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Johannes M. Van Aken, University of Kansas, Lawrence, Kansas
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TIP AERODYNAMICS FROM WIND TUNNEL TEST OF SEMI-SPAN WING

Johannes M. Van Aken[1] and Robert H. Stroub

Ames Research Center

SUMMARY

This report presents the results of a low-speed wind tunnel test on a 5.33-aspect-ratio, semi-span wing with 30° and 35° swept tapered tips. The test results include aerodynamic data for the tip itself and for the entire wing including the tip. The metric tip extended inboard 1.58 wing chord lengths. The aerodynamic drag data show the strong influence of tip incidence angle on tip drag for various lift levels. Pitching-moment characteristics show the effect of a moment center at 0.13 c and 0.25 c.

NOMENCLATURE

ALFT, α_t — corrected angle of attack of the tip, deg

ALFW, α_w — corrected angle of attack of the wing, deg

b_t — tip span, m

b_w — wingspan including tip, m

c_t — tip reference chord, m

c_w — wing reference chord, m

CDT — tip drag coefficient, $\frac{\text{DRAG}}{0.5\rho S_t V^2}$

CLLT — tip rolling-moment coefficient about root of the tip, positive tip up, $\frac{\text{ROLLING MOMENT}}{0.5\rho S_t b_t V^2}$

CLLW — wing rolling-moment coefficient about wing root, positive tip up, $\frac{\text{ROLLING MOMENT}}{0.5\rho S_w b_w V^2}$

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[1]University of Kansas, Lawrence, KS.

CLNT — tip yaw-moment coefficient about tip-root quarter-chord point, positive tip aft, $\frac{\text{YAWING MOMENT}}{0.5\rho S_t b_t V^2}$

CLNW — wing yaw-moment coefficient about wing-root quarter-chord point, positive tip aft, $\frac{\text{YAWING MOMENT}}{0.5\rho S_w b_w B^2}$

CLT — tip-lift coefficient, $\frac{\text{LIFT}}{0.5\rho S_t V^2}$

CLW — wing-lift coefficient, $\frac{\text{LIFT}}{0.5\rho S_w V^2}$

CMT — tip pitching-moment coefficient about tip-root quarter-chord point, positive nose up, $\frac{\text{PITCHING MOMENT}}{0.5\rho S_t c_t V^2}$

CMW — wing pitching-moment coefficient about wing-root quarter-chord point, positive nose up, $\frac{\text{PITCHING MOMENT}}{0.5\rho S_w c_w V^2}$

CYT — tip side-force coefficient, positive out right wing, $\frac{\text{SIDE FORCE}}{0.5\rho S_t V^2}$

CYW — wing side-force coefficient, positive out right wing, $\frac{\text{SIDE FORCE}}{0.5\rho S_w V^2}$

CMT AT — tip pitching-moment coefficient about tip-root 0.13-chord line, positive nose up, CMT - 0.12CLT

S_t — tip planform area, m^2

S_w — wing planform area, m^2

TIP ANGLE — tip incidence angle relative to inboard portion of wing, deg

α_t — corrected angle of attack of tip, deg

$\Lambda_{c/4}$ — quarter-chord sweep angle of tip outer region, deg

ρ — air density, kg/m^3

INTRODUCTION

A determination of the aerodynamic characteristics of the tip region was required for the design of a free tip for rotor blades. The free-tip concept requires the tip to be able to weathervane into the local relative wind as a way of correcting for velocity perturbations in magnitude and direction. This weathervaning capability is a direct function of the aerodynamic pitching-moment characteristics about the tip's pitch axis; hence, the tip pitching-moment characteristics were a key factor in the design of the free tip. The overall purpose of the aerodynamic investigation was to determine the pitching-moment characteristics of several tip configurations as an aid in designing a free-tip configuration. The free-tip configuration would be incorporated into a rotor system that would be tested in a wind tunnel to evaluate benefits of the concept.

The direct simulation of a tip on the end of a rotor blade in forward flight was not achievable with a wind tunnel test of a semi-span wing. However, the aerodynamic data from a semi-span wing test would provide sufficient data to significantly aid in the design. Of particular importance would be the data obtained with the tip at positive and negative incidence angles relative to the inboard portion of the wing. Positive and negative incidence angles of the free tip were predicted in the analytical studies reported in reference 1.

A series of wind tunnel tests were undertaken to investigate the aerodynamic characteristics of several candidate tip configurations. The tip configurations tested encompassed numerous combination of tip-chord taper and sweep; two configuration parameters that would greatly affect the dynamic characteristics of the free tip. The purpose of this report is to present the test data for two tip planforms. The test data support the analysis of the results from the test of the first successful free-tip rotor (FTR) configuration (ref. 2).

MODEL DESCRIPTION

The geometric data for both the wing and the tip are presented in figure 1 and in table 1. Two swept-tip configurations were tested: a 30° swept tip and a 35° swept tip. Both swept tips had the same planform area and chord taper. Coordinates for the modified NACA 23010 airfoil are presented in table 2.

