Performance analysis of aerofoil for Unmanned Aerial Vehicle

Kh Md Faisal[1]
Lecturer, Aeronautical Engineering Department
Military Institute of Science and technology
Dhaka, Bangladesh
mistfaisal@gmail.com[1]

Md Easir Arafat Papon[2], Akhter Mahmud Nafi[3]
Lecturer, Aeronautical Engineering Department
Military Institute of Science and Technology
Dhaka, Bangladesh
a.easir@ae.mist.ac.bd[2], nafi.ae@gmail.com[3]

***Abstract*— The growing interest in development of UAV has created a need for the comparative analysis of performance parameters of different aerofoils. Using this concept different characteristics of aerofoils are explored to design the wing of various UAV fulfilling various purposes. In this research work, the requirements of our desired UAV are established. These requirements are translated into performance parameters. Then the aerofoil that best meet the requirements was optimized from different arbitrary aerofoils through experimental investigation of the performance parameters.**

***Index Terms*—Aerofoil, UAV, Drag, Lift co-efficient, pitching moment, lift-drag ratio.**

I. Introduction

The most important factor for flying an aerial vehicle is the amount of lift generated. Again the generation of lift depends on how much the flow is turned, which depends on the shape of the object. In general, the lift is a very complex function of the shape. Thus optimizing a desired shape of aerofoil is a matter of great importance. This paper deals with performance analysis of cambered aerofoil for unmanned aerial vehicle based on subsonic wind tunnel test. The design of an aerofoil usually starts with the definition of the desired or required characteristics. These can be a certain range of lift coefficients, Reynolds numbers, where the aerofoil should perform best, moment coefficient, thickness, low drag, high lift or any combination of such requirements. As there is no such aerofoil available, which perfectly fits the desired conditions and fulfills all requirements, hence this effort was attempted to design something new with improved performance.

II. Aerofoil Design Consideration

Aerofoil characteristics are strongly affected by the "Reynolds numbers" at which they are operating. Reynolds number, the ratio between the dynamic and the viscous forces in a fluid, is equal to ($\rho Vl/\mu$), where V is the velocity, l the length the fluid has travelled down the surface, ρ the fluid density, and μ the fluid viscosity coefficient. The Reynolds number influences whether the flow will be laminar or turbulent, and whether flow separation will occur. Another consideration in modern aerofoil design is the desire to maintain laminar flow over the greatest possible part of the aerofoil. Thickness ratio has some effect upon the maximum lift coefficient. The drag increases with increasing thickness due to increased separation. For initial selection of the thickness ratio, the historical trend shown in figure-1 can be used. Note that a supercritical aerofoil would tend to be about 10% thicker (i.e., conventional aerofoil thickness ratio times1.1) than the historical trend. In incompressible flow conditions relatively high thickness to chord ratios of up to 0.2 are acceptable. The basic Aerofoil must have a low profile drag coefficient for the range of lift coefficients used in cruising flight [1].

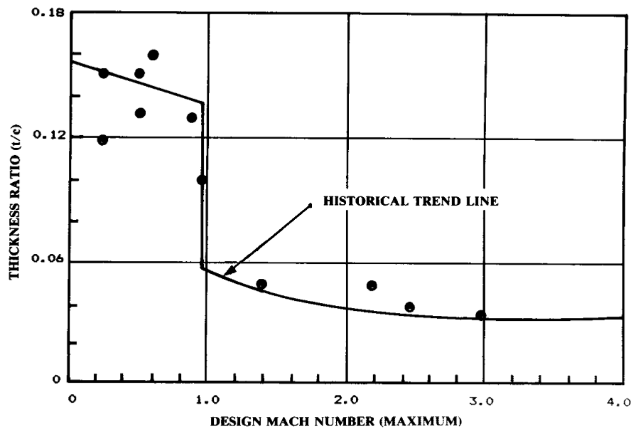

Fig-1: Thickness ratio vs Design Mach number [1]

The maximum lift coefficient both at low and higher Mach numbers are one of the requirements. The stalling characteristic where a gentle loss of lift is preferable is another need, especially for light aircraft. All these requirements cannot be satisfied by one single Aerofoil. Span wise variation of the sectional shape and some measure of compromise will therefore generally be accepted [3]. The aerofoil drag especially in aircraft climb and cruise conditions, when the lift to drag ratio should be as high as possible .

