Numerical, Experimental and Flight Investigation of MAV Aerodynamics

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Presented are the results of complex numerical, experimental and flight investigations of MAV aerodynamics. Numerical investigations concern the questions of pressure distribution on the profile. A comparison with the experimental results was made. A set of experiments was conducted in wind tunnel: pressure distribution on the wing, experiments with the wings of various shapes but the constant wing span, with and without winglets. Also the influence of profile thickness and the effect of flexible wing on aerodynamical characteristics were investigated. The full MAV model (which is used in flight tests) with working powerplant and deflected control surfaces was investigated in wind tunnel. Characteristics of whole MAV balanced for level flight and the influence of air flow from the powerplant on the MAV characteristics were obtained. To compare the results obtained with the real MAV characteristics there a set of flight experiments was conductred. Finally, the experiments of flow visualization on MAV during the level flight and for the set of maneuvers were carried out.

Nomenclature

C_L	=	lift force coefficient
C_D	=	drag force coefficient
C_D	=	drag force coefficient at zero lift force
D	=	drag force
L	=	lift force
S	=	wing area
x	=	coordinate along the chord
z	=	coordinate along the wing span
λ	=	aspect ratio

I. Introduction

MICRO Aerial Vehicles (MAVs) fly at Reynolds numbers, which corresponds to a laminar-turbulent flow transition. There are a lot of factors affecting the vehicle aerodynamics such as the boundaries smoothness, initial flow conditions, wing shape, etc. Moreover, the low aspect ratio implies a significantly three-dimensional flow. That's why the analytical methods are not good enough for the aerodynamical MAV design.

Nevertheless, for the design process one must have some knowledge about the aerodynamics peculiarities of MAV wings (influence of wing shape, aspect ratio, winglets etc.). So, complex investigations concerning the possibilities of numerical calculations of MAV characteristics and their validation through the wind tunnel and

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flight experiment were conducted. Also a set of wing tunnel experiments concerning the influence of some factors on the MAV aerodynamics such as wing shape, wing thickness, wing flexibility, flow from powerplant and winglets wee carried out. A set of joint tunnel and flight experiments of real MAV “KORSHUN” with working powerplant and deflected control surfaces to compare wing tunnel results with “real” ones were made.

II. Numerical investigations

Numerical investigations of pressure distribution and integral characteristics (C_L, C_D) of profile and its comparison with the experimental results were conducted.

These investigations for pressure distribution were made with the help of XFoil program. The experiment was carried out with drained model in T-124 wind tunnel (TsAGI) (Fig. 1). Results for z=0.5, C_L=0.245 and Re=205000 are shown in Fig 1. One can see that there exists a separation bubble on the upper surface of the wing. XFoil with free laminar-turbulent transition gives the result which is near to the experiment. But it should be mentioned that XFoil with fixed transition cannot catch separation.

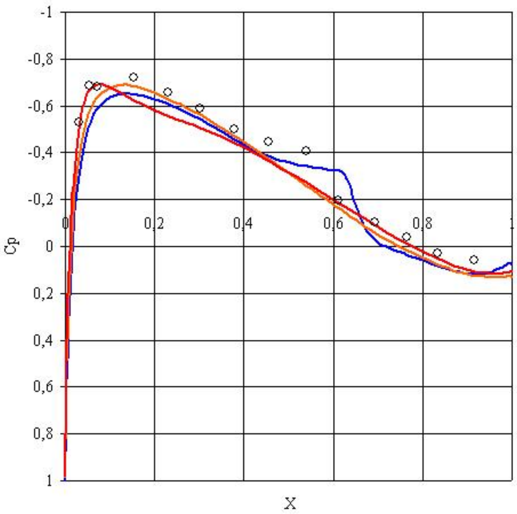


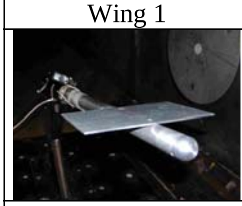
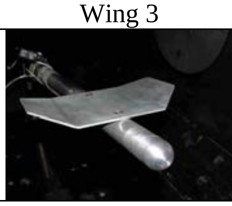
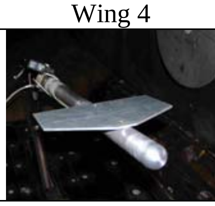
Figure 1. Experimental model for pressure distribution (left) and the results of experiment for Z=0.5, C_D=0.245, Re=205479 (right). Red line – XFoil with fixed transition location, blue line – XFoil with free transition location, small circles – experiment results.