The tips were mounted on an internal strain-gage balance whose base was mounted inside the inboard portion of the wing. Figure 2(a) shows the strain-gage balance arrangement. The tip strain-gage balance was located at the quarter chord of the root section of the tip. The tip incidence angle could be indexed at -5°, 0°, and +5° relative to the inboard portion of the wing. When the tip was indexed, it was pivoted about the strain-gage balance since the balance was fixed relative to the wing. The gap between the tip and the inboard section was unsealed. Previous tests with this model arrangement had shown that sealing the gap with grease resulted in no measurable data change; therefore, no significant pitching moment or drag penalty was expected.

MODEL INSTALLATION

The semi-span wing was mounted on an internal strain-gage balance whose base was attached to the wind tunnel scale system underneath the tunnel floor. The wing jutted through the floor, and through a boundary-layer splitter plate (fig. 2(b)). The splitter plate was nonmetric; hence, there was a large gap between the wing and the splitter plate. In the gap, a soft, nonporous foam was installed to prevent intrusion of flow from outside the wind tunnel.

TEST CONDITIONS

The conditions of the test were dynamic pressure, 2154 Pa; Mach number, 0.176; and Reynolds number, 4.06×10^6/m.

DATA REDUCTION

Tip aerodynamic characteristics were measured with an internal strain-gage balance inside the tip as shown in figure 2(a). With this arrangement, tip airloads were directly measured without the measurement system causing any interference to the tip data. The metric tip region is depicted as the black portion of the wing shown in figure 2(b). The wing was attached to a second, internal, strain-gage balance located under the tunnel floor. The strain gage balanced the measured forces and moments in the body-axis system; these forces and moments were transformed to the wind-axis system for presentation. The forces and moments were referred to the respective moment centers for the wing and for the tip. The moment center for the wing was at the root of the exposed wing on the wing quarter-chord line. The tip moment center was at the root of the tip on the quarter-chord line.

For the tip and the wing, the forces and moments are considered to be from a left wing. Figure 3 presents the force and moment nomenclature. Two corrections were applied to the data. First, corrections were applied that account for the torsion deflection of the tip balance as it affected resolution of the forces and moments into the wind-axis system. Second, standard wall corrections for blockage and angle of attack (ref. 3) were applied to the data.

RESULTS

The test data are presented in both graphs and tables. Tabulated data for both swept tips are presented in tables 3 and 4 for the 30° swept tip and the 35° swept tip, respectively. Lift, drag, and pitching-moment data are presented in figure 4 for the 30° swept tip, and in figure 5 for the 35° swept tip. The effect of deflecting the tip relative to the inboard section of the wing for tip incidence angles of -5°, 0°, and 5° is presented in figure 5. The major importance of incidence angle is its effect on the tip drag characteristics. At negative incidence angles and positive wing lift, the drag of the tip is less than at zero incidence angles. Conversely, at positive incidence angle and positive wing lift, the drag is greater than at zero angle.

Pitching-moment data referred to the 0.13 chord line are also presented. This shows the influence of having the pitch axis forward of the quarter chord. This pitch-axis location is the same as the FTR configuration.

CONCLUSIONS

A low-speed wind tunnel test of a semi-span wing showed the drag of a tip to be sensitive to its incidence angle and to its lift coefficient. In addition, the test showed that the chordwise location of the moment center had a strong influence on tip pitching-moment variation with tip lift coefficient.

REFERENCES

1. Stroub, Robert H.: Performance Improvements With the Free Tip Rotor. Paper I-4, Amer. Helicopter Soc. National Specialists' Meeting, Rotor System Design, Philadelphia, PA, Oct. 1980.

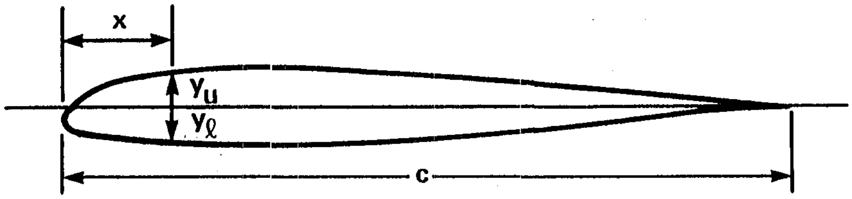
2. Stroub, Robert H.: Analysis of the Free-Tip Rotor Wind Tunnel Test Results. NASA TM-86751, 1985.

3. Pope, Alan: Wind Tunnel Testing. John Wiley & Sons, Inc., New York, 1954.

TABLE 1.- WING AND TIP GEOMETRICAL DATA

Wing (including tip)	
Span, m	1.053
Reference chord, m	.198
Root chord, m	.209
Planform area, m^2	.208
Tip	
Span, m	0.312
Reference chord, m	.170
Chord at root, m	.209
Planform area, m^2	.053
Swept section of tip	
Span, m	.163
Chord at root, m	.209
Chord at tip, m	.063
Quarter chord sweep angle	30°, 35°
Taper ratio	0.3