If it is unduly large there may be a significant trim drag penalty. The nose radius should be relatively large to give good maximum lift coefficient. Trailing edge angle, which is often best made as small as is feasible. The maximum lift coefficient of a basic, two dimensional, aerofoil can vary over a wide range. In the case of a low speed aerofoil and an advanced one for use at high subsonic Mach number a maximum lift coefficient of about 1.6 is typical. Increase of thickness to chord ratio also results in a reduction of critical Mach number. Various formulae and data sources have been derived to enable critical Mach number to be evaluated. Subsonic airliner: $M_{CRIT} = 0.9 - (t/c)$ approx. For preliminary design purposes the most critical aerofoil parameters are the maximum lift coefficient and the related high speed drag characteristics, and lift curve slope [2].

III. Performance Requirements

On an air surveillance mission, purpose is to watch for ground or sea activity of various sorts, or monitoring the path and characteristics of a hurricane. Our main concern is staying in the air for the longest possible time. We want the airplane to have long endurance. A good solution to the long endurance flight is to operate the aircraft at almost maximum lift and lowest cruise speed with engine power just good enough to maintain the altitude and against the wind, so as to reach the minimum fuel consumption and longest mission endurance. By definition, endurance is the amount of time that an airplane can stay in the air on one load of fuel. We know for jet propelled airplane thrust specific fuel consumption is given by, $dt = -\frac{dW_f}{c_t T}$ (1)

Since T=D and L=W in steady, level flight,

$$dt = -\frac{dW_f}{c_t D} = -\frac{L}{D}\frac{1}{c_t}\frac{dW_f}{W} \quad (2)$$

Integrating from t=0, where $W=W_0$, to t=E, where $W=W_1$, we have

$$E = -\int_{W_0}^{W_1}\frac{1}{c_t}\frac{L}{D}\frac{dW_f}{W} = \int_{W_1}^{W_0}\frac{1}{c_t}\frac{L}{D}\frac{dW_f}{W}$$

$$E = \frac{1}{c_t}\frac{L}{D}\int_{W_1}^{W_0}\frac{dW_f}{W}$$

$$E = \frac{1}{c_t}\frac{L}{D}\ln\frac{W_0}{W_1} \quad (3)$$

This is the general equation for endurance E of an airplane. From above equation we see that (L/D) is the only aerodynamic parameter upon which endurance depends upon and as our purpose is surveillance which requires best endurance. So we will get best endurance for $(L/D)_{max}$. Hence we should search for such aerofoils which will give us best (L/D). The requirements which are required to meet to develop new long-endurance aerofoils are high operational lift co-efficient, high endurance factor, less value of slope of C_l vs α curve, limited pitching moment co-efficient, large relative thickness.

IV. Experimental Investigation

Three different aerofoils were tested in subsonic wind tunnel at different Reynolds number ranging from 100000 to 400000 with air density 1.225 kg/m^3 and viscosity of 1.83×10^{-5} Pa-s. As these are arbitrary aerofoils so, their geometric specifications are given prior to performance analysis.

A. Geometric specification for aerofoil-1

The specifications for selected aerofoil-1 are shown in table-1 and generated aerofoil is in figure-1.

TABLE-1: Geometric Specification of Aerofoil-1

X(L)	Y(L)	X(U)	Y(U)	Thickness	t/c
1	0	1	0.0012	0.0012	0.0012
0.95	-0.00138	0.95	0.01352	0.0149	0.015684
0.9	-0.00276	0.9	0.02524	0.028	0.031111
0.8	-0.00552	0.8	0.04668	0.0522	0.06525
0.7	-0.00828	0.7	0.06522	0.0735	0.105
0.6	-0.01104	0.6	0.08046	0.0915	0.1525
0.5	-0.0138	0.5	0.0916	0.1054	0.2108
0.4	-0.01656	0.4	0.09774	0.1143	0.28575
0.3	-0.01932	0.3	0.09818	0.1175	0.391667
0.2	-0.02208	0.2	0.09052	0.1126	0.563
0.15	-0.02346	0.15	0.08204	0.1055	0.703333
0.1	-0.02454	0.1	0.06936	0.0939	0.939
0.075	-0.02453	0.075	0.06097	0.0855	1.14
0.05	-0.02352	0.05	0.05068	0.0742	1.484
0.025	-0.02071	0.025	0.03559	0.0563	2.252
0.0125	-0.01696	0.0125	0.02395	0.04091	3.2728

