DELTA WING WITH LEADING EDGE EXTENSION AND PROPELLER PROPULSION FOR FIXED WING MAV

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Abstract

Air turbulence is perceived as a major problem for MAV outdoor applications. It seems reasonable to use MAVs in these situations providing the flow is attached to the control surfaces even at high angles of attack. This will ensure effective control during turbulence.

Delta wings are known to have excellent large angle of attack qualities. However, quantitative data about leading edge vortex effectiveness at low Reynolds numbers were not available, so an experiment was undertaken to measure them. Generally, the effect appeared to be similar to that obtained for large aeroplanes including advantages of leading edge extensions (LEX). There was no observed negative effect of LEX/propeller interference. In fact an increase of stall angle was observed as a result of the propulsion operation.

The following presents force and visualisation results from a series of MAV configurations.

1 Introduction

The Micro Aerial Vehicle is defined here as a small (hand launched, storable in portable container), light (weight 150-200g), simple and inexpensive unmanned flying vehicle for direct, over the hill reconnaissance. The focus is on fixed wing, forward thrust aircraft since the ability to negotiate strong opposing winds is required. On the other hand, the ability to hover or at least slow flight is desirable.

Air turbulence is perceived as a major problem in the case of such applications. According to recent work [1], short duration vertical gusts may have velocity comparable to MAV airspeed, so brief periods of flight at very large angles of attack have to be considered. In these circumstances it seems reasonable to apply a MAV design with as high stall angle of attack as possible. In particular, the flow has to be attached to control surfaces to perform effective control during turbulent flight conditions.

Delta wings are known to have excellent large angle of attack qualities. Generation of a leading edge vortex allows to the flow to reattach and improve stall qualities. Therefore a delta wing was considered as a candidate for MAV design. However, quantitative data about leading edge vortex effectiveness at low Reynolds numbers were not available. Therefore an experiment was undertaken in order measure them [2]. Generally, the effect appeared to be similar to that obtained for large, manned aeroplanes including advantages of additional application of Leading Edge Extensions (see Figure 1).

Design of the delta wing MAV's with LEX appears to be non-trivial because of the LEX propeller interference problem. Details of the design, wind tunnel tests results, including flow visualization of such configuration, are now presented in this paper.

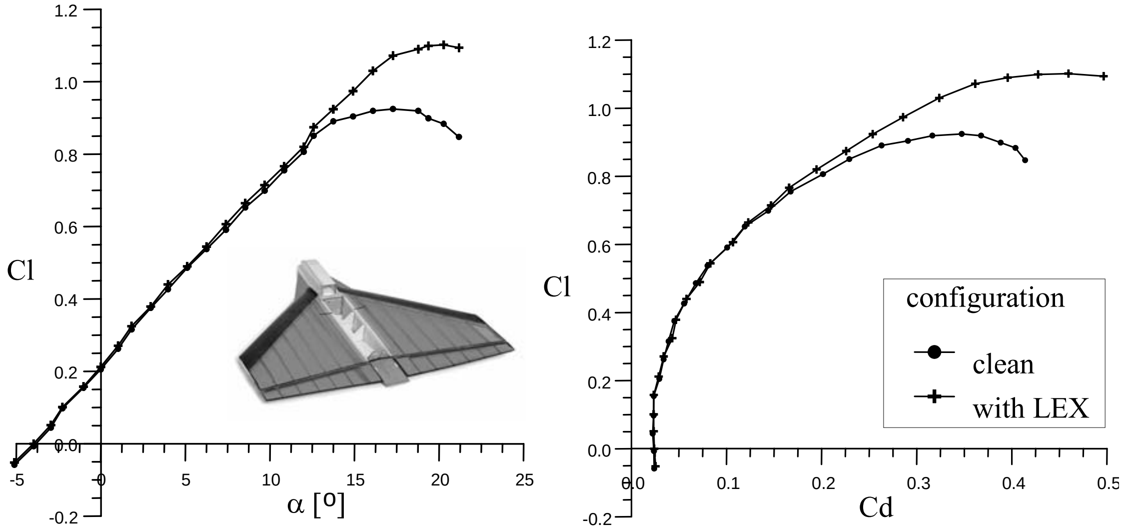


Fig.1 Leading Edge extension effect on the delta MAV wing performance

2 MAV design

Propeller propulsion seems the most suitable for a fixed wing MAV. The propeller should be located in front of the CG if stable hovering is desirable. Unfortunately, the propeller at the front of the vehicle would strongly interfere with the leading edge vortex. Therefore an aircraft configuration was developed with propeller located in the slot inside the wing contour.

Fig.2 MAV general design

The model built for wind tunnel tests had a wing area of 0.1m², a wing span of .45m, an aspect ration of 2 and a leading edge sweep angle of 39º. Aerofoils NACA 23003 and NACA 0004 were applied from the wing root to the wing tip.

The model was tested in clean configuration and with LEX of four different shapes: triangular, trapezoidal, circular and polynomial. The LEX area was the same in each case. The span of LEX was always slightly longer than the slot length.

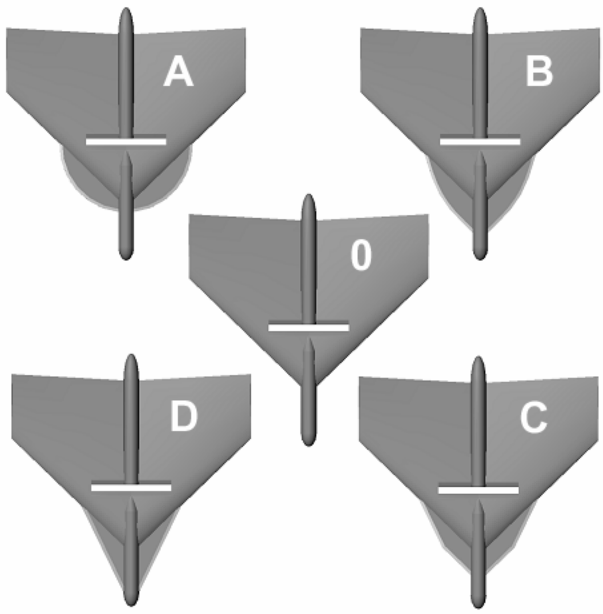


Fig.3 Tested configurations

There was a doubt about propulsive efficiency of such a configuration. So it was decided to test whether ducted propeller concept could help to improve it. The ring would have also the additional advantage of protecting the person hand-launching the vehicle as well as isolating the propeller stream from the leading edge vortex. However, since this feature may cause problems in storage, the ring design should be foldable and deployed at launch. In such case, the ring may be divided into two parts and have the diameter slightly greater than propeller to avoid collision with the propeller during the deployment. That is why in the case of the test model the distance between propeller tip and the ring was as large as 1.5mm. It was also decided not to test the stream/vortex isolation potential, since the test should verify the concept in worst case scenario. Therefore a simple, narrow ring was applied.