TABLE 2.- AIRFOIL COORDINATES FOR MODIFIED NACA 23012 AIRFOIL



x/c	y_u/c	y_ℓ/c	x/c	y_u/c	y_ℓ/c
0.0	-0.0225	-0.0225	0.43	0.0465	-0.0487
.005	-.0078	-.0329	.47	.0446	-.0468
.01	-.0024	-.0362	.51	.0424	-.044
.015	.0019	-.0378	.55	.0397	-.0412
.025	.0096	-.0394	.59	.0369	-.038
.035	.0155	-.0404	.63	.0336	-.0346
.047	.0214	-.0412	.67	.0301	-.0308
.06	.0265	-.042	.71	.0263	-.0269
.08	.0327	-.0434	.75	.0223	-.0226
.11	.0396	-.0449	.79	.0181	-.0182
.15	.0455	-.0471	.83	.0137	-.0136
.19	.0489	-.0494	.87	.0093	-.0093
.23	.0499	-.0513	.91	.0056	-.0057
.27	.0499	-.0522	.945	.0028	-.0031
.31	.0497	-.05215	.96	.00235	-.00235
.35	.049	-.0517	1.0	.00235	-.00235
.39	.048	-.0505			

Leading edge radius, r/c = 0.0158
Center of leading edge circle at x/c = 0.0158, y/c = -0.0225

TABLE 3.- AERODYNAMIC CHARACTERISTICS OF THE WING ANDD OF THE TIP WITH 30° SWEEP

Run 44 Tip 27 Tip angle -5.0 $\Lambda_{c/4}$ = 30°

NO	ALFW	ALFT	CDW	CYW	CLW	CLLW	CMW	CLNW	CDT	CYT	CLT	CLLT	CMT	CLNT
5	-0 5	-5.5	0.013	-0.003	-0.10	-0.13	-0.009	-0.008	0.024	0.000	-0.29	-0.13	0.013	-0.009
6	1.5	-3.3	.012	.000	.04	.01	-.077	-.006	.016	.002	-.14	-.06	-.001	-.005
7	2.5	-2.3	.012	.011	.12	.03	-.042	-.006	.013	.005	-.06	-.03	-.007	-.004
8	3.5	-1.3	.013	.004	.18	.11	-.074	-.007	.013	.006	-.00	-.01	-.011	-.004
9	4.6	-.3	.014	.004	.25	.16	-.040	-.007	.011	.008	.08	.03	-.018	-.003
10	5.6	.7	.017	.030	.36	.16	.044	-.009	.012	.010	.11	.04	-.023	-.003
11	6.6	1.7	.021	.008	.44	.23	.082	-.005	.014	.012	.18	.07	-.026	-.003
12	7.7	2.7	.026	.007	.58	.23	-.046	-.010	.015	.012	.25	.10	-.035	-.003
13	9.7	4.7	.036	.012	.68	.33	-.074	-.020	.023	.015	.41	.17	-.047	-.006
14	11.7	6.8	.051	.022	.84	.40	-.059	-.017	.031	.014	.57	.23	-.062	-.007
15	13.8	8.8	.072	.028	.98	.49	-.062	-.026	.033	.011	.69	.29	-.077	-.008
16	15.8	10.8	.088	.030	1.09	.57	-.110	-.048	.044	.001	.83	.35	-.092	-.011
17	17.8	12.8	.141	.037	1.14	.48	-.139	-.073	.065	-.007	.90	.39	-.100	-.018
18	19.8	14.8	.165	.028	1.14	.46	-.147	-.100	.105	-.018	1.02	.44	-.113	-.028
19	-.5	-5.5	.013	-.007	-.06	-.13	.010	-.032	.025	-.000	-.31	-.13	.014	-.010
20	-2.6	-7.5	.029	-.008	-.28	-.19	-.019	-.022	.048	.000	-.44	-.19	.026	-.020
21	-4.6	-9.6	.053	-.020	-.36	-.32	-.029	-.039	.079	.001	-.54	-.23	.046	-.033
22	-6.6	-11.6	.097	-.013	-.56	-.32	-.058	-.062	.130	.001	-.64	-.27	.116	-.055
23	-.5	-5.5	.017	.006	-.17	-.07	-.008	-.012	.024	.001	-.28	-.12	.011	-.008
24	-.5	-5.5	.017	-.009	-.12	-.10	-.016	-.009	.024	.000	-.29	-.13	.013	-.009

TABLE 3.- CONTINUED.