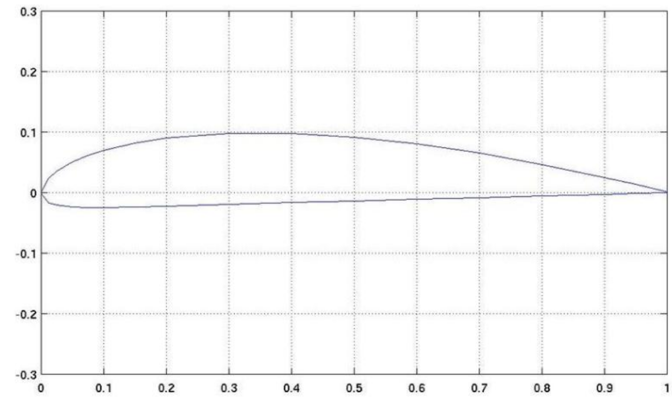

Fig-2: Aerofoil-1

B. Geometric specification of aerofoil-2

The specification for aerofoil-2 is shown in table-2 and designed aerofoil is in figure-2.

TABLE-2: GEOMETRIC SPECIFICATION OF AEROFOIL-2

X(L)	Y(L)	X(U)	Y(U)	Thickness	t/c
1	0	1	0	0	0
0.99572	-0.00025	0.99572	0.00115	0.0014	0.001406
0.98296	-0.00094	0.98296	0.00448	0.00542	0.005514
0.96194	-0.0019	0.96194	0.00972	0.01162	0.01208
0.93301	-0.00302	0.93301	0.01656	0.01958	0.020986
0.89668	-0.00429	0.89668	0.02475	0.02904	0.032386
0.85355	-0.00575	0.85355	0.034	0.03975	0.04657
0.80438	-0.00741	0.80438	0.04394	0.05135	0.063838
0.75	-0.00928	0.75	0.05412	0.0634	0.084533
0.69134	-0.01131	0.69134	0.06405	0.07536	0.109006
0.62941	-0.01345	0.62941	0.07319	0.08664	0.137653
0.56526	-0.01566	0.56526	0.08105	0.09671	0.171089
0.5	-0.01792	0.5	0.08719	0.10511	0.21022
0.43474	-0.02018	0.43474	0.09128	0.11146	0.256383
0.37059	-0.02242	0.37059	0.09312	0.11554	0.311773
0.33928	-0.02351	0.33928	0.09318	0.11669	0.343934

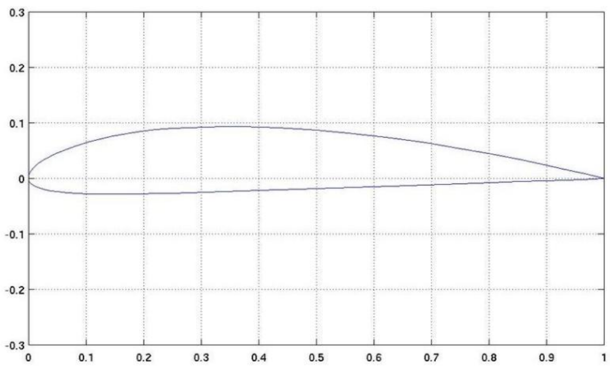

Fig-2: Aerofoil-2

C. Geometric specification for aerofoil-3

The specification for aerofoil-3 is shown in table-3 and designed aerofoil is in figure-3.

