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Force Measurements on a Reflex Cambered Delta Wing

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Abstract

A REFLEX spanwise cambered delta wing with a conical camber designed for $M=1.4$, using the method of Ref. 1, was tested at the design Mach number as well as off-design Mach number $M=0.15$ and 2.3, respectively. The test results are compared with those of a plane wing and also with the available theoretical results at the design condition. At subsonic speed, the cambered wing has less lift at a given incidence and higher lift-to-drag ratio at a given lift than the plane wing, while at supersonic speeds, both of these quantities were less on the cambered wing. At supersonic speed, at the design incidence and Mach number, there is good agreement between results from theory and experiment. The center of pressure on the cambered wing is ahead of that on the plane wing at subsonic speed, while the reverse is true at supersonic speeds. Finally, it is found that over a useful range of lift the cambered wing is aerodynamically more efficient at subsonic speeds, and less so at supersonic speeds, than the plane wing.

Nomenclature

AR	= aspect ratio
C_{D0}	= zero lift/drag coefficient
C_{L0}	= lift at zero incidence
$C_{L\alpha}$	= lift curve slope
C_L, C_D, C_M	= lift, drag, and moment coefficients, respectively
C_r	= root chord
e	$= C_L^2/\pi AR(C_D - C_{D0})$
L/D	$= C_L/C_D$ = lift/drag ratio
$\bar{X}$	= center of pressure distance from apex/C_r
α	= incidence angle
α_{ZL}	= zero lift angle

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Test Program

Force measurement tests were conducted on a plane wing and a reflex spanwise cambered delta wing, both of aspect ratio $AR=1.6$. The mean camber shape was designed, using the method of Ref. 1, to have zero leading-edge suction force at an incidence of 3.74 deg and $M=1.4$. A modified NACA 65A006 section with 3% thickness ratio was used to fabricate the laminated teakwood full models (root chord $C_r=100$ cm) for subsonic tests and brass half models ($C_r=10$ cm) for supersonic tests. At subsonic speed, the tests were conducted in the range $-6\text{ deg}\leq\alpha\leq 20$ deg using a six component strain gage balance in a 14×9-ft open-circuit wind tunnel at Indian Institute of Science (IISc); while at supersonic speeds, a sidewall-mounted three component balance was used to measure the data in the range $-4\text{ deg}\leq\alpha\leq 12$ deg at $M=1.4$ and $-6\text{ deg}\leq\alpha\leq 16$ deg at $M=2.3$, in a 7×5-in. blowdown wind tunnel (IISc). Taking into consideration all possible sources of error, it has been determined that the lift, drag, and moment coefficients are accurate within ±0.5% at subsonic and ±3% at supersonic speeds. During the course of these tests, at subsonic speeds, flow visualization tests as well as force measurements at different yaw angles were also made but not reported here.

Discussion

The wing shapes and the test results at subsonic speed are shown in Figs. 1 and 3b, and those at supersonic speeds in Figs. 2 and 3a. A summary of the results is also given in Table 1. The results presented in the table and figures are self-explanatory, and we will discuss only the salient features, leaving out the details. At subsonic speed, the cambered wing has less C_L at a given α, a positive zero lift angle, and an $(L/D)_{max}$ of 9.9 which is about 50% greater than that of the plane wing. Over a fairly wide range of C_L values (i.e., $0.05\leq C_L\leq 0.6$) the L/D (Fig. 1c) and e (Fig. 3b) values of the cambered wing are higher than those of the plane wing. This large improvement in L/D is due to the reduction in the drag on the cambered wing mainly due to the high suction force, created by leading-edge vortices, acting on the forward drooping portion of the wing. In addition, there is also a reduction in zero lift drag (Table 1). Results similar to the present one were also obtained by Lamar[2] for wings with circular arc conical cambered delta wings in subsonic flow.