Run 45 Tip 29 Tip angle 0.0 $\Lambda_{c/4} = 30°$

NO	ALFW	ALFT	CDW	CYW	CLW	CLLW	CMW	CLNW	CDT	CYT	CLT	CLLT	CMT	CLNT
5	-0.5	-0.3	0.010	0.000	-0.03	0.05	-0.053	-0.007	0.010	0.004	-0.08	-0.03	-0.002	-0.003
6	.5	.7	.010	.004	-.01	.04	-.069	-.009	.012	.005	-.00	.00	-.011	-.003
7	1.5	1.7	.012	.004	.15	.03	-.037	-.006	.013	.006	.07	.03	-.019	-.003
8	2.6	2.7	.011	.000	.21	.10	-.134	-.006	.015	.007	.14	.06	-.026	-.003
9	3.6	3.7	.012	-.002	.28	.16	-.045	-.008	.019	.008	.20	.08	-.031	-.004
10	5.6	5.7	.022	.021	.47	.23	-.084	-.009	.028	.007	.37	.16	-.050	-.006
11	7.7	7.8	.032	.011	.61	.33	-.085	-.015	.038	.006	.51	.22	-.066	-.009
12	9.7	9.8	.043	.015	.77	.38	-.107	-.017	.050	.001	.64	.27	-.086	-.012
13	11.8	11.8	.060	.017	.97	.45	-.149	-.027	.051	-.010	.81	.36	-.107	-.011
14	13.8	13.8	.078	.014	1.04	.57	-.107	-.034	.073	-.018	.91	.40	-.119	-.017
15	15.8	15.8	.100	.020	1.17	.62	-.107	-.054	.097	-.035	1.07	.47	-.139	-.023
16	17.8	17.8	.153	.036	1.18	.51	-.138	-.110	.191	.020	1.03	.41	-.147	-.084
17	.5	.7	.008	.004	.13	-.04	-.101	-.029	.012	.004	.02	.01	-.013	-.003
18	-.5	-.3	.008	.007	-.00	-.06	-.032	-.030	.011	.003	-.06	-.03	-.004	-.002
19	-1.5	-1.5	.009	-.020	-.05	-.14	-.030	-.017	.011	.003	-.12	-.05	.000	-.002
20	-2.6	-2.5	.013	-.026	-.21	-.12	-.080	-.016	.010	.002	-.20	-.08	.008	-.002
21	-3.6	-3.5	.022	-.019	-.27	-.17	-.041	-.023	.011	.002	-.29	-.12	.020	-.004
22	-4.6	-4.5	.034	-.024	-.35	-.22	-.041	-.023	.016	.002	-.35	-.14	.026	-.006
23	-6.6	-6.5	.069	-.010	-.50	-.30	-.077	-.050	.034	.003	-.50	-.20	.042	-.015
24	-8.7	-8.6	.122	-.019	-.60	-.33	-.037	-.054	.068	.003	-.59	-.24	.066	-.030
25	-.5	-.3	.012	-.003	-.10	.01	-.038	-.006	.011	.004	-.05	-.02	-.005	-.003
26	-.5	-.3	.015	-.024	-.06	-.03	-.025	.027	.010	.004	-.06	-.02	-.005	-.003

TABLE 3.- CONCLUDED.

Run 43 Tip 27 Tip angle 5.0 $\Lambda_{c/4} = 30°$

NO	ALFW	ALFT	CDW	CYW	CLW	CLLW	CMW	CLNW	CDT	CYT	CLT	CLLT	CMT	CLNT
5	-0.5	4.7	0.016	0.009	0.07	0.02	-0.073	-0.008	0.019	0.007	0.15	0.07	-0.022	-0.005
6	1.6	6.7	.021	.017	.23	.10	-.099	-.007	.031	.006	.30	.13	-.035	-.008
7	3.6	8.7	.025	.025	.43	.16	-.074	-.014	.042	.004	.45	.20	-.049	-.012
8	5.7	10.8	.035	.034	.59	.25	-.115	-.018	.057	.000	.58	.26	-.064	-.017
9	7.7	12.8	.045	.016	.73	.36	-.175	-.023	.073	-.007	.73	.33	-.083	-.021
10	9.7	14.8	.057	.014	.85	.46	-.151	-.027	.095	-.017	.85	.38	-.097	-.027
11	11.7	16.8	.077	.036	.85	.65	-.187	-.041	.160	.012	.92	.39	-.115	-.069
12	13.7	18.8	.114	.033	.84	.77	-.125	-.058	.205	.025	.97	.39	-.131	-.089
13	15.8	20.8	.148	.058	1.29	.50	-.179	-.088	.246	.040	.95	.36	-.151	-.103
14	11.8	16.8	.090	.064	1.14	.39	-.164	-.060	.158	.012	.93	.39	-.116	-.069
15	-.4	4.7	.018	.018	.23	.00	-.044	-.014	.018	.006	.22	.10	-.028	-.005
16	-2.5	2.7	.020	-.002	-.02	-.14	-.071	-.014	.011	.007	.02	.02	-.012	-.003
17	-3.5	1.7	.026	.012	-.11	-.17	-.085	-.028	.009	.006	-.04	-.01	-.007	-.003
18	-4.6	.7	.035	.002	-.22	-.19	-.125	-.021	.009	.007	-.10	-.03	-.002	-.003
19	-5.6	-.5	.046	-.006	-.28	-.22	-.085	-.025	.008	.007	-.18	-.06	.003	-.003
20	-6.6	-1.5	.060	.009	-.35	-.30	-.099	-.033	.006	.008	-.26	-.10	.009	-.002
21	-7.6	-2.5	.087	.006	-.48	-.26	-.035	-.044	.009	.009	-.36	-.14	.019	-.004
22	-8.6	-3.5	.113	-.011	-.50	-.28	-.117	-.041	.015	.009	-.39	-.15	.024	-.007
23	-10.6	-5.6	.139	.026	-.49	-.34	-.093	-.057	.035	.008	-.51	-.20	.041	-.017
24	-.5	4.7	.019	.019	.05	.05	-.118	-.006	.015	.007	.14	.07	-.022	-.005
25	-.5	4.7	.019	.013	.08	.02	-.113	-.004	.016	.007	.16	.07	-.022	-.005

