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An Investigation of the Effect of Aspect Ratio on the Airfoil Performance

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Abstract: The effect of aspect ratio on the airfoil performance is investigated for airflow about axially symetric wings as a function of the angle of attack. The magnitudes of aerodynamic forces and moments on airfoils resulting from the incompressible viscous flow fields are determined experimentally. The TE54 wind tunnel used for the experiments is an open conduit and has a 300x300 mm x-section with a closed test chamber. The TE81 digital measurement device is used which has three components. Three different types of airfoil profiles are tested under the airflow speed of 33.76 m s^{1} and it is concluded that the airfoil with the aspect ratio of 2.761 yields the optimum performance.

Key words: Airfoil, Drag Coefficient, Air Flow, Airfoil Performance

INTRODUCTION

The lifting surface of an immersed body may be defined as a tool which developes a useful reaction force during its motion relative to the fluid. The surfaces of wings and tails of aeroplanes, propellers and blades of turbomachinary are some of the examples of lifting surfaces. The optimum design of a lifting surface yields the production of the maximum possible lift force and the production of the minimum possible drag force in directions perpendicular to the direction of motion. Some studies dealing with the numeric solution of the fluid flow around wings exists, for example [1-3]. In these studies the Allen method is used which is an extension to the potential flow theory. In the following investigations [4, 5] bondary layer and potential flow theories are considered together. Obayashi and Takanashi used the genetic optimization method for the optimization of pressure distribution over wings [6]. Using numerical methods Raughunathan and Mitchell determined the effect of heat transfer in transonic flow about the NACA 0012 airfoil [7]. Kerho and Bragg [8] investigated the effect of surface roughness on the attack side of an airfoil on the formation of a boundary layer. Yılmaz [9, 10] experimentally investigated the performance of NACA 0012 profile with three different aspect ratios at different subsonic flow speeds in the wind tunnel. Caroglia and Jones [11] investigated a methodology for the experimental axtraction of indicial functions for streamlined and bluff deck sections. In the present study, the lift, drag and moment coefficients of three different profiles at the fow speed of 33.76 m s^{1} are determined using experimental data. Hence, an optimum airfoil is obtained for the corresponding flow speed.

Theoretical Framework: Lift force L acting on an airfoil about which a uniform flow exists is defined by

$$L = \rho\, U\, \Gamma, \qquad (1)$$

Where, ρ is the air density, U is the cross-flow velocity of air, Γ is the circulation that occurs around the airfoil profile.

Circulation around the airfoil develops only in the case of nonsymmetric flow. The reason of the change of symmetry of flow is the angle of attack and the curvature of airfoil.

Lift force and pitching moment are respectively defined by:

$$L = \int_0^c (P_2 - P_1)dx\ , \qquad (2)$$

$$M = -\int_0^c (P_2 - P_1)x dx \cdot \qquad (3)$$

Here, c denotes the chord length of airfoil, P_1 and P_2 denote respectively the pressure functions on the upper and lower surfaces of airfoil.

Pressure difference between the lower and and upper surfaces is expressed as a function of the curvature $\gamma(x)$ as follows:

$$P_2 - P_1 = \quad P \quad \cong \quad U \ (x) \qquad (4)$$

Equations (4), (2) and (3) are used to derive the expressions of lift and pitching moment:

$$L = \ U\int_0^c \ (x)dx \qquad (5)$$

$$M = - \ U\int_0^c \ (x)x dx \qquad (6)$$

Steady-state or mean vertical lift (assumed vertical with respect to the relative wind direction) (Fig. 1) can be described by the expression

$$L=\frac{1}{2}\,U^2AC_L, \tag{7}$$

Where, A is plane surface of airfoil (A=bc), b and c are wingspan and chord length respectively. C_L is the static lift coefficient with respect to the angle of attack α. C_L is expressed using (7) as follows:

