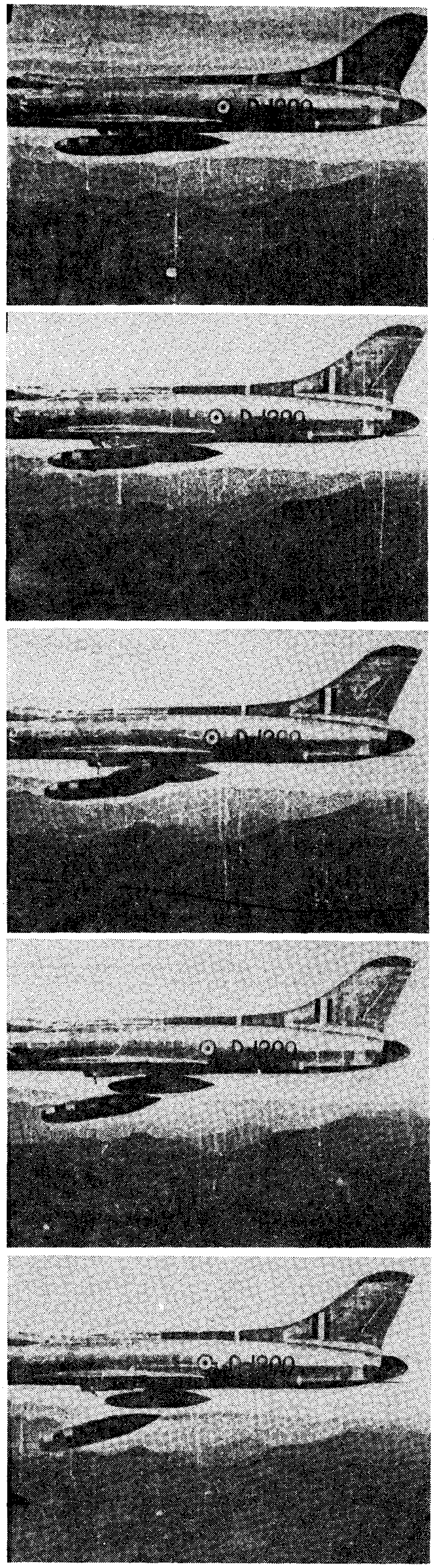


Fig. 6 Typical movie record of a store jettison.

The dimensionless equations of motion of the store under the action of the aerodynamic forces and moments for gravity jettison are given by[9]:

$$\ddot{\xi} = (C_L \sin\gamma - C_D \cos\gamma)(\dot{\xi}^2 + \dot{\zeta}^2)/2\mu \tag{5a}$$

$$\ddot{\zeta} = (g\delta^2/l) - (C_L \cos\gamma + C_D \sin\gamma)(\dot{\xi}^2 + \dot{\zeta}^2)/2\mu \tag{5b}$$

$$\ddot{\theta} = -C_M (\dot{\xi}^2 + \dot{\zeta}^2)/2\mu K_{yy}^2 \tag{5c}$$

with the dots refer to dimensionless derivatives with respect to τ. Equations (5) may be solved for C_L, C_D, and C_M in terms of the angle γ, and the time derivatives of ξ and ζ are expressed as

$$C_L = A[\ddot{\xi}\sin\gamma + (g\delta^2/l - \ddot{\zeta})\cos\gamma] \tag{6a}$$

$$C_D = A[(g\delta^2/l - \ddot{\zeta})\sin\gamma - \ddot{\xi}\cos\gamma], C_M = -AK_{yy}^2\ddot{\theta} \tag{6b}$$

where

$$A = 2\mu/(\dot{\xi}^2 + \dot{\zeta}^2) \tag{7a}$$

$$\alpha = \gamma - \theta, \dot{\alpha} = \dot{\gamma} - \dot{\theta} \tag{7b}$$