TABLE 4.- AERODYNAMIC CHARACTERISTICS OF THE WING AND OF THE TIP WITH 35° SWEEP

Run 42 Tip 27 Tip angle 0.0 $\Lambda_{c/4}$ = 35°

NO	ALFW	ALFT	CDW	CYW	CLW	CLLW	CMW	CLNW	CDT	CYT	CLT	CLLT	CMT	CLNT
5	-0.5	-0.3	0.010	-0.004	-0.03	-0.04	-0.075	-0.008	0.010	0.005	-0.05	-0.02	-0.008	-0.003
6	1.5	1.7	.012	.000	.09	.08	-.013	-.003	.012	.007	.11	.05	-.021	-.003
7	3.6	3.7	.012	-.006	.28	.16	-.096	-.005	.016	.008	.22	.09	-.030	-.004
8	5.6	5.7	.018	.011	.40	.28	-.091	-.015	.027	.008	.37	.16	-.042	-.007
9	7.7	7.8	.030	.005	.60	.33	-.117	-.012	.038	.007	.53	.23	-.059	-.010
10	9.7	9.8	.043	.004	.77	.40	-.107	-.018	.048	.003	.63	.28	-.076	-.013
11	11.7	11.8	.063	.005	.93	.48	-.135	-.021	.062	-.004	.80	.35	-.089	-.017
12	13.8	13.8	.082	.009	1.06	.57	-.072	-.028	.075	-.014	.93	.41	-.104	-.022
13	15.8	15.8	.118	.023	1.17	.61	-.103	-.075	.148	.016	.99	.41	-.119	-.086
14	17.8	17.8	.161	.034	1.18	.51	-.149	-.106	.195	.026	1.01	.40	-.134	-.087
15	15.8	15.8	.114	.019	1.18	.60	-.083	-.074	.153	.017	.99	.41	-.123	-.069
16	.5	.7	.008	-.010	.07	.02	-.062	-.036	.011	.005	.02	.01	-.012	-.003
17	-.5	-.3	.007	-.005	-.04	-.02	-.049	-.031	.011	.004	-.05	-.02	-.008	-.003
18	-1.5	-1.3	.009	-.023	-.06	-.12	-.011	-.020	.011	.003	-.12	-.05	-.002	-.002
19	-2.6	-2.5	.014	-.030	-.22	-.11	-.037	-.022	.012	.003	-.18	-.07	.002	-.003
20	-4.6	-4.5	.033	-.041	-.34	-.21	-.049	-.024	.014	.003	-.33	-.13	.015	-.005
21	-6.6	-6.5	.067	-.021	-.52	-.29	-.051	-.048	.036	.003	-.49	-.20	.034	-.015
22	-8.7	-8.6	.122	-.023	-.60	-.31	-.036	-.062	.070	.005	-.59	-.24	.056	-.030
23	-.5	-.3	.010	-.010	-.09	-.01	-.092	-.010	.011	.005	-.04	-.02	-.007	-.003
24	-.5	-.3	.012	-.010	-.07	-.00	-.029	-.009	.011	.004	-.06	-.02	-.006	-.003