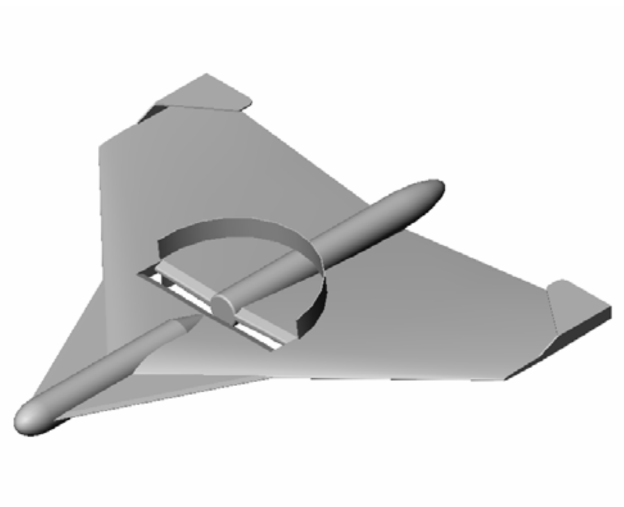


Fig.4 MAV prepared for storage

The model was equipped with standard electric motor Speed 300 with standard propeller 6x3.

According to [3] wings equipped with membrane type covering provide more stable lift coefficient and $C_l^{3/2}/C_d$ ratio in an oscillating free stream. This feature was perceived as advantageous since turbulence resistance was the goal of the experiment. Therefore a structure with a carbon/epoxy torsion box near the leading edge and ribs covered by membrane film at the rest of the wing was selected.

3 Propulsion efficiency tests

There were two experiments exploring propulsion efficiency. First of them allowed to measure the static thrust and second provided information about power needed to balance the drag for cruise with increasing wind tunnel airspeed. Results are presented in Figures 5 and 6.

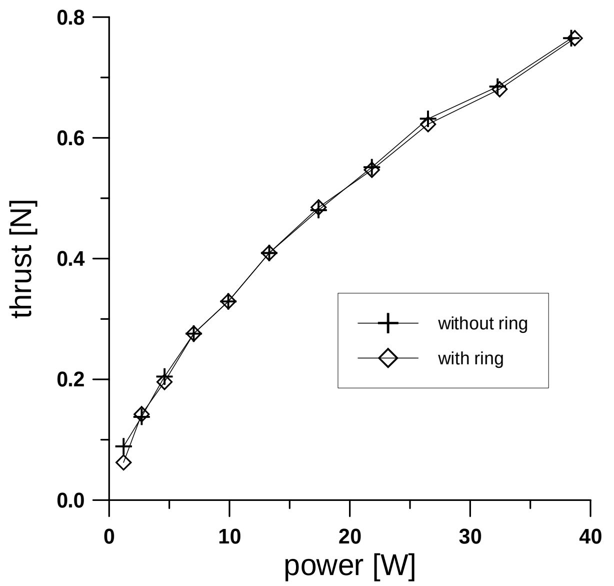


Fig.5 Static thrust

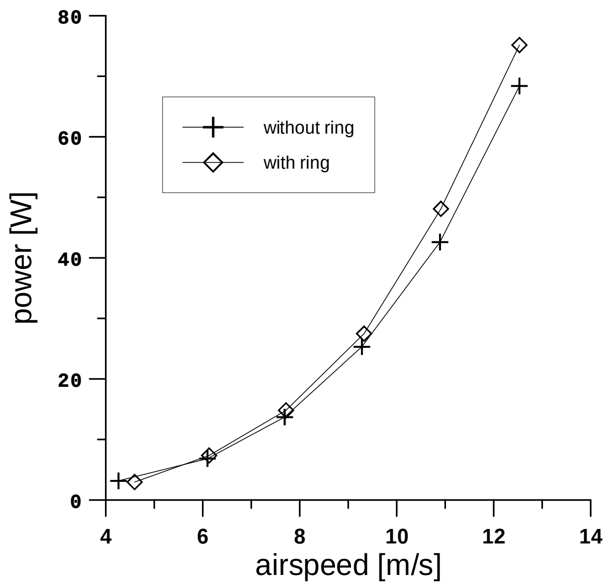


Fig.6 Cruise power characteristics

Power required to provide static thrust appeared to be the same for both configurations with and without ring. Conversely, the cruise power was greater for the configuration equipped with the ring. This result may in part be due to the ring drag being larger than the increase in propulsive efficiency. Therefore both experiments did not reveal any advantages of the ducted configuration. Another reason for this discrepancy may be the large gap between the propeller and the ring which is not an optimized design. Further study should be undertaken to provide an answer about potential efficiency improvement due to the presence of the ring. Therefore the ducted configuration was temporarily abandoned, since it was not critical for LEX verification.

4 LEX/propeller cooperation

4.1 Test procedure

The experiment was conducted in two parts. Firstly, steady flight lift/drag polars were measured for each LEX shape. Secondly, tests with running propeller were completed for selected steady flight conditions. The test sequence was as follows:

- For certain elevator deflections, angles of attack and wind tunnel airspeeds, the motor was set to an rpm which provided a drag reading equal to zero.
- The angle of attack was gradually increased with all other parameters constant.