In supersonic flow, at the design $M=1.4$ (Fig. 2 and Table 1) the theoretical results in respect of the zero lift angle, C_L at the design incidence of $\alpha=3.74$ deg and C_L at $\alpha=0$, of the cambered wing, as well as the C_L of both the wings, agree well with the test data. In the case of the cambered wing at the design condition, the drag due to lift coefficient (C_{DL}) $=0.039$ from theory plus the test data of $C_{D0}=0.0295$ give a total $C_D=0.0034$ which agrees well with the test result of $C_D=0.033$. Further, as predicted by theory, the camber wing lift is smaller than that of the plane wing, and from test data this is seen to be true even at off-design $M=2.3$. Also from the test data it is seen that α_{ZL} decreases with an increase in speed from subsonic to supersonic range (Table 1). From Fig. 3 we see that the cambered wing has a L/D ratio comparable to that of a plane wing up to $C_L\approx 0.15$ at both the test Mach numbers; but at higher C_L values, it has less L/D than the plane wing. Again from Fig. 3b, considering the e factors of

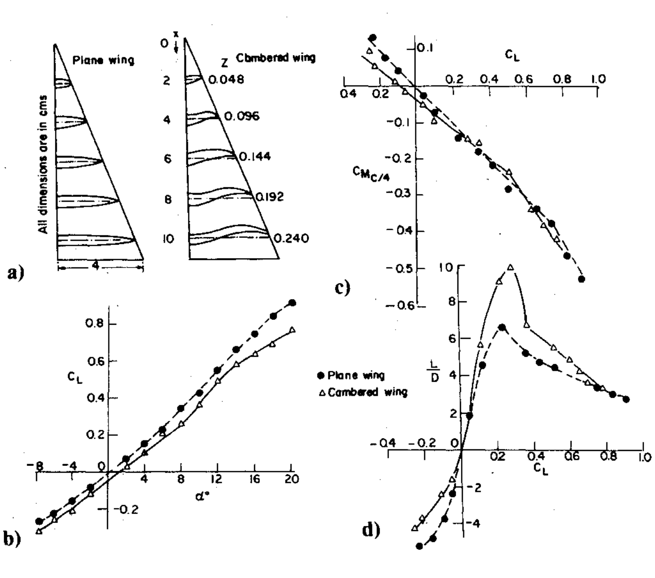

Fig. 1 Wing shapes and aerodynamic characteristics at subsonic speed.

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Table 1 Summary of aerodynamic data of the two wings at the three test speeds

		Plane wing			Cambered wing		
		Subsonic $M=0.15$	$M=1.4$	$M=2.3$	Subsonic $M=0.15$	$M=1.4$	$M=2.3$
α_{ZL}	Theory	0	0	0	2.1 deg	1.02 deg	...
	Experiment	0	0	0	1.2 deg	1.1 deg	0.8 deg
C_{L0}	Theory	0	0	0	−0.02	−0.0383	...
	Experiment	0	0	0	−0.06	−0.042	0.02
C_{L_α} /deg	Theory	0.042	0.0382	0.03	0.042	0.0382	0.03
	Experiment	Nonlinear	0.03650	0.0275	Nonlinear	0.0375	0.0261
C_{D0}	Experiment	0.0252	0.028	0.0219	0.0178	0.0295	0.0256
$(L/D)_{max}$	Experiment	6.7	4.7	4.0	9.9	4.2	3.7
e	Theory	0.849	0.435 (NS)[a] 0.723 (S)[b]	0.35 (NS) 0.428 (S)	0.7837	...	...
	Experiment	0.57-0.62 at C_L up to 0.8	0.5-0.575	0.275-0.525	0.69-0.74 at C_L up to 0.8	0.465-0.53	0.24-0.27
$\bar{X}$		0.75-0.85	0.708	0.65	0.7-0.8	0.72	0.68
Reynolds no.		4.15×10^6	3.9×10^6	3.22×10^6	4.15×10^6	3.9×10^6	3.22×10^6

[a]NS means without leading-edge suction. [b]S means with leading-edge suction.

