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Performance of a Stepped Airfoil at Low Reynolds Numbers

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Abstract

Small Unmanned Aerial Vehicles (UAVs) are becoming more viable replacements for manned flights on dangerous, tedious and expensive missions. Small UAVs provide a complex aerodynamic problem. Compared to manned aircraft, their small size and relatively slower flight speeds, combined with the turbulent nature of the air flow close to the ground, increases the likelihood of the aircraft stalling. As a result the development of new and innovative means of generating lift, which are less susceptible to stalling, would be extremely beneficial to small UAV design. One potential solution is the series of stepped airfoils designed by Kline and Fogleman (KFm). These airfoils, popular with some Radio Control (RC) model pilots, are claimed to be stall resistant. Stall resistance is a desirable property for aircraft operating close to maximum lift, or maximum angle of attack, as would be expected of a small UAV carrying sensory and communication equipment. This work aims to determine the validity of these claims by testing a Rolf Girsberger (RG) -15 airfoil section with a KFm-2 step in a low-turbulence, closed-loop wind tunnel. The tests have been conducted at 4 Reynolds numbers between Re 28 000 and Re 100 000, which we believe are the expected operating conditions of a small UAV. A load cell test rig has been used to determine the maximum angle of attack before the airfoil stalls as well as the efficiency of the airfoil. An unmodified RG-15 airfoil has also been tested as a control. The addition of the KFm-2 step was found to have no useful aerodynamic benefits. The standard RG-15 section would be more suitable for use as a small UAV wing section.

Nomenclature

A_m = Projected model area (m^2)
A_{ts} = Test section area (m^2)
B = Blockage ratio
c = Chord length of airfoil (m)
C_d= Drag coefficient
C_l= Lift coefficient
D = Drag force (N)
h_{ts} = Test section height (m)
L = Lift force (N)
Re = Reynolds number
S = Planform area of wing section (m^2)
V = Air velocity (m/s)
α = Angle of attack (°)
ρ = Air density (kg/m^3)
μ = Air viscosity (Pa.s)

Introduction

UAVs are increasingly replacing manned aircraft, particularly in roles that are dangerous or menial. The benefits, in terms of risk management and operational costs, of using a UAV instead of a manned aircraft are substantial. The potential use of UAVs is ever expanding. One area of active development is small UAVs. With the current pace of electronics development, it has become feasible to design very small, controllable aircraft. These are superior to their larger counterparts in terms of mobility. The current limitation in further development is aerodynamics. Small wings and traveling at low speeds, do not perform well in combination [11]. To generate the necessary lift to support the weight of onboard loads the wings have to be at a large angle of attack, for higher lift. This makes the aircraft susceptible to stalling. There are solutions to this aerodynamics problem that have proven to be successful. The Delft University of Technology for instance has overcome this problem using an ornithopter design [1]. Ornithopters are quite complex, making a simpler solution very desirable. In 1970 Richard Kline and Floyd Fogleman filed a patent for a stepped airfoil; they claimed that this airfoil resisted stalling as a bound vortex formed behind the step [4, 7]. In theory the vortex creates a negative pressure region, which allows the airfoil to achieve a higher angle of attack before the airflow separates. This airfoil has gained a particularly large following within the radio controlled airplane community, with most users claiming that very high angles of attack can be reached before the airfoil stalls. It reaches far greater angles than an ordinary airfoil could reach [7]. Whilst these claims have been investigated for the flight conditions experienced by larger aircraft, there have been few investigations to date focusing on the performance of a stepped airfoil undergoing the flight conditions experienced by small UAVs. Figure 1 illustrates the typical geometry of a stepped airfoil. If the claims made by Kline and Fogleman are correct, under these flight conditions, the Kline-Fogleman airfoil could be a viable solution to the susceptibility of small UAVs to stalling.

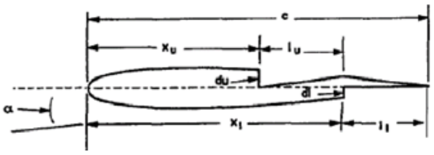

Figure 1. Geometry of a stepped airfoil [3]

There have been a number of investigations looking into the effects of steps on the stall angle of a given airfoil [2, 3, 5]. Investigations using NACA23012 [2] and NACA0012 [3] showed that adding a step to an airfoil did improve its performance, especially increasing significantly its stall angle [2]. On the other hand, with a stepped wedge, [5] found no extra lift, only higher drag than a flat plate. This paper reports experiments performed on a normal RG-15 airfoil (used as a control) and a RG-15-with-KFm-2 stepped airfoil. Comparison with similar experiments completed at Princeton University and the University of Illinois at Urbana Champaign (UIUC) is also made.