This sequence allowed the simulation of entrance into a strong vertical gust. It was not an ideal simulation since measurement was static. Therefore dynamic effects were ignored. But the measurements provided an estimate of LEX effect and LEX/propeller interaction.

4.2 Test conditions

Tests were conducted in the closed jet tunnel of the Cranfield University at RMCS Shrivenham. The facility allowed for tests of real size vehicle with airspeeds similar to those experienced in flight, so a true Reynolds number was obtained. Figure 7 shows the range of Reynolds numbers applied during the measurements.

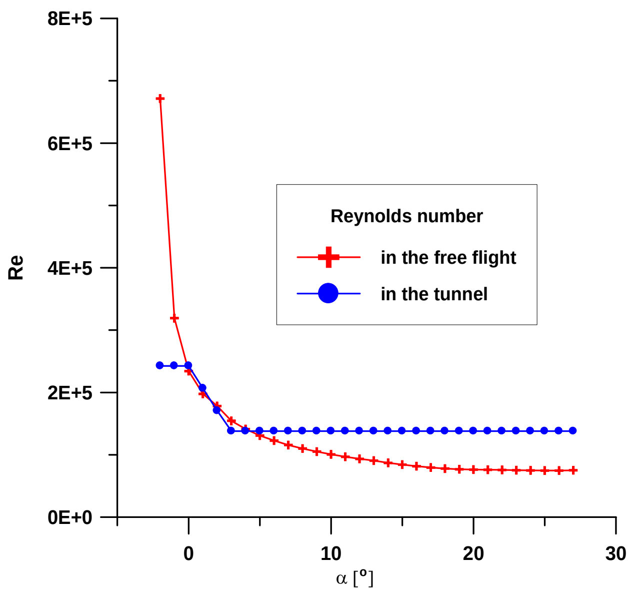


Fig.7 Wind tunnel Reynolds number applied to measure the steady flight polar. For the comparison Reynolds number experienced in flight by a 170g MAV.

Maximum wind tunnel airspeed was constrained because of the uncertainty concerning the shape of lift coefficient versus angle of attack characteristic (Cl(α)). The maximum airspeed predicted for free flying airplane could damage it in the wind tunnel if used with an incorrect angle of attack. The minimum wind tunnel airspeed was also constrained. Thus, it was anticipated that flow instability at large angles of attack would be magnified if the wind tunnel airspeed were not stabilised. Hence the airspeed was kept constant after Cl=0.3 was achieved. Airspeeds that could be achieved by 170 g airplane in the free flight are presented for comparison. They were calculated given the lift coefficients measured in the experiment.

4.3 Measurement results

Figures 8–10 show the main result. In this case the elevator was set to the loitering position. It is clear that all the LEX configurations provide increased maximum lift coefficient and stall angle in the motor off mode as expected. Unexpectedly, both maximum lift coefficient and stall angle are even greater in the motor on mode. Thus, propeller operation appears not to be problematic for the leading edge vortex in this configuration. The LEX effect is increased rather than reduced.

The vertical thrust component was subtracted from the measured lift curves to verify if lift could be increased by rotation of thrust vector only. Figures 11-15 show the results of this operation. Motor off lift curves measured during first part of experiment are shown for comparison. Unfortunately, the Re number for the motor-off curves are slightly smaller than the steady flight Re number applied during the second phase of experiment. However, the thrust vector rotation effect seems to be too small to explain the total lift increase.