$$C_L=\frac{L}{\frac{1}{2}\,U^2A}. \tag{8}$$

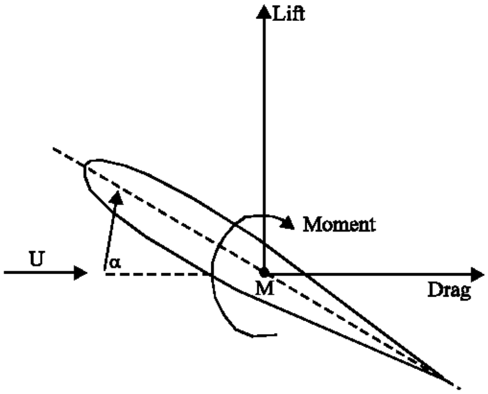

Fig. 1: Steady-state Forces on an Airfoil—M Mid-chord

MATERIALS AND METHODS

Three different types of wing profiles with different aspect ratios are tested in the TE54 type of a wind tunnel which has a 300x300 mm x-section (Fig. 2). Aspect ratio AR is the dinensinless ratio, AR = b / c. The airfoils are tested at the air flow speed of 33.76 m s^{1} at different attack angles. Lift and drag forces exerted on the wing profiles are measured by the use of the digital measurement device TE81 which has a three directional measurement capability. Air flow speed is measured in the experimental setup by the use of the total and static pressure tubes and is computed by:

$$U=\sqrt{\frac{(H_2-H_1)*9.81*2}{}} \tag{9}$$

Here H_2 denotes the total pressure as it is the water height in the tube and measured in mm and H_1 denotes the static pressure in mm.

For the determination of lift force the data are recorded as FORE and AFT on the TE81 measurement device and DRAG data is recorded for the determination of drag force. The experimental data is used to obtain the lift force and the pitching moment.

Lift force which reads in Newtons is:

$$L= AFT + FORE \tag{10}$$

Pitching moment M in N.m is:

$$M= 0.127*(FORE-AFT) \tag{11}$$

The factor 0.127 in equation (11) is the magnitude of momoent arm.

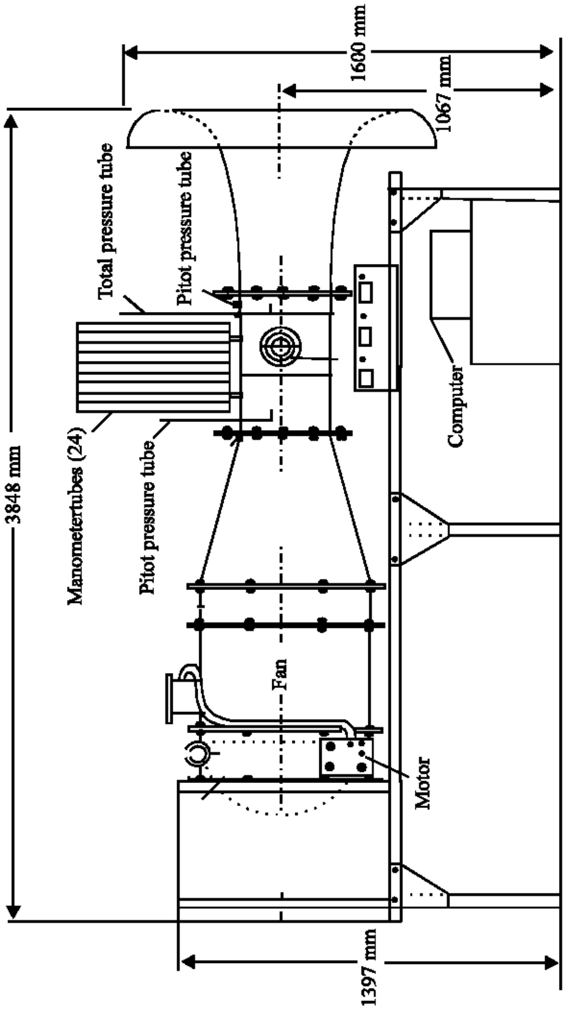

Fig. 2: Schematic View of the Wind Tunnel

Drag force D in Newtons is:

$$D = DRAG \tag{12}$$

It is more practical to use certain nondimensional coefficients rather than the magnitudes of forces and moments for the optimization of wings. Static lift coefficient was defined by (8) and other nondimensional coefficients are similarly defined which are, respectively, the coefficient of drag C_D and the coefficient of moment C_M. The two coefficients are defined as follows:

$$C_D = \frac{D}{\frac{1}{2}\ U^2 A} \qquad (13)$$

$$C_M = \frac{M}{\frac{1}{2}\ U^2 Ac} \qquad (14)$$

RESULTS AND DISCUSSION

NACA 0012 type wing profiles with three different aspect ratios are tested in the TE54 type wind tunnel at the air flow speed of 33.76 m s ^{1}. Data measured using the TE81 type digital measurement device are substituted in equations (10-12) and the magnitudes of the lift force, the drag force and the pitching moment are computed.

Data presented in Table 1-3 are substituted in eq. 8, 13 and 14 to obtain the magnitudes of certain nondimensional coefficients. The coefficients obtained for the three profiles are given in Table 4-6. The two coefficients used for the optimization of wings are the coefficient of efficiency C_E which is defined by:

$$C_E = \frac{C_L}{C_D} \qquad (15)$$

and the coefficient of performance C_P which is

$$C_P = \frac{C_L^{1.5}}{C_D} \qquad (16)$$

Variations of the cofficients of efficiency and performance are tabulated in Table 7 and 8.

A comparison of the lift coefficients of profiles is shown in Fig. 3 and the variations of the coefficients of efficiency and performance are respectively, shown in Fig. 4 and 5.

Table 1: Variation of Force and Moment in the NACA 0012 Profile (AR= 1.9474)

α, °	L, N	D, N	-M, Nm
0	0.84±0.1	0.59±0.01	0.033±0.003
2	6.94±0.3	0.91±0.03	0.031±0.004
4	14.43±0.1	1.21±0.01	0.077±0.012
6	21.65±0.1	1.56±0.02	0.148±0.016
8	27.43±0.1	1.96±0.03	0.180±0.019
10	32.75±0.2	2.51±0.06	0.210±0.029
12	36.05±0.7	3.95±0.10	0.328±0.098
14	34.85±0.6	7.62±0.15	0.938±0.071
16	34.71±0.6	9.86±0.10	1.181±0.100
18	34.00±0.3	12.27±0.06	1.322±0.049
20	33.85±0.5	13.91±0.13	1.437±0.064

Table 2: Variation of Force and Moment in the NACA 0012 Profile(AR = 2.761)

α, °	L, N	D, N	-M, Nm
0	0.75	0.39	0.001
2	9.63	0.43	0.044
4	20.89	0.63	0.004
6	30.06	0.84	0.043
8	37.14	1.24	0.178
10	43.30	1.74	0.343
12	38.97	8.21	0.690
14	32.72	10.59	1.102
16	31.37	12.07	1.121
18	30.15	13.46	1.120
20	29.20	15.28	1.135

Table 3: Variation of Force and Moment in the NACA 0012 Profile (AR=3.0198)

α, °	L, N	D, N	-M, Nm
0	2.86±0.07	0.38±0.01	0.038±0.018
2	8.37±0.13	0.46±0.02	0.067±0.011
4	13.76±0.07	0.52±0.03	0.107±0.009
6	18.10±0.07	0.70±0.02	0.121±0.006
8	21.85±0.29	1.04±0.04	0.126±0.032
10	22.70±0.90	2.43±0.40	0.285±0.117
12	21.72±0.45	4.48±0.07	0.397±0.057
14	21.27±0.41	5.96±0.11	0.493±0.042
16	20.42±0.36	7.03±0.03	0.522±0.065
18	19.54±0.45	7.92±0.07	0.525±0.067
20	18.75±0.18	8.72±0.04	0.575±0.031