Experiment

This work was conducted with the closed-loop wind tunnel (figure 2) in the Aerodynamics laboratory at the University of Technology, Sydney (UTS). The aim of the experiment was to determine the validity of the claims made by Kline and Fogleman relating to the stall resistance of the KFm-2 stepped airfoil at flight conditions experienced by small UAVs.

Figure 2. Closed loop wind tunnel located at the University of Technology, Sydney (UTS).

The manufacturing of the airfoils involved a "home-made" computer-controlled hot-wire system (figure 3), followed by placing fiberglass on the airfoils surface. This was left to settle in a vacuum bag, until a smooth surface finish was obtained. The airfoils tested were an unaltered RG-15 airfoil (control) and a RG-15 airfoil section with a KFm-2 step (figures 4 and 5).

Figure 3. David Cox's hot wire cutting machine.

A) Before **B)** After

Figure 4. Images showing the before and after construction of RG-15 and RG-15 with KFm-2 stepped airfoil.

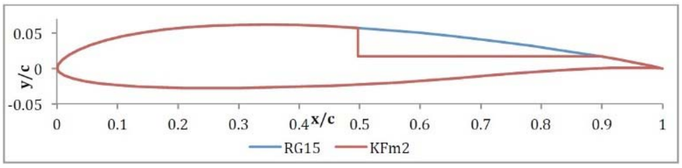

Figure 5. RG-15 and KFm-2 airfoil shape.

Like all manufacturing and experimental work, problems arise which need to be appropriately addressed to achieve the desired objectives i.e. accurate specimen to test coupled with reliable instrumentation. Some of the common problems encountered during the manufacturing and experimental testing included:

<u>Perspex unevenness:</u> It was found that the wind tunnel wall section in which the airfoil was to be housed had uneven thicknesses throughout the length of the material, ultimately resulting in inaccurate results. The thicknesses ranged from 7 mm to 9 mm, depending on location. For this reason, the effected sections were milled to provide a smooth and even finish. The maximum unevenness after the milling process was found to be 0.3 mm, which was deemed to be a reasonable level for this research.

<u>Airfoil roughness:</u> Obvious indentations and rough sections were evident after manufacture. This was overcome by using spray putty which was then sanded very lightly to ensure a smooth finish. The average surface roughness was measured to be approximately 0.42 μm and 0.37 μm for the RG-15 and RG-15 with a KFm-2 step, respectively.

<u>Cutting wire temperature:</u> The difficulty of controlling the hot wire temperature during the cutting process was time consuming, especially due to the short chord length of the airfoil. In addition, the thickness of the cut was found to be quite difficult to predict, as the control mechanism only accounted for cut thickness and not the actual thickness of the airfoil. A trial and error method was utilized which produced reasonable results.

<u>Measurement:</u> Dimensions of the wind tunnel were found to be slightly inaccurate, and as such, measurements were taken to ensure no leakage occurred and the airfoil fit correctly within the test section. Key dimensions included the port length, height and width of the tunnel.

Prior to commencement of testing, custom made components needed to be designed and manufactured for the closed loop wind tunnel, so as to ensure the accuracy of results obtained.

Closed Loop Wind Tunnel

The existing wind tunnel consists of several interchangeable smoothing screens and a settling chamber (recent addition). McCaffery et al. [6] showed that prior to the recent addition (a settling chamber), the most optimal value of turbulence intensity was between 0.42-0.55% depending on the position and fan speed. They stated that with the addition of the settling chamber the turbulence intensity would be less than 0.25%, yet to be confirmed. A study by Selig et al [8-10] showed the turbulence intensities at both Princeton and UIUC to be between 0.17-0.563% and 0.08-0.1%, respectively. Comparisons were made with Princeton and UIUC, based on the E387 section at Re 60000 and the results were very similar, differing by a maximum 10%; but in comparison to NASA, Delft and Stuttgart wind tunnels, they differed quite substantially [9]. The tests at Re 100000 showed better agreement, but the Stuttgart results were significantly different in both lift and drag [9].