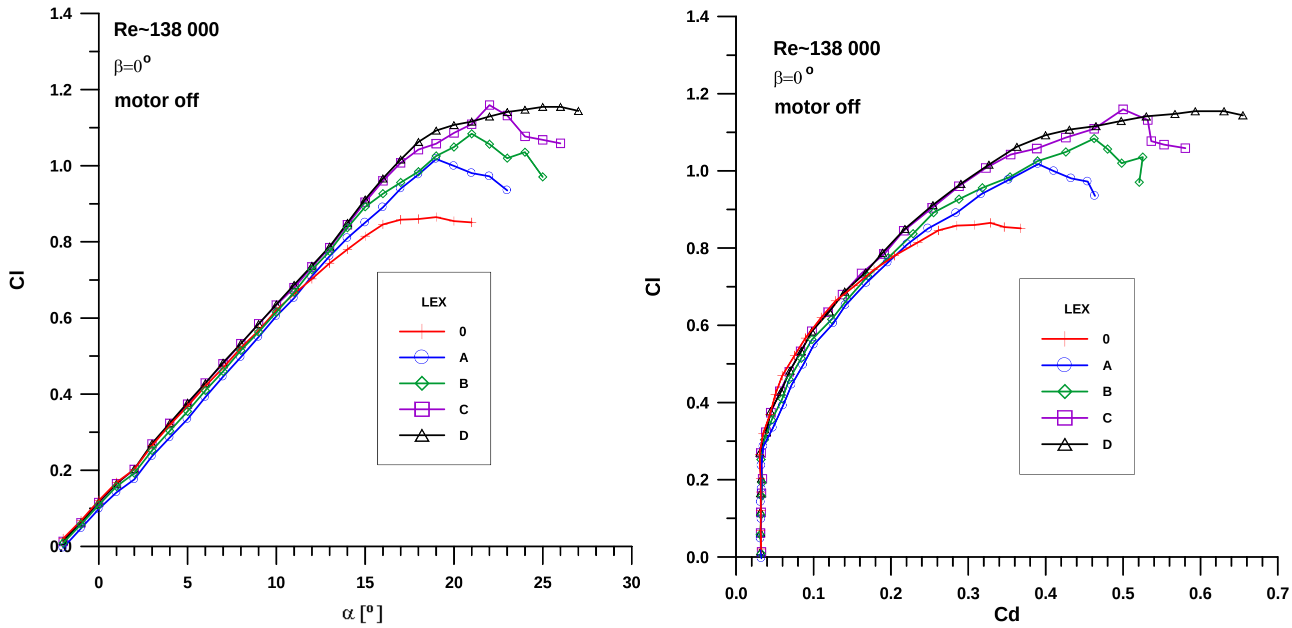


Fig.8 Characteristics measured with elevon neutral and motor switched off

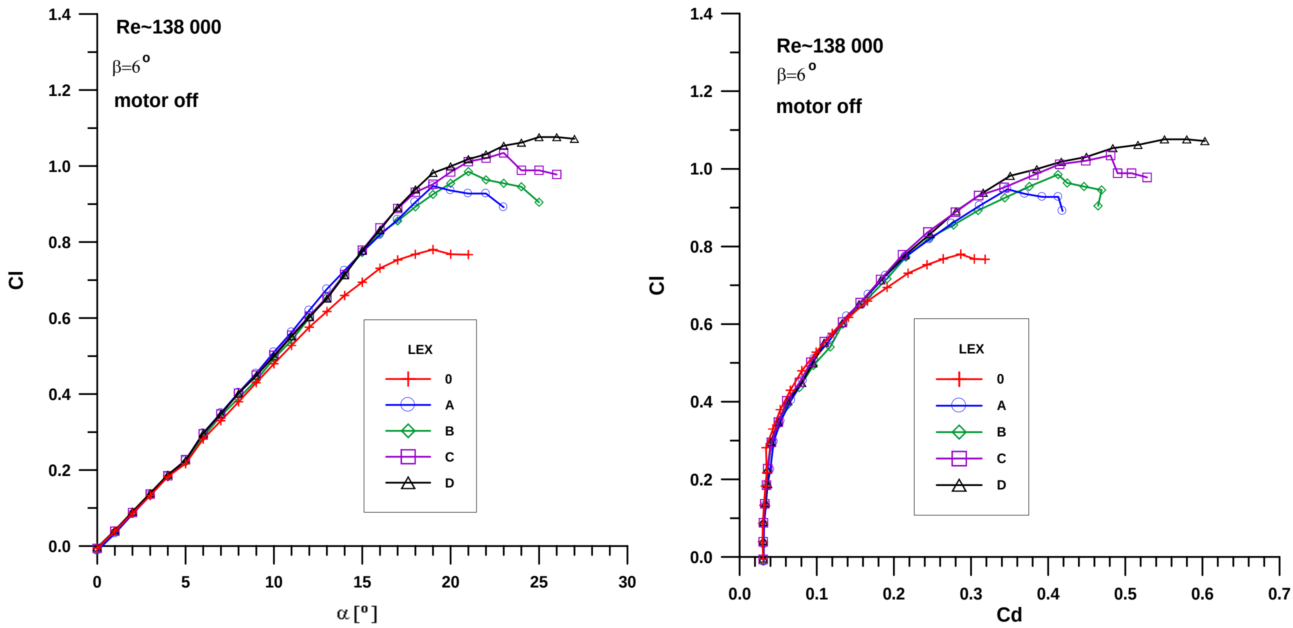


Fig.9 Characteristics measured with elevon angle of 6° and motor switched off

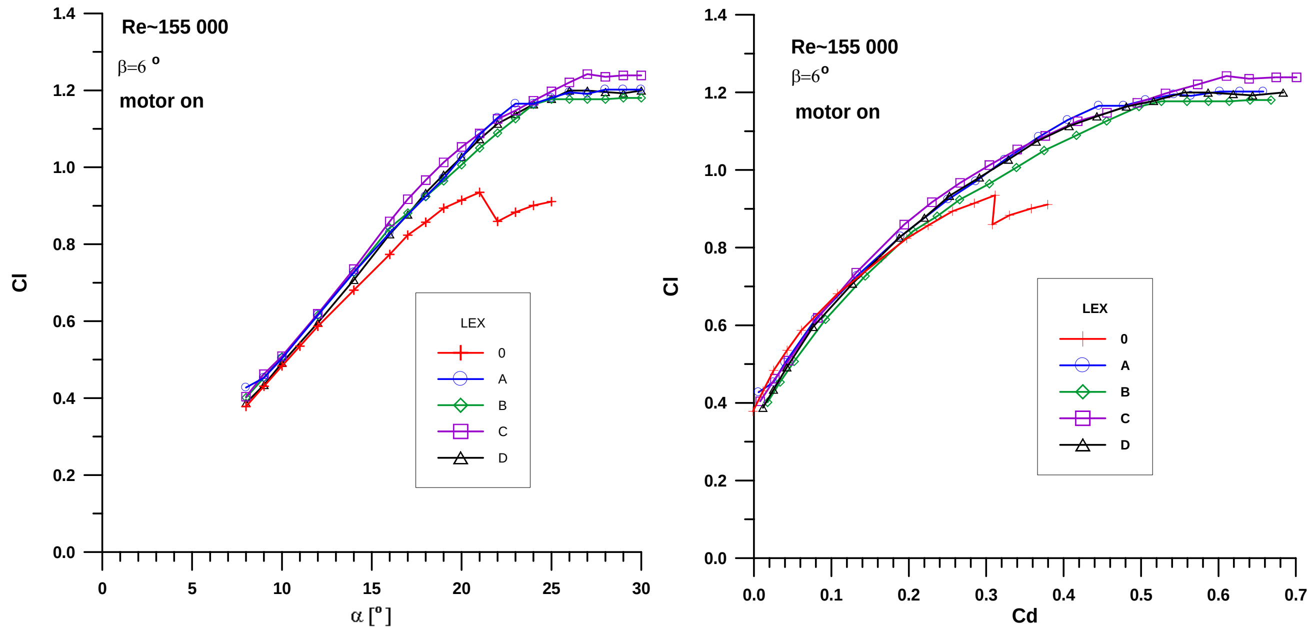


Fig.10 Characteristics measured with elevon angle of 6^o, motor switched on and Re~60 000

Figures 9 and 10 allow another comparison where it can be seen that the difference between LEX performance seems to be smaller if the motor is operating. This observation may suggest that the angle of attack was effectively decreased in front of the propeller thus excluding this part of the LEX from vortex generation. In such cases only outboard LEX segments would be responsible for lift increases. The difference between LEX geometries was much smaller in outboard segments.