Table 4: Variation of Aerodynamic Coefficients in the NACA 0012 Profile (AR=1.9474)

α, °	C_L	C_D	$-C_M$
0	0.0274	0.0194	0.0069
2	0.2255	0.0297	0.0066
4	0.4691	0.0393	0.0164
6	0.7035	0.0507	0.0315
8	0.8915	0.0638	0.0384
10	1.0646	0.0815	0.0447
12	1.1716	0.1284	0.0699
14	1.0103	0.2477	0.1998
16	0.9282	0.3204	0.2516
18	0.9151	0.3987	0.2816
20	0.9002	0.4520	0.3061

Table 5: Variation of Aerodynamic Coefficients in the NACA 0012 Profile (AR=2.761)

α, °	C_L	C_D	$-C_M$
0	0.016	0.008	0.0001
2	0.205	0.009	0.0061
4	0.445	0.013	0.0065
6	0.640	0.018	0.0070
8	0.791	0.026	0.0249
10	0.922	0.037	0.0479
12	0.830	0.175	0.0964
14	0.697	0.226	0.1539
16	0.668	0.257	0.1566
18	0.664	0.287	0.1565
20	0.683	0.325	0.1586

Table 6: Variation of Aerodynamic Coefficients in the NACA 0012 Profile (AR=3.0198)

α, °	C_L	C_D	$-C_M$
0	0.1358	0.0182	0.0179
2	0.3971	0.0217	0.0315
4	0.6531	0.0247	0.0501
6	0.8592	0.0332	0.0567
8	1.0372	0.0494	0.0591
10	1.0777	0.1154	0.1341
12	0.8941	0.2128	0.1865
14	0.8770	0.2829	0.2317
16	0.8540	0.3339	0.2452
18	0.8440	0.3762	0.2469
20	0.8400	0.4138	0.2703

Table 7: Variation of the Coefficient of Efficiency of Profiles ($C_E= C_L/C_D$)

AR α	1.9474	2.761	3.0198
0	1.41	2.00	7.44
2	7.59	22.78	18.28
4	11.94	34.23	26.44
6	13.88	35.56	25.88
8	13.97	30.42	20.99
10	13.06	24.92	9.34
12	9.15	4.74	4.20
14	4.08	3.08	3.10
16	2.90	2.60	2.56
18	2.30	2.31	2.24
20	1.99	2.10	2.03

Table 8: Variation of the performance coefficient of profiles($C_P= C_L^{1.5}/C_D$)

AR α	1.9474	2.761	3.0198
0	0.233	0.253	2.750
2	3.605	10.313	11.532
4	8.175	22.835	21.368
6	11.638	28.444	23.989
8	13.194	27.058	21.383
10	13.478	23.927	9.695
12	9.907	4.321	3.973
14	4.099	2.575	2.903
16	2.791	2.124	2.364
18	2.196	1.885	2.061
20	1.890	1.737	1.860

The magnitude of the coefficient of lift of the profile with AR=1.9474 is seen to be the maximum from Fig. 3. The maximum value, that is, C_{Lmax}=1.1716 was reached at the angle of attack value of α=12°. In the interval, 12° < α < 16° the magnitude of the coefficient of lift was reduced dractically and displayed a variation close to the horizontal for α 16°. The coefficients of lift of other profiles are smaller compared to this one.

The other coefficient that must be considered for the optimization of wings is the coefficient of drag. An examination of Table 4-6 yields the result that, the profile with AR=2.761 has the samallest drag coefficient among others.