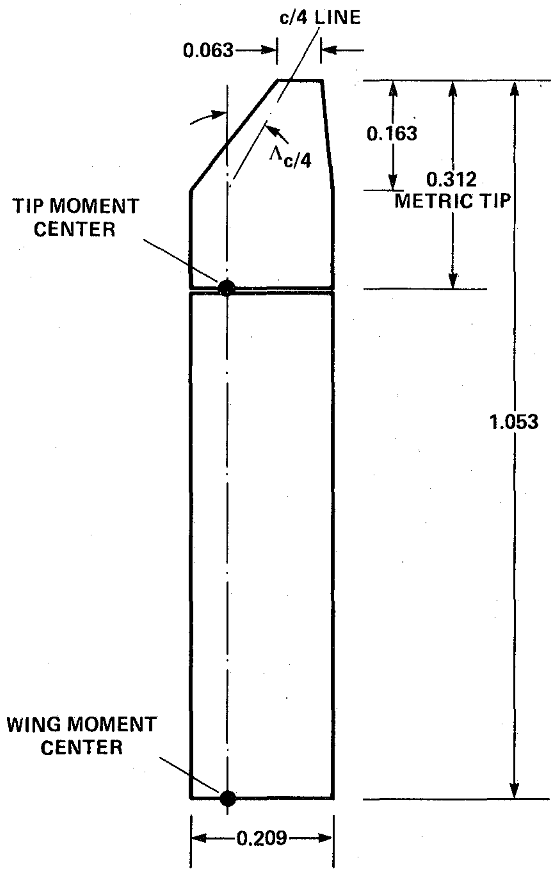
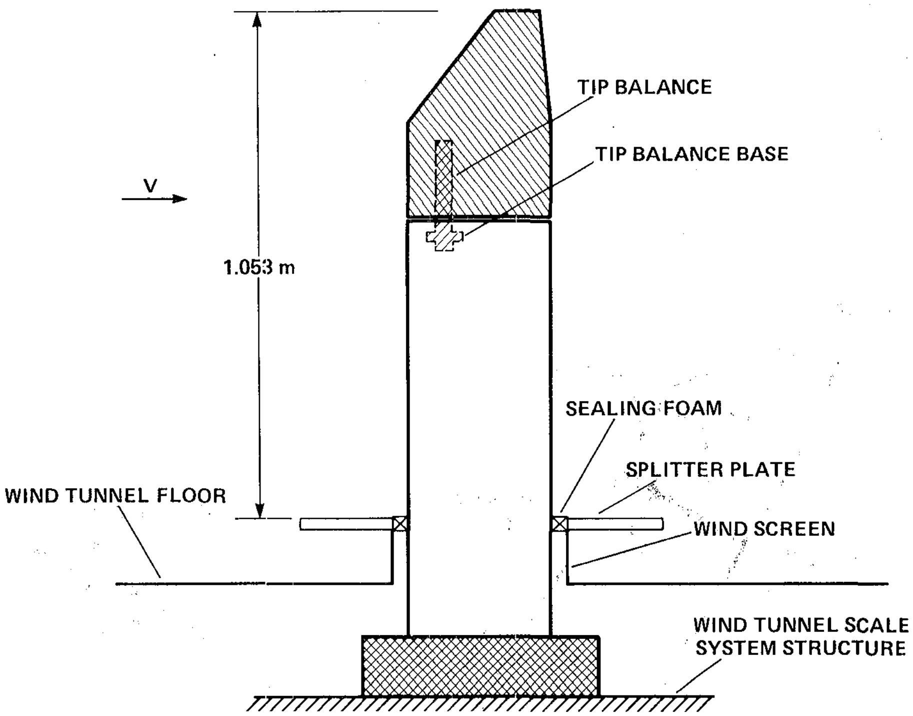
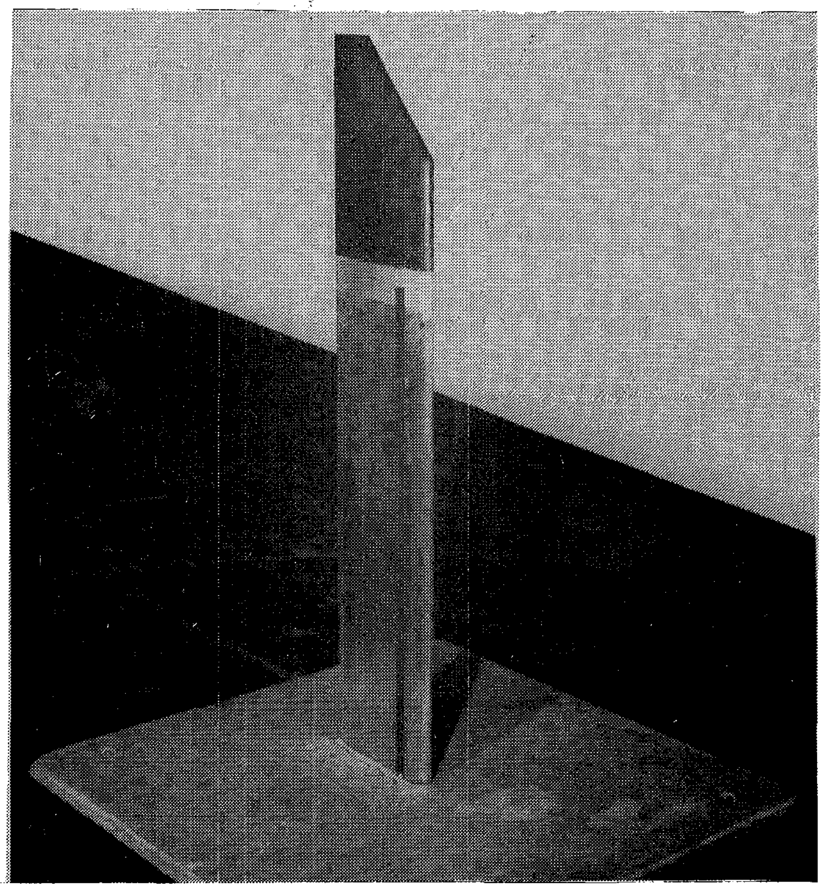


Figure 1.- Wing and tip geometric data.