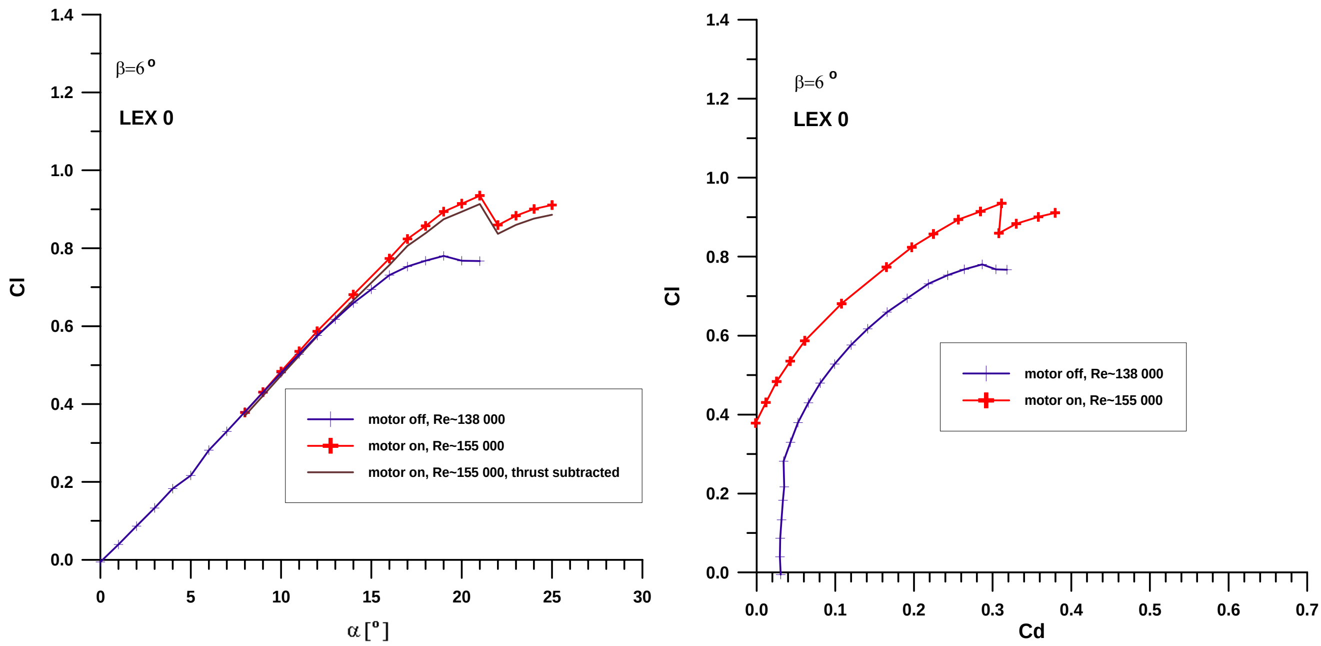


Fig.11 Clean configuration characteristics measured with elevon angle of 6^o

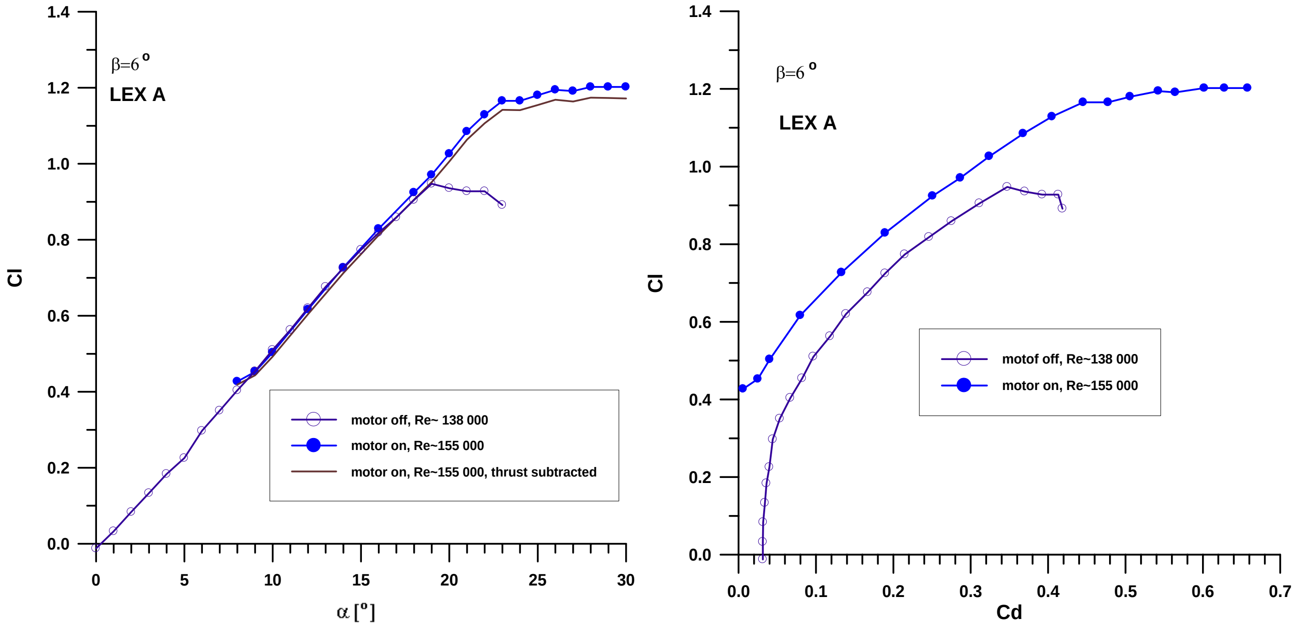


Fig.12 Characteristics of the configuration with LEX A measured with elevon angle of 6°