An inspection of Fig. 4 indicates that the airfoil with an aspect ratio of 2.761 has an increasing coefficient of efficiency up to the angle of attack value of α = 6°, attaining the maximum value of $C_{E,max}$= 35.56. A rapid decrease in the coefficient of efficiency occurs in the interval 6° < α < 12°. For α >12° a variation close to the horizontal line is observed. The airfoil whose AR=3.0198 has $C_{E,max}$=26.44 at α = 4° and in the interval 6^{o} < α <12^{o} has a rapidly decreasing coefficient of efficiency. For α >12° the variation of the coefficient is close to the horizontal line. The profile with the smallest aspect ratio among the specimens tested has got a comparatively smaller coefficient of efficiency, that is, $C_{E,max}$= 13.97. An examination of Fig. 4 yields the result that the profile with AR=2.761 is the most efficient.

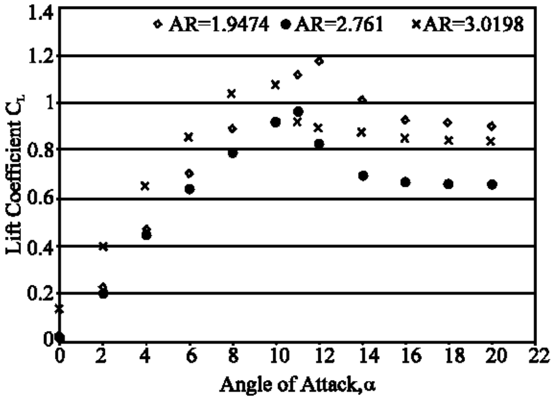

Fig. 3: Comparison of the Lift Coefficients of Profiles (U=33.76 m s ^{1})

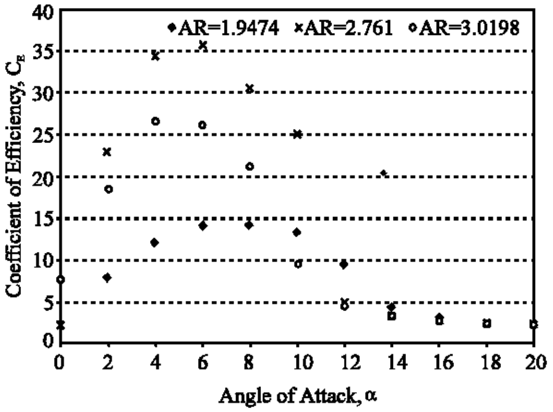

Fig. 4: Comparison of the Efficiency Coefficients of Profiles (U=33.76 m s ^{1})

The variations of performance coefficients of airfoils with respect to the angles of attack (Fig. 5) are seen to be similar to the variations of efficiency coefficients in

Fig. 4. The profile with AR = 2.761 is seen to be the best according to the coefficient of performance. The optimum interval of this specimen is, 6° < α < 10°

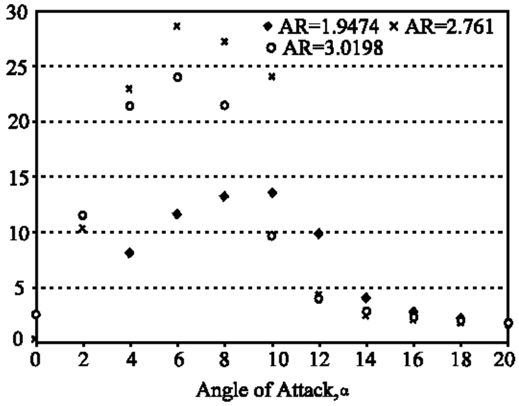

Fig. 5: Comparison of the Performance Coefficients of Profiles(U=33.76 m s ^{1})

CONCLUSIONS

The present experimental investigation yielded the conclusion that the airfoil with AR=1.9474 attains the maximum coefficient of lift compared to the other specimens. However the simultaneous high value of the coefficient of drag in this profile decreases the coefficient of efficiency and the coefficient of performance. Moreover reduction in the aspect ratio increases the cofficient of lift at higher angles of attack. If the profiles tested are judged according to the coefficients of efficiency and performance the one with AR=2.761 is found to be the optimum.

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