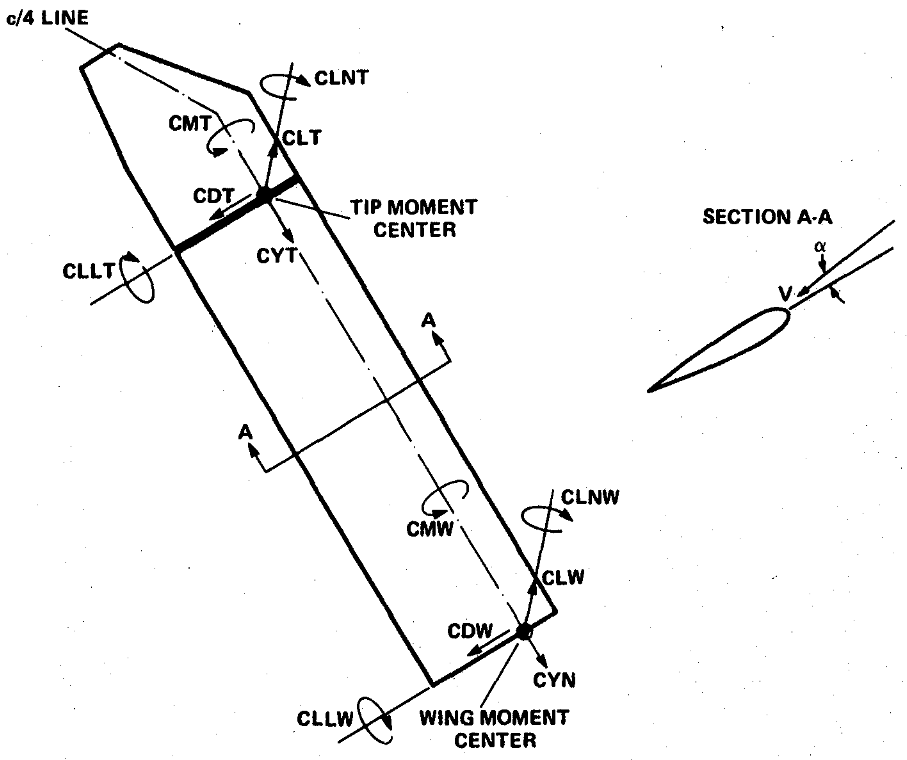


(a) Strain-gage balance arrangement and model installation.



(b) Semi-span wing installation in wind tunnel.

Figure 2.- Semi-span wing.



NOTE: Left wing configuration. Arrows indicate positive direction of forces, moments, and angular displacement.

Figure 3.- Force and moment nomenclature.

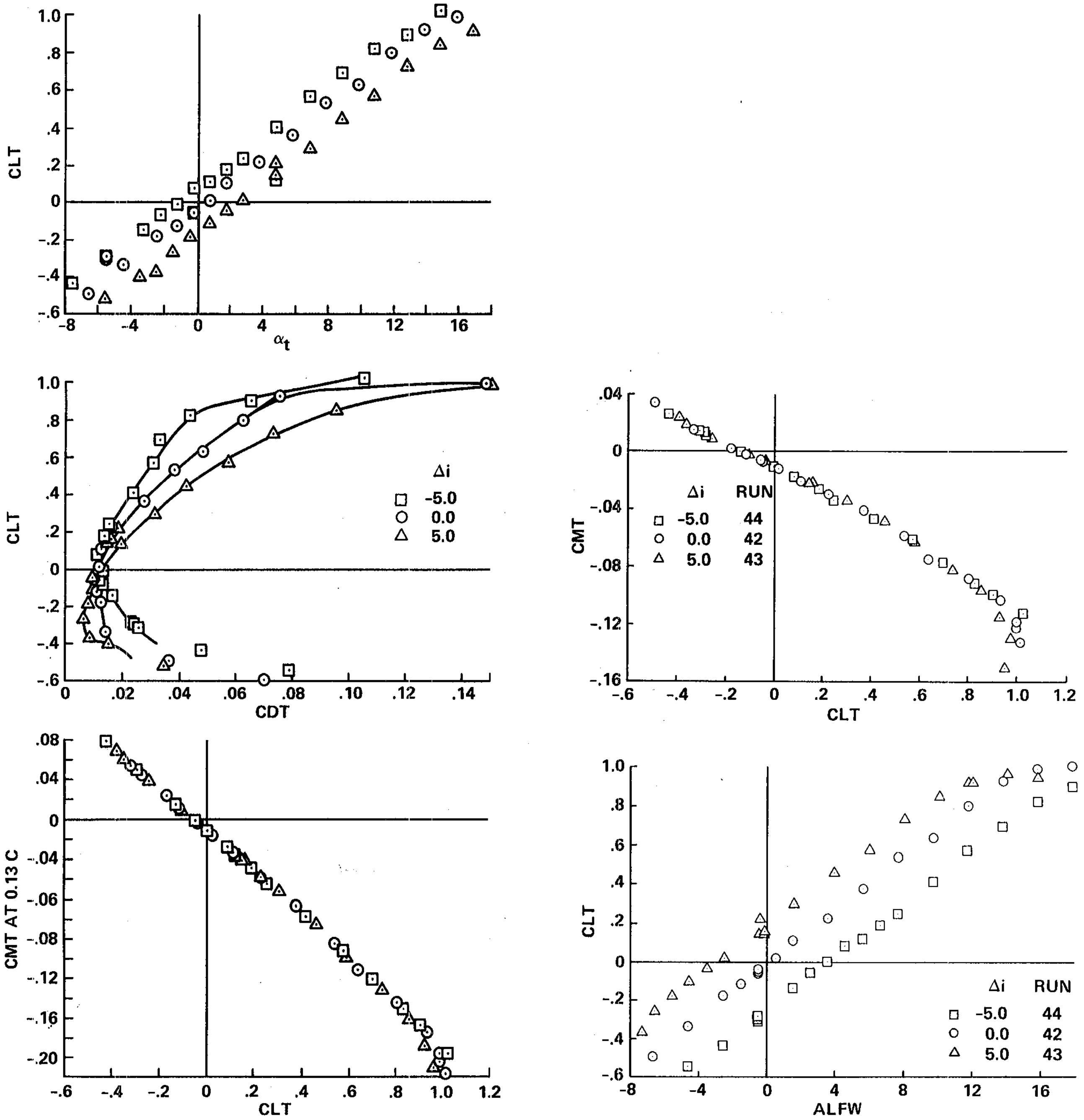


Figure 4.- Lift, drag, and pitching-moment characteristics of the 30° swept tip at -5°, 0°, and +5° incidence angles.