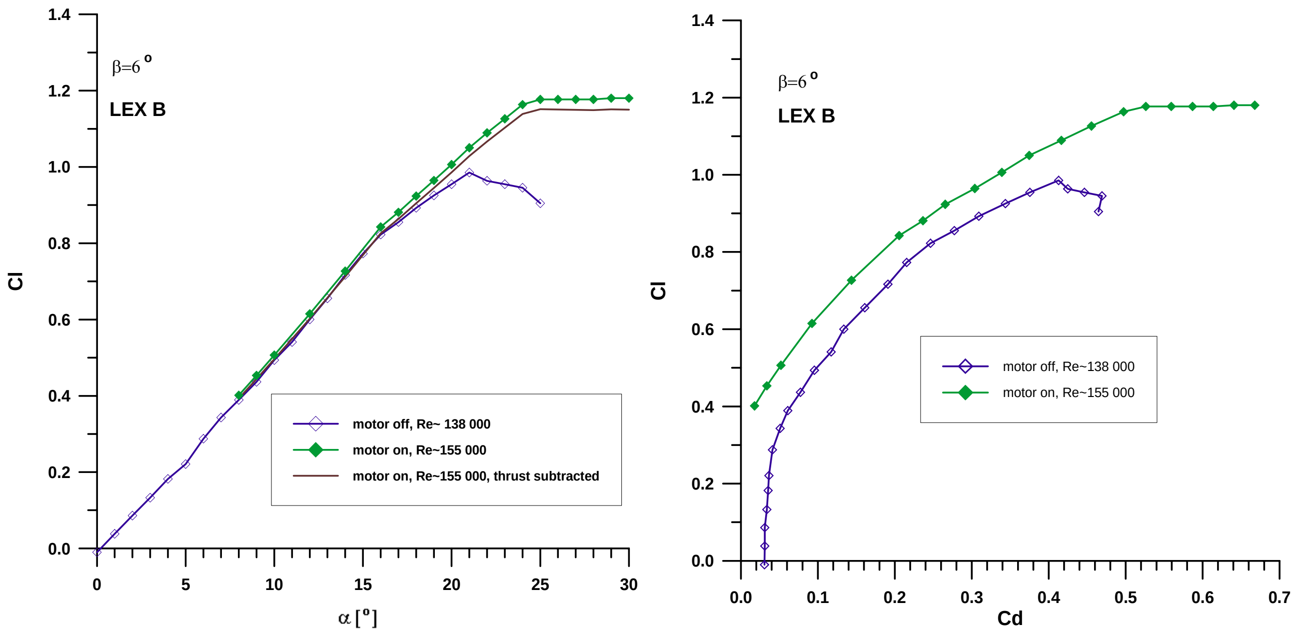


Fig.13 Characteristics of the configuration with LEX B measured with elevon angle of 6°

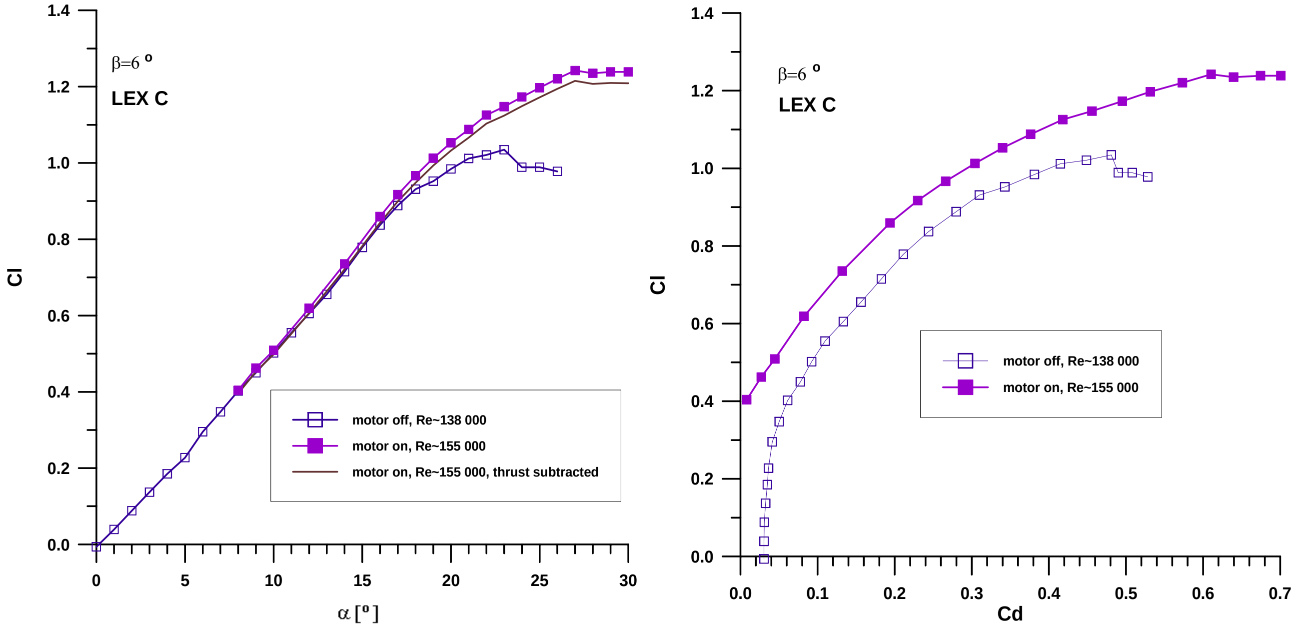


Fig.14 Characteristics of the configuration with LEX C measured with elevon angle of 6º