The local slope γ of the flight path and its time derivative $\dot{\gamma}$ may be expressed in terms of (ξ, ζ) by

$$\gamma = \arctan(\dot{\zeta}/\dot{\xi}) \tag{8a}$$

$$\dot{\gamma} = (\dot{\xi}\ddot{\zeta} - \ddot{\xi}\dot{\zeta})/(\dot{\xi}^2 + \dot{\zeta}^2) \tag{8b}$$

so that the aerodynamic coefficients of the stores may be calculated from Eq. (6) if the store dynamical quantities comprising the time derivatives of ξ, ζ, and θ are known. Further, the store incidence and incidence rate $\alpha, \dot{\alpha}$, respectively, may also be calculated from Eq. (7).

Solution

From the coordinates $(\hat{x}_t, \hat{z}_t, \hat{\theta})$ in the successive frames of the movie record, a set of quadruplet $(\xi, \zeta, \theta, \tau)$ are obtained for each frame from Eqs. (1-4) for calculating the first and second derivatives of ξ, ζ, and θ with respect to τ. A simple finite-difference determination of these derivatives from the set of quadruplet is prone to large discontinuities due to the inevitable scatter in the observational data. Consequently, an n-point spline fit for each of the dependent variables (ξ, ζ, θ) in terms of τ could be used by fitting an nth degree curve passing through all the points and in addition, matching the slope at the first point. This approach, however, still shares the weakness of the finite-difference method although to a smaller extent, primarily due to its lack of the required smoothing property. Consequently, a least-squares polynomial regression fit to smooth the entire data at first and then evaluate the derivatives proved satisfactory and has been used for all computations. The derivatives obtained from these regression polynomials were used to calculate the values of C_L, C_D, C_M, $\alpha, \dot{\alpha}$ at each instant. Some of the results have been reported earlier in Ref. 11.

To obtain the aerodynamic coefficients C_L and C_M in terms of $(\alpha, \dot{\alpha})$, the following procedure is adopted. The lift coefficient C_L is written as

$$C_L = C_{L_o} + a_1\alpha + a_2\dot{\alpha} + a_3\alpha^3 + a_4\dot{\alpha}^3 + a_5\alpha^2\dot{\alpha} \tag{9}$$

excluding quadratic terms in α and $\dot{\alpha}$ like $\alpha^2, \dot{\alpha}^2$ and $\alpha\dot{\alpha}$ on the basis of symmetry conditions for the store behavior. For a finned store, the small fin setting is assumed to affect only C_{L_o} so that $C_L - C_{L_o}$ will be odd in $(\alpha, \dot{\alpha})$ so that

$$(C_L - C_{L_o})_{(\alpha,\dot{\alpha})} = -(C_L - C_{L_o})_{(-\alpha,\dot{\alpha})}$$

$$(C_L - C_{L_o})_{(\alpha,-\dot{\alpha})} = -(C_L - C_{L_o})_{(-\alpha,\dot{\alpha})} \quad (10)$$

Hence the second-order terms $\alpha^2, \dot{\alpha}^2, \alpha\dot{\alpha}$ which violate these symmetry requirements are omitted. Further, the term $\alpha\dot{\alpha}^2$ has been omitted in Eq. (9) due to the unrealistic results obtained by its retention. In the same manner, the pitching moment coefficient C_M about the store center of gravity may be written.

$$C_M = C_{M_o} + b_1\alpha + b_2\dot{\alpha} + b_3\alpha^3 + b_4\dot{\alpha}^3 + b_5\alpha^2\dot{\alpha} + b_6\alpha\dot{\alpha}^2 \quad (11)$$

where the term in $\alpha\dot{\alpha}^2$ has been retained, unlike in Eq. (9) again satisfying symmetry relations similar to those of Eq. (10).