TABLE-3: GEOMETRIC SPECIFICATION OF AEROFOIL-3

X(L)	Y(L)	X(U)	Y(U)	Thickness	t/c
1	-0.0006	1	0.000599	0.001199	0.001199
0.99	-0.00097	0.99	0.002969	0.003936	0.003975
0.98	-0.00133	0.98	0.005334	0.006667	0.006803
0.97	-0.0017	0.97	0.007687	0.009388	0.009678
0.96	-0.00207	0.96	0.010023	0.012092	0.012595
0.94	-0.0028	0.94	0.014624	0.017427	0.018539
0.92	-0.00354	0.92	0.019116	0.022653	0.024623
0.9	-0.00427	0.9	0.023503	0.027774	0.03086
0.88	-0.00501	0.88	0.027789	0.032795	0.037268
0.86	-0.00574	0.86	0.031974	0.037715	0.043854
0.84	-0.00648	0.84	0.036054	0.042529	0.05063
0.82	-0.00721	0.82	0.040025	0.047234	0.057603
0.8	-0.00794	0.8	0.043884	0.051828	0.064785
0.78	-0.00868	0.78	0.047628	0.056307	0.072188
0.76	-0.00941	0.76	0.051257	0.06067	0.079829
0.74	-0.01015	0.74	0.054768	0.064915	0.087723

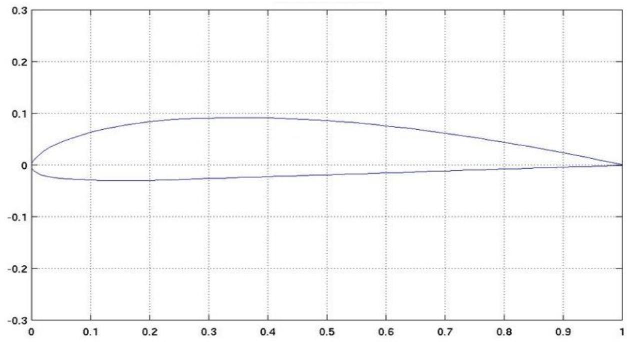

Fig-3: Aerofoil-3

V. PERFORMANCE ANALYSIS AT DIFFERENT REYNOLDS NUMBER

The three aerofoils; A-1, A-2 and A-3 are tested under different Reynolds number ranging from 100000 to 400000. The analysis is as follows in different forms in figure-4-9.

A. Performance at Reynolds number 100000

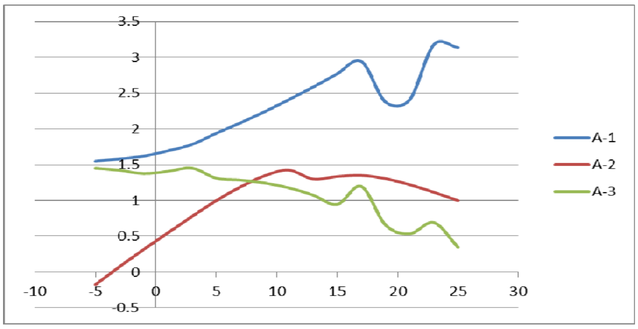

Fig-4: C_l Vs α

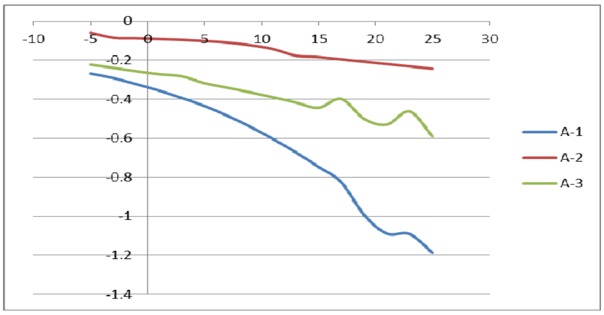

Fig-5: C_m Vs α

Results from this analysis is stated below in table-4.