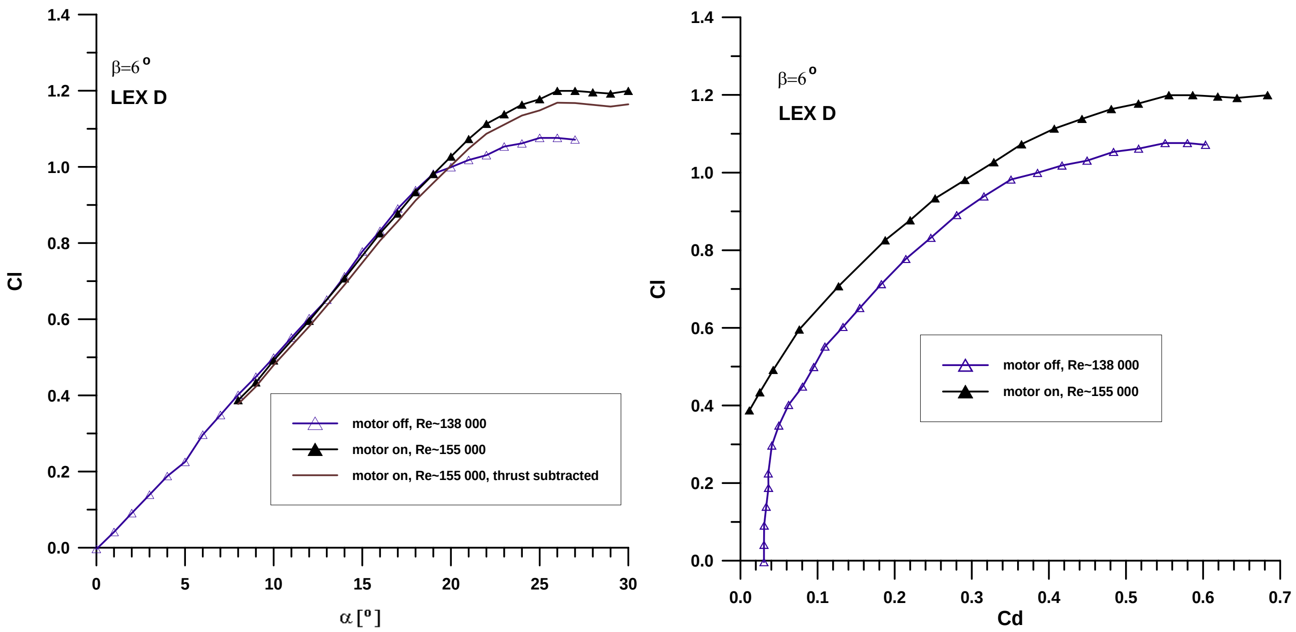


Fig.15 Characteristics of the configuration with LEX D measured with elevon angle of 6º

A flow visualisation experiment was also undertaken to further explain the lift increases.

4.4 Flow visualisation

Figures 16-18 show the separated flow close to the wing tip in motor off mode and attached in motor on mode. Three outboard tufts close the leading edge provide the clearest evidence. This shows that the lift increase is not caused by a vertical thrust component only, but also by more general flow improvement over the whole wing. The phenomenon observed here seems to be similar to sonic flow excitation effects described in [4-7]. The major difference is the method of excitation. At this time propeller passes through the slot with a frequency of about 250Hz thus generating pressure waves. This probably makes the flow less likely to separate hence increasing both the lift coefficient and stall angle.

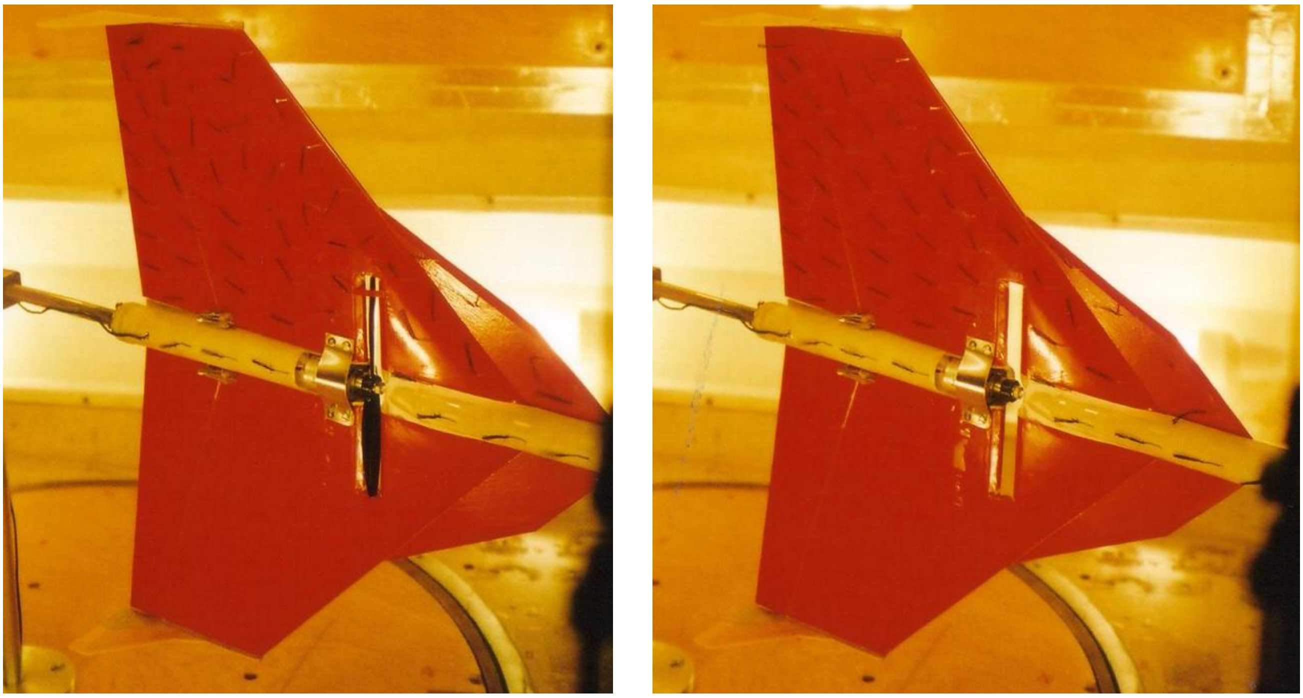


Fig.16 Propeller effect for angle of attack of 20°.