A least-square technique was used to determine the set of regression coefficients $C_{L_o}, a_1, \ldots a_5, C_{M_o}, b_i$, to b_6 in Eqs. (9) and (11) by permitting all of the coefficients to float freely and attain their equilibrium values. The resulting equations for C_L and C_M may be written as

$$C_L = 1.568 + 0.3349\alpha - 1.3978\dot{\alpha} - 0.0001469\alpha^3 + 0.01333\dot{\alpha}^3 + 0.000902\alpha^2\dot{\alpha} \quad (12a)$$

$$C_M = 0.0382 + 0.02946\alpha + 0.0797\dot{\alpha} + 0.0000212\alpha^3 + 0.001835\dot{\alpha}^3 + 0.0001265\alpha^2\dot{\alpha} + 0.000328\alpha\dot{\alpha}^2 \quad (12b)$$

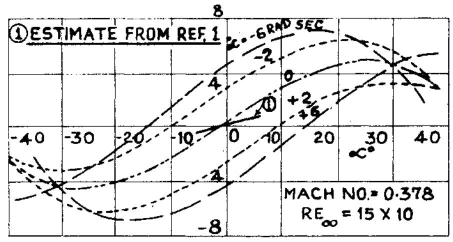
An attempt made to determine the coefficients a_1 to a_5 by constraining C_{L_o} to take values ranging from 0.044 to 1.568 showed the weak dependence of these coefficients on the value assigned to C_{L_o}. Thus, for C_{L_o} = 0.044, C_L is given by

$$C_L = 0.044 + 0.27\alpha - 1.3956\dot{\alpha} - 0.0001355\alpha^3 + 0.017965\dot{\alpha}^3 + 0.000816\alpha^2\dot{\alpha} \quad (13)$$

which may be compared with the coefficients of Eq. (12a). A similar insensitivity of the coefficients b_1 to b_6 to the assigned value of C_{M_o} was also observed, so that the numerical values of the coefficients C_{M_o}, b_1 to b_6 given earlier are all freely attained values.

Results and Discussion

Information on the aerodynamic coefficients of the store up to an incidence of $\alpha = 30$ deg and pitch rates of $\dot{\alpha} = 6$ rad/s have been retrieved from these flights using the above-mentioned parameter identification technique for stores gravity released from an unswept, fixed wing aircraft. The variation of C_L vs α with $\dot{\alpha}$ as a parameter is given in Fig. 7 from which it is observed that for $\dot{\alpha} = 0$, $C_{L\max} = 4.7$ occurs at α = 26 deg. As seen in Fig. 7, when the store pitches down, $\dot{\alpha} < 0$, the lift curve shifts leftward with $C_{L\max}$ increasing and attaining a supreme of $C_{L\max} = 7.57$ at $\dot{\alpha} = -4.6$ rad/s and α = 28 deg (Fig. 9). Further, the pitching moment curve shifts rightward (Fig. 8), a behavior explained by the fact that for a given $\alpha > 0$, $\dot{\alpha} < 0$, the effective angle of attack of the store $\alpha_{eff} > \alpha$, thereby giving a higher C_L accompanied by a change in the pressure distribution and an increase in the positive pitching moment. Plots for C_L *vs* α (Fig. 7) and C_M *vs* α (Fig. 8) show that for a given $\dot{\alpha}$, the variation of C_L and C_M with α are nearly sinusoidal with a wavelength $\alpha \approx 100$ deg. The lift coefficient $C_{L_o} = 0.044$ corresponds to a steady-state theoretical estimate for the given store regarded as a body of revolution with a small fin at the back in an unbounded fluid. The value of C_{M_o} = 0.0382 may be compared with the stady-state theoretical estimate C_{M_o} = 0.0195 for the store in an



Fig, 7 Plots of C_L vs α for various $\dot{\alpha}$.