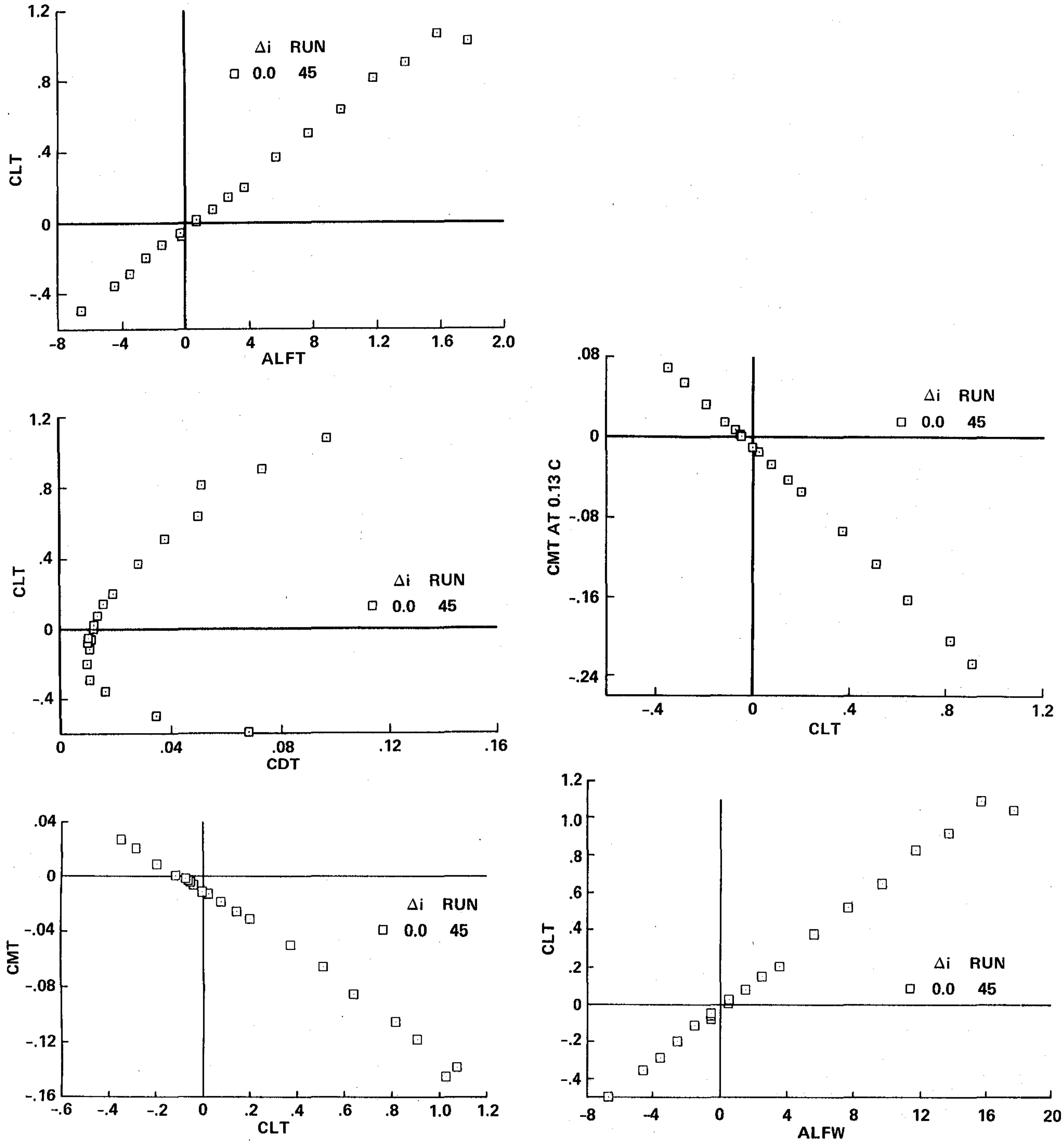


Figure 5.- Lift, drag, and pitching-moment characteristics of the 35° swept tip at zero incidence angle.

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Moffett Field, CA 94035 (415) 694-6732 or FTS 464-6732

16. Abstract

This report presents the results of a low-speed wind tunnel test on a 5.33-aspect-ratio, semi-span wing with 30° and 35° swept tapered tips. The test results include aerodynamic data for the tip itself and for the entire wing including the tip. The metric tip extended inboard 1.58 wing chord lengths. The aerodynamic drag data show the strong influence of tip incidence angle on tip drag for various lift levels. Pitching-moment characteristics show the effect of a moment center at 0.13 c and 0.25 c.

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