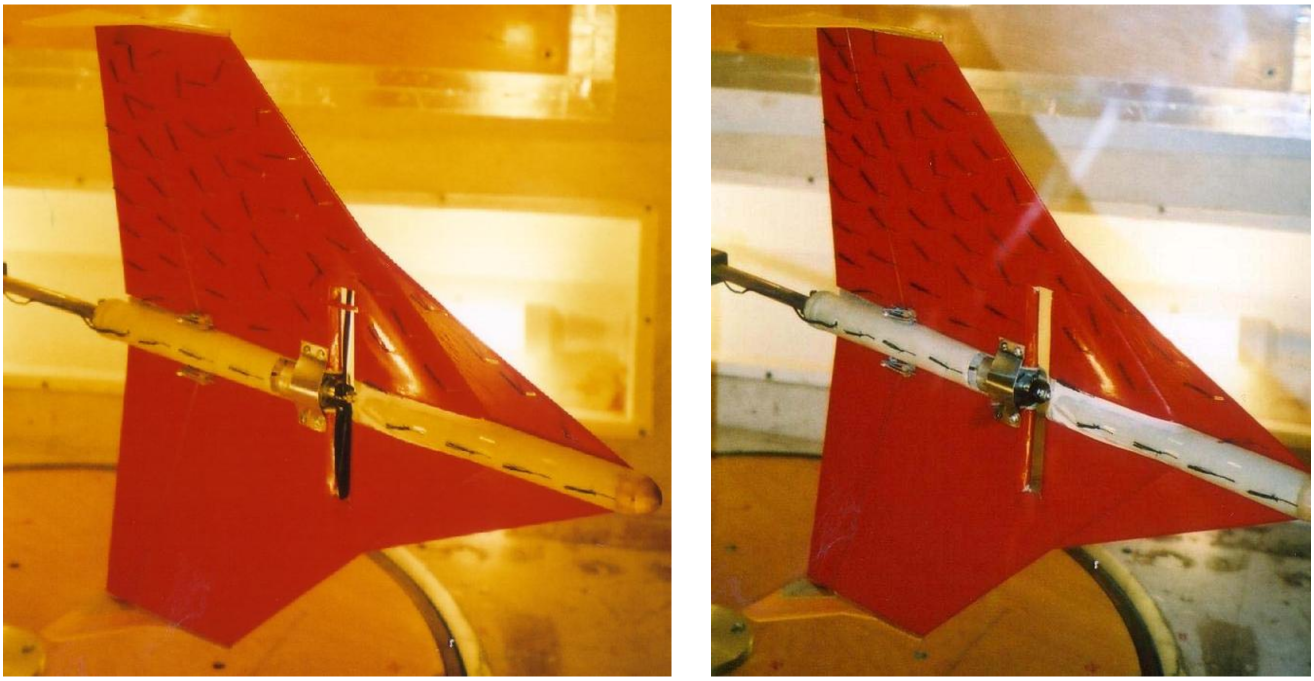
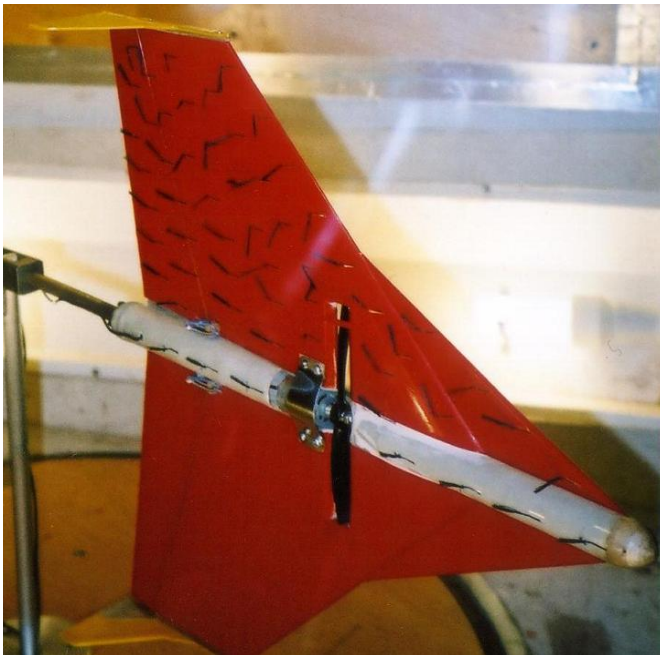


Fig.17 Propeller effect for angle of attack of 25°.



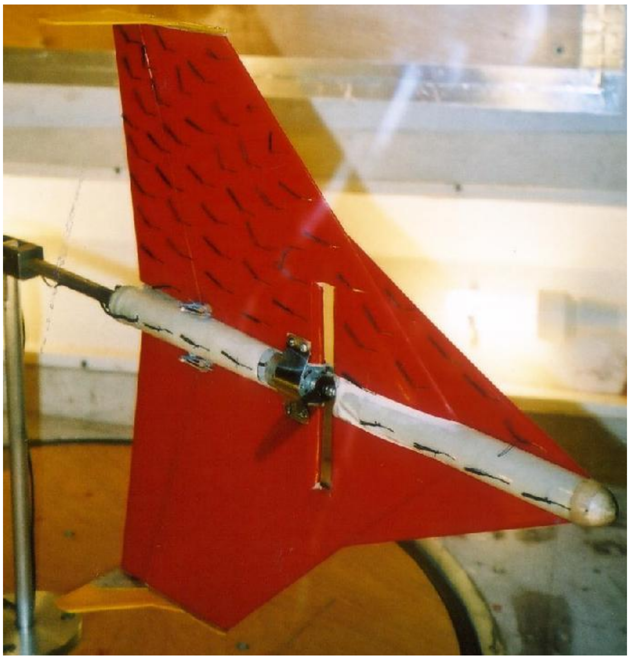


Fig.18 Propeller effect for angle of attack of 30°.

5 Conclusions

- Leading edge extensions (LEX) can be successfully integrated with the propeller propulsion, generating a leading edge vortex in the neighborhood of the propeller stream.
- The effect of the propeller rotating in the slot seams to be similar to the effect of a vibrating membrane.
- Flow asymmetry effects due to LEX/propeller interference should be explored before described configuration is applied in a flying prototype.

6 References

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