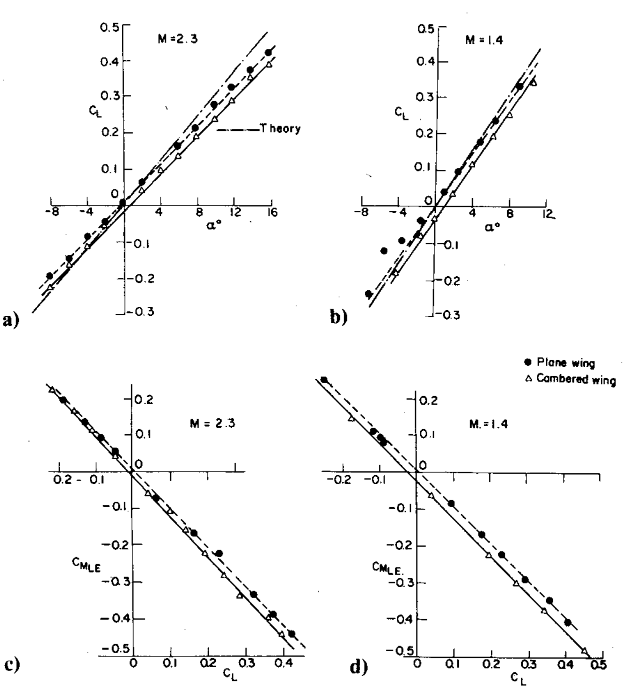

Fig. 2 Lift and moment characteristics at $M=1.4$ and 2.3.

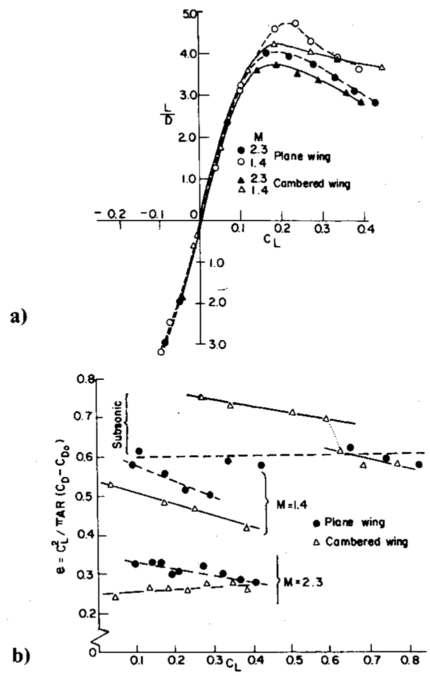

Fig. 3 a) L/D vs C_L at supersonic speeds. b) Aerodynamic efficiency at subsonic and supersonic speeds.

the two wings, it is seen that, unlike the subsonic case, the cambered wing is less efficient than the plane wing in the range of C_L values tested. So we conclude that, considering L/D and e values, while at subsonic speeds the spanwise cambered wing is decidedly superior to the plane wing, the same is not true at off-design conditions at supersonic speeds. Even at the design condition, while L/D is comparable to that of the plane wing, aerodynamically it is less efficient. However, at marginal off-design conditions of α and M, the cambered wing is as good as the plane wing. Finally, a word about the test data for the center of pressure (c.p.) location on the two wings, calculated using appropriate lift and moment coefficient curves (Figs. 1a, 2c, and 2d): At subsonic speed, $\bar{X}$ of the plane wing (Table 1) lies aft of that of the cambered wing, and this is attributed to higher aft load due to more intensive leading-edge separation on the plane wing, as was observed during flow visualization tests. At supersonic speeds, both at the design and off-design Mach numbers, the cambered wing has more aft location of center of pressure than the plane wing, and with an increase in Mach number the c.p. moves forward. This may be due to the diminishing effect of leading-edge separation with an increase in speed in supersonic flow. In fact, in these tests separation effects were not as predominant at supersonic speeds as compared to those at subsonic speed.

Conclusions

1) The reflex cambered wing is aerodynamically more efficient than the plane wing in subsonic flow. 2) Good agreement between theory and experiment was observed at the design Mach number for the cambered wing. 3) In supersonic flow, at the design as well as moderate off-design conditions the cambered wing L/D is comparable to that of the plane wing, but aerodynamically it is less efficient. 4) Both at subsonic and supersonic speeds at comparatively large incidences (high C_L values), the two wings have comparable values of L/D and e, which indicates that camber effects are negligible at those conditions.

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