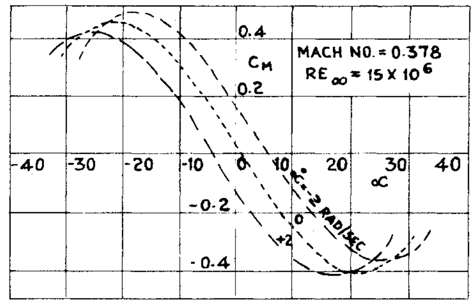


Fig. 8 Plot of C_M vs α for various $\dot{\alpha}$.

unbounded fluid. The differences in the values of C_{L_o} and C_{M_o} between the steady-state values in an unbounded fluid and the preceding values may be primarily ascribed to the strong influence field of the aircraft for $\alpha = \dot{\alpha} = 0$. It must be pointed out here that the coefficients previously determined pertain to the store position after the sixth picture frame, i.e., 0.078 s after release. The sixth frame data were used to work backwards and estimate the installed lift and moment coefficients of the store (first frame). The lift and moment coefficients of the store at release were C_L = −0.97 and C_M = −0.773.

Identification of the drag coefficient C_D from the motion picture is dependent predominantly on an accurate estimation of ξ and, therefore $\ddot{\xi}$. In the short time interval used in these studies, the longitudinal velocity reduction of the store due to aerodynamic drag is somewhat imperceptible so that errors in the measurement of x from the enlarged picture is of the same order as x itself. Consequently, the attempt at identification of the store drag coefficient was abandoned. An alternative method of store drag coefficient determination from flight tests is given by Ramachandra.[8] It may be mentioned here that errors in $\ddot{\xi}$ estimation do not significantly vitiate the identification of C_L since in Eq. (6), C_L contains $\ddot{\xi}\sin\gamma$ where $\gamma \approx$ 2-3 deg, so that the product is negligible compared to the other term.

Analysis of Errors

The usage of experimental data for computation of the coefficients a_1 to a_5 and b_1 to b_6 in Eqs. (9) and (10) will naturally be vitiated by measurement errors in addition to the round-off errors of numerical computation. Furthermore, errors are also introduced by the mathematical or physical model used for the parameter identification analysis. An estimate of the various errors involved in the preceding analysis is given in the following:

Movie Camera Frame Speed

Camera speed enters into the time identification of the individual frames. Although the camera used for the photography has a nominal speed of 64 frames/s, its speed has generally been varying between 56-64 frames/s, giving rise to time-interval variations from 15.6-17.9 ms. While the pitching moment coefficient is unaffected by this frame speed variation, the maximum error introduced into the lift coefficient C_L is estimated at 3%.

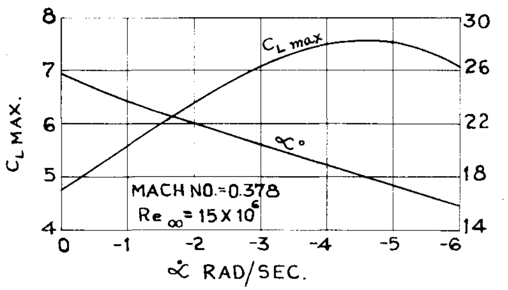


Fig. 9 Plots of $C_{L\max}$ and α for various $\dot{\alpha}$.

Errors in Position Measurement

The entire photographic technique outlined here depends on the precision with which position and angular data of the store relative to the reference point on the aircraft can be determined. In the present case, it has been possible to measure the quantities (x,z,θ) in the photograph only with a tolerance of ± ½ mm in distance and ±2 deg in the angle coorresponding to a maximum error in C_L of between 1-9% and an error of 1-3.5% in C_M. As mentioned earlier, confinement of the flight photography to the vertical plane with a single camera precluded recording of the yawing and transverse motion. Errors introduced by this motion in (x,z,θ) are assumed to be small and ignorable compared to the other errors considered here, as care was taken to use only that segment of the trajectory where the store length was within ±0.5 mm of its value in the first frame.