TABLE-4: SUMMARY OF AEROFOIL PERFORMANCE AT REYNOLDS NUMBER 100000

Parameters	Aerofoil-1	Aerofoil-2	Aerofoil-3	Comments	At Re=100k A-1 perform best
$C_{l\ max}$	3.178	1.485	1.452	A-1	
$(dC_l/d\alpha)_{max}$	0.085625	0.103	-0.0366	A-2	
Cm	-0.269	-0.059	-0.223	A-1	

B. Performance at Reynolds number 200000

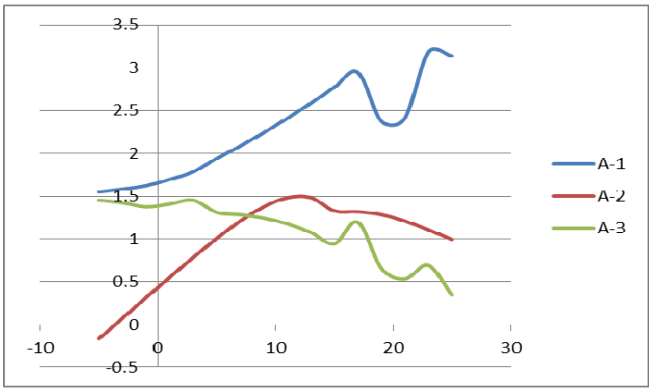

Fig-6: C_l Vs α

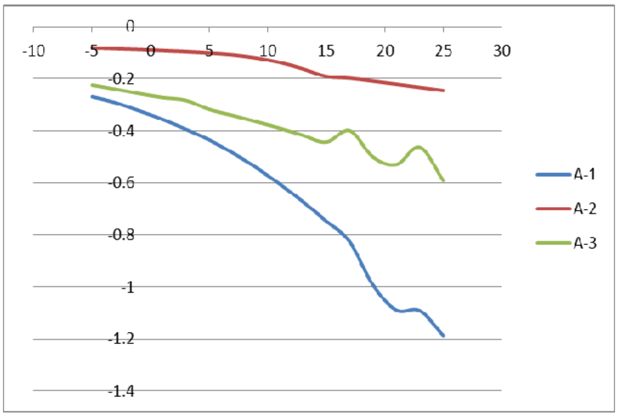

Fig-7: C_m Vs α

Results from this analysis is stated below in table-5.

TABLE-5: SUMMARY OF AEROFOIL PERFORMANCE AT REYNOLDS NUMBER 200000

Parameter	Aerofoil-1	Aerofoil-2	Aerofoil-3	Comments	At Re=200k A-1 perform best
$C_{l\ max}$	3.178	1.482	1.452	A-1	
$(dC_l/d\alpha)_{max}$	0.08916	0.103125	-0.0366	A-2	
Cm	-0.269	-0.082	-0.224	A-1	

C. Performance at Reynolds number 300000

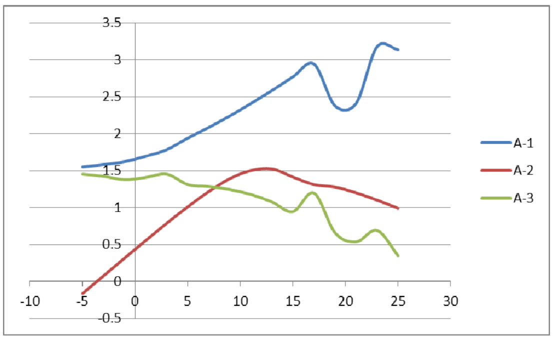

Fig-8: C_l Vs α

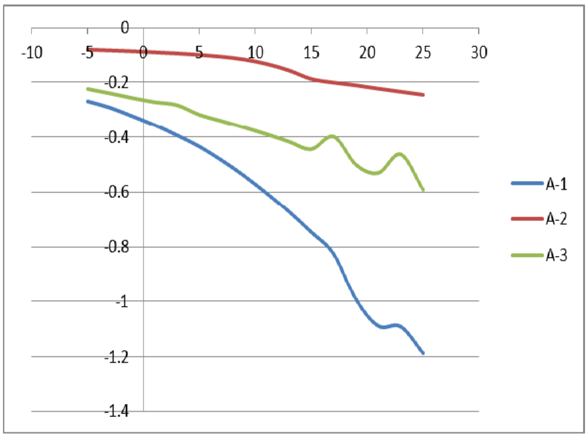

Fig-9: C_m Vs α

TABLE-6: SUMMARY OF AEROFOIL PERFORMANCE AT REYNOLDS NUMBER 300000

Parameter	Aerofoil-1	Aerofoil-2	Aerofoil-3	Comments	At Re=300k A-1 perform best
$C_{l\ max}$	3.178	1.524	1.452	A-1	
$(dC_l/d\alpha)_{max}$	0.0805	0.10066	-0.0366	A-2	
Cm	-0.269	-0.082	-0.224	A-1	