In this work, careful considerations of the best possible methods for wind tunnel/airfoil design have been taken. Examples of such considerations are shown below:

<u>Solid Blockage:</u> Blockage ratio B is calculated to be

$$B = \frac{A_m}{A_{ts}} = \frac{1.219 \times 0.305 \times sin20}{0.853 \times 1.219} = 0.12$$

Rearranging and using the wind tunnel dimensions at UTS, we get chord length:

$$c = \frac{Bh_{ts}}{\sin \alpha} = \frac{0.12 \times 0.2667}{sin20} = 0.094\ m$$

By using the maximum velocity of the UTS wind tunnel (28 m/s, corresponding to Mach number M = 0.0823), the NASA blockage-recommended-value can be calculated from the following:

$$\frac{A_m}{A_{ts}} \leq 1 - \frac{0.25(3M+1)}{\left(1 + \frac{\left(0.25(3M+1)\right)^2 - 1}{6}\right)^3} = 0.49$$

As 0.12 is well below the NASA's recommended limit (0.49), the chord length of 0.09m would thus not cause excessive blockage.

Reynolds number Re: Assuming now a chord length of 0.1 m and knowing the range of air velocities of 4.2 – 28 m/s for the UTS wind tunnel, Re = ρVc/μ can be seen to be in the possible range of 27000 – 178000. Specifically in this work, the Re values used were 28000, 40000, 60000 and 100000, corresponding to air velocities 4.31, 6.23, 9.23, and 15.51 m/s, respectively.

Boundary layer: With the distance x = 0.81 m from the start of the test section to the airfoil and the minimum air velocity at 4.2 m/s (corresponding to x-based Reynolds number $Re_x = \rho Vx/\mu = 219000$), the wall boundary-layer thickness was determined from $\delta = 5x/Re^{1/2}$ to be δ = 0.0086 m. This makes the percentage of the airfoil width that will be affected by the wall boundary layers to be 2δ/w = 4.5%, if the airfoil was made the full width (0.381 m) of the wind tunnel section.

Results and Discussion

Measurements of both lift and drag at Re 28000, 40000, 60000 and 100000 were compared to results obtained at UIUC and Princeton Universities. Lift coefficient C_l and drag coefficient C_d were obtained from measured lift force L and drag force D according to $C_l = L/(\rho V^2 S/2)$ and $C_d = D/(\rho V^2 S/2)$ respectively. Figure 6 showed that at Re = 60000, the lift result for the angle of attack α from 1°-8° were within 10% of that provided by UIUC and Princeton. However, above approximately 10°, our results indicate airfoil stalling with a sudden decrease in lift; the Princeton and UIUC results indicate higher stall angle, at 11° and 13°, respectively. Figure 7 showed that C_d values obtained from our tests (at Re = 60000) were significantly larger than both UIUC and Princeton. On the other hand, our lift and drag results at Re = 100000 were much closer to UIUC's and Princeton's (figure 8); at low lift, our C_d is smaller, but it reverts to being larger at higher lift. Figure 9 shows that at Re = 100000 the UIUC, Princeton and our results are all similar; but our lift peaks at α approximately 10° (same as for Re 60000), while Princeton's and UIUC's at α of 11° and 13°, respectively.

Figure 10 shows C_l and C_d results for the RG15 airfoil at different Re values. As Re increases, so too does C_l. Unlike the RG15 airfoil, the KFm-2 step at a lower Reynolds number has a higher drag and lower lift (figure 11).

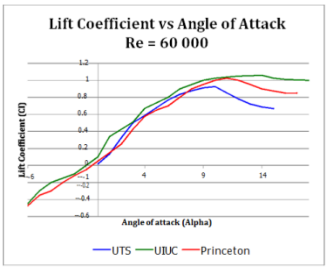

Figure 6. Comparison of Lift coefficient vs Angle of Attack for an RG15 airfoil at Re 60,000.

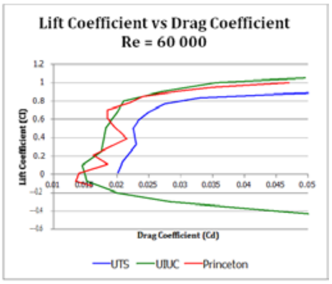

Figure 7. Comparison of Lift coefficient vs Drag Coefficient of a RG15 airfoil at Reynolds number 60,000.

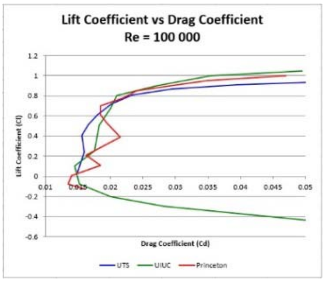

Figure 8. Comparison of Lift coefficient vs Drag Coefficient of a RG15 airfoil at Re 100,000.