Aircraft Response

The aircraft was assumed to continue in a steady level flight even after jettison. As shown in Ref. 8, the aircraft experiences a longitudinal and a vertically upward acceleration and a pitching motion due to store jettison. Since the store motion is measured in the aircraft body axis system, these accelerations affect the lift, drag, and pitching moment coefficients. Within the limits of measurement possible here, however, the estimated acceleration of the roundel was less than 1%, considered negligible compared to the store accelerations.

Round-Off Errors

The errors from this cause were checked only in an indirect manner by comparing the observed store flight trajectory with the trajectory estimated by recycling the calculated aerodynamic coefficients. The trajectory deviations were within 2%.

In addition, the results of trajectories for swept wings indicated the presence of pronounced side force and moment on the store at the time of release as has also been reported by other investigators. As mentioned earlier, however, due to the limitations of the photography, this lateral motion is not visible in the picture frames.

Conclusions

The possibility of using a flight vehicle to determine the aerodynamic characteristics of external stores from full-scale drop tests with simple photographic data is established. Analysis of the photographic data shows the presence of large store incidences and high store pitching rates during its free motion. A comparison of the theoretical aerodynamic data with those determined from the flight photograph shows the important effect of the incidence rate $\dot{\alpha}$ in addition to α on both C_L, C_M, and $C_{L\max}$.

References

[1] "DATCOM-USAF Stability & Control Methods," Vol. I., 1968.

[2] Christopher, J., and Costs, J., "Etude en Souffierie des Interactions Aerodynamiques dues aux charges largables," *AGARD Conference Proceedings on Aerodynamic Interference*, No. 71, AGARD CP-71-71, AGARD Fluid Dynamics Panel Specialists Meeting, Silver Springs, Md., Sept. 1970.

[3] Furey, R. J. and Martin, J.J., "A Study of Captive Flight Drag and Separation Characteristics of Lifting Body (Half-Bomb and Half-Pod) Store Configurations," AGARD CP-71-71, Sept. 1970.

[4] Goodwin, F.K., Dillenius, M.F.E., and Nielsen, J.N., "Prediction of Six Degree of Freedom Store Separation Trajectories at Speeds Up to the Critical Speed, Vol. I-Theoretical Methods and Comparisons with Experiment, Vol. II-Users Manual for the Computer Programs," AFFDL-TR-72-8, Oct. 1974.

[5] Kochin, N.E., Kibel, I.A., and Roze, N.V., *Theoretical Hydromechanics,* Inter Science Publishers, N.Y., 1961.

[6] Landers, E.R., Simpson G.J., and Bishop, G., "Store Separation from Aircraft Using a Captive Trajectory Yawmeter System," W.R.E. TN 1522 (WR&D), Oct. 1975.

[7] Marsden, P., and Haines, A.B., "Aerodynamic Loads on External Stores: A Review of Experimental Data and Method of Prediction," R&M No. 3503, 1967.

[8] Ramachandra, S.M., "On the Perturbed Motion of an Aircraft Following Jettisoning of a Store," Aircraft/Stores Compatibility Symposium, Fort Walton Beach, Fla., Oct. 1977.

[9] Ramachandra, S.M., "Comparison of Predicted and Flight Test Trajectories of Stores Jettisoned from Aircraft," *Journal of Aircraft*, Vol. 15, Oct. 1978, pp. 641-642.

[10] Roberts R.H., and Myers, J.R., "Flow Field Characteristics and Aerodynamic Loads on External Stores near the Fuselage and Wing-Pylon Positions of a Swept-Wing/Fuselage Model at Mach numbers of 0.4 and 0.7-Phase V," Rept. No. AEDC-TR-73-87, March 1974.

[11] Sudhakar, K., Kiran, N.S., and Ramachandra, S.M., "Application of Parameter Identification Technique to Aerodynamic Characteristics of a Family of Externally Carried Stores from Drop Tests," *Proceedings of 29th Annual Meeting of Aeronautical Society of India,* Trivandrum, May 1977.