D. Performance at Reynolds number 400000

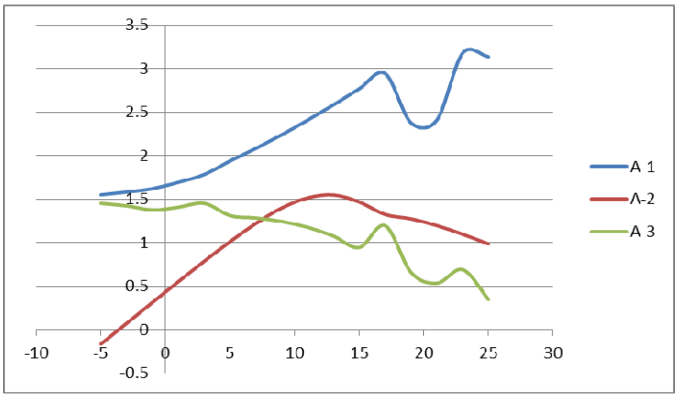

Fig-10: C_l Vs α

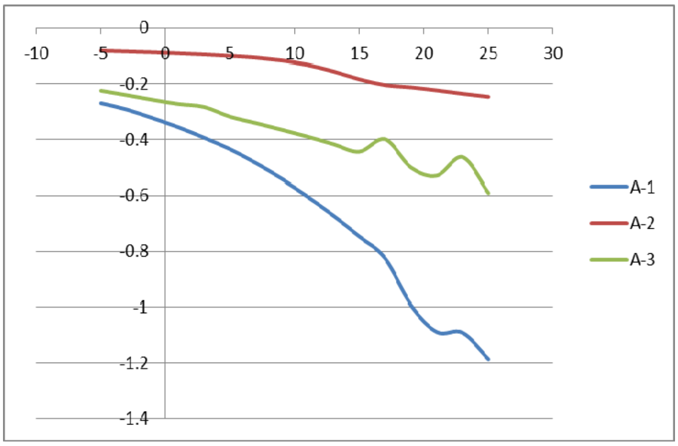

Fig-11: C_m Vs α

Results from this analysis is stated below in table-6.

TABLE-6: SUMMARY OF AEROFOIL PERFORMANCE AT REYNOLDS NUMBER 400000

Parameter	Aerofoil-1	Aerofoil-2	Aerofoil-3	Comments	At Re=400k A-1 perform best
$C_{l\ max}$	3.178	1.548	1.452	A-1	
$(dC_l/d\alpha)_{max}$	0.0829	0.101833	-0.02675	A-2	
Cm	-0.269	-0.082	-0.224	A-1	

In every experimental investigation of different Reynolds number ranging from 100000 to 400000, it is found that Aerofoil -1 performs best in terms of our requirement.

CONCLUSION

A number of conclusions can be drawn from the tests and investigations that have been done such as; at all Reynolds Number Aerofoil-1 performs best while investigating the variation of lift co-efficient with the variation of angle of attack. After investigating the comparative performance of aerofoils individually, it has been decided that Aerofoil-1 can best meet performance requirements. Although in some cases Aerofoil-2 show better performance but aerofoil-2 failed to maintain a stable variation of pitching moment with angle of attack which is one of our major performance requirements. Future work should focus on developing more detailed wind tunnel testing results. Similar analysis can be done with the other types of aerofoil like semi-symmetrical aerofoil, symmetrical aerofoil. The methodology of this research will be useful in further development of the research of aerodynamic characteristics of cambered aerofoil. The optimized aerofoil of this research work can be used for designing a suitable wing for unmanned aerial vehicle.

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