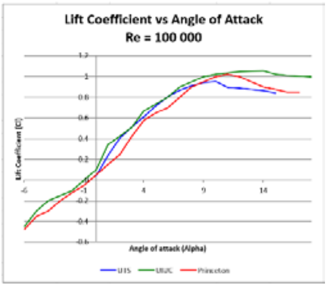

Figure 9. Comparison of Lift coefficient vs Angle of Attack for an RG15 airfoil at Re 100,000.

When comparing the angle of attack α and lift coefficient for the two airfoils, the KFm-2 step shows greater lift at lower α at all Reynolds numbers than the RG15 airfoil (figures 12 and 13). The findings are consistent with Fertis [2] who found a step configuration increased lift at lower α. We were however unable to confirm the increase in stall angle with the stepped section, as had been shown by Fertis. Our findings indicate that at low Re (28000 and 40000), the maximum lift of the KFm2 was significantly less than RG15 airfoil. This shows that there is no benefit to using a KFm2 step airfoil over the RG15 section at the Reynolds numbers tested in this work. The drag on KFm2 step can also be seen to be greater than RG15 for all Re values (except at Re 40000 and lower lift). The low drag bucket of the KFm2 step airfoil (at C_l 0-0.7) was noticeably narrower than the RG15's (at C_l 0-0.8); see figures 10, 11. This indicates that the RG15 without a step would be more applicable to turbulent environments where an effective angle of attack varies.

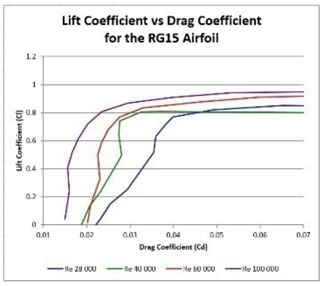

Figure 10. Comparison of Lift coefficient vs Drag coefficient for a RG15 airfoil at different Reynolds numbers.

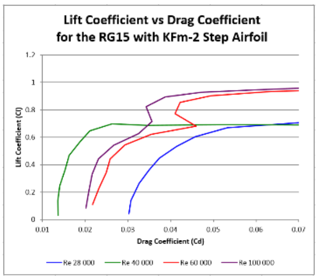

Figure 11. Comparison of Lift coefficient vs Drag coefficient for a RG15 with KFm2 step airfoil at different Reynolds numbers.

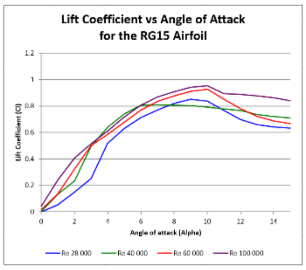

Figure 12. Comparison of Lift coefficient vs Angle of Attack for an RG15 airfoil at different Reynolds numbers.

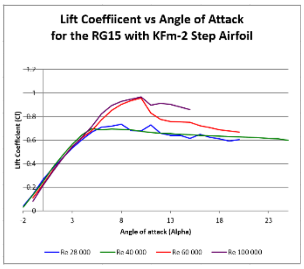

Figure 13. Comparison of Lift coefficient vs Angle of Attack for an RG15 with KFm2 step airfoil at different Reynolds numbers.

Conclusions

The claims made by Kline that the stall angle of attack is significantly increased by the addition of a step have not been substantiated. In fact the stall angle of attack at Re 28000 and 40000 of the KFm-2 airfoil was less than that of the RG-15. The maximum lift of the KFm-2 airfoil was at best equivalent to the RG-15 airfoil. At Re 28000 and 40000 the maximum KFm-2 lift was significantly less than the RG-15 section. The efficiency of the KFm-2 section was not as good as the RG-15 section over most of Reynolds numbers; and the results were less consistent across a range of Re values. From the results obtained during this investigation, it is evident that a bound vortex does not form in the step as Kline hypothesizes. Considering all these factors it is not recommended that a RG-15 section with a KFm-2 step to be used as a wing section for a small UAV.

Whilst this investigation demonstrates that a modified RG-15 section with a KFm-2 step doesn't have any improved performance characteristics over the Re range of 28000 – 100000, many other configurations are possible which could have improved performance. For further investigation, it's recommended to vary the step depth, location and length in a similar manner to Fertis [2]. Another avenue for investigation would be to change the airfoil section used. The GM-15 section for instance has better low Reynolds number performance than the RG-15 section. If manufactured using different materials the GM-15 section could be made strong enough to be tested with a step despite its minimal cross-sectional area. A further avenue for investigation would be to test multi-stepped airfoils, such as the KFm-10.

Acknowledgments

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