As the conclusion, Xfoil program can be used for the investigation of pressure distribution on the wing for the Reynolds numbers corresponding to MAV flight conditions.

III. Wind tunnel investigations

A set of wind tunnel investigations was conducted. First of all, influence of the wing shape and aspect ratio λ on wing characteristics was investigated. Five wings with the same wingspan (0.3 m) but different shapes and wing areas were tested (see Table 1). Profiles of all the wings were flat planes with the thickness of 4 mm.

Table 1

Wing 1	Wing 2	Wing 3	Wing 4	Wing 5
				
λ=1.5	λ=1.92	λ=1.7	λ=1.76	λ=1.82

Shown in Fig. 2 are polar curves for these models.

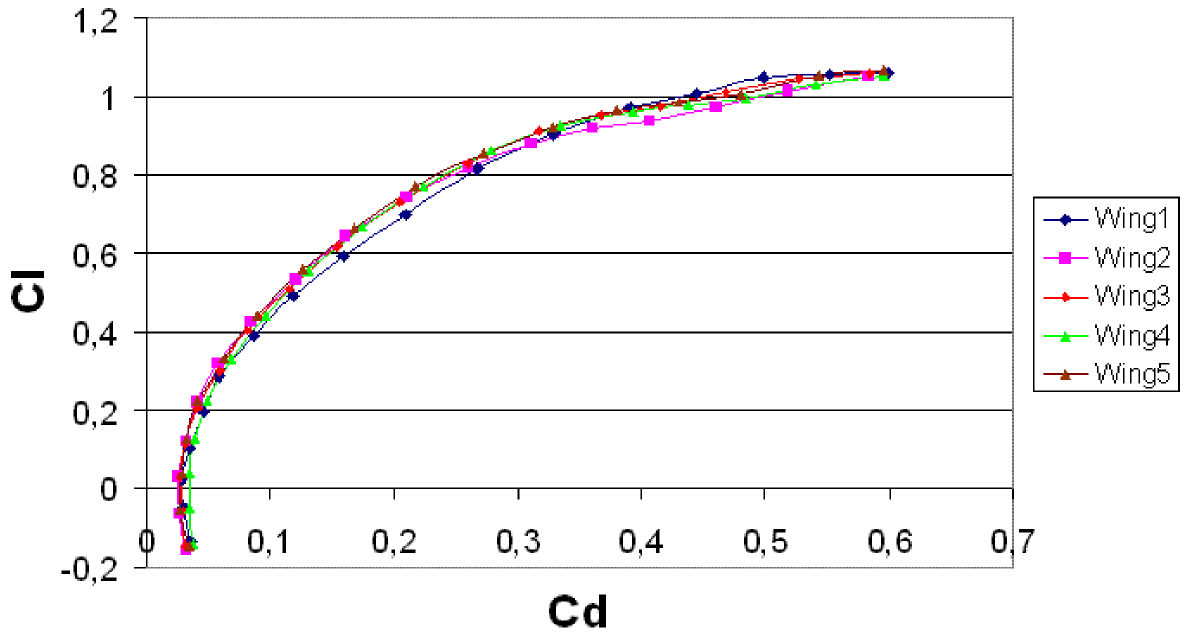


Figure 2. Polar curves for the wing investigated

One can see that THE elliptical wing has the smallest value of C_{D0} but has higher A value of C_D at high C_L. Also it should be noted that the rectangle wing has higher values of C_D at low C_L but lower C_D at higher C_L.

But these data are of great importance only if we can vary the wing span (and, as a consequence, wing area). For MAVs the maximum wingspan value is fixed, so the wing shape automatically defines the wing area. From this, one must have the “real” polar curve $S{\cdot}C_L(S{\cdot}C_D)$, or, in dimensionless case, $C_L(C_D/\lambda)/\lambda$. This curve gives us the necessary information about the advantages or disadvantages of various wing shapes. Such curves are shown in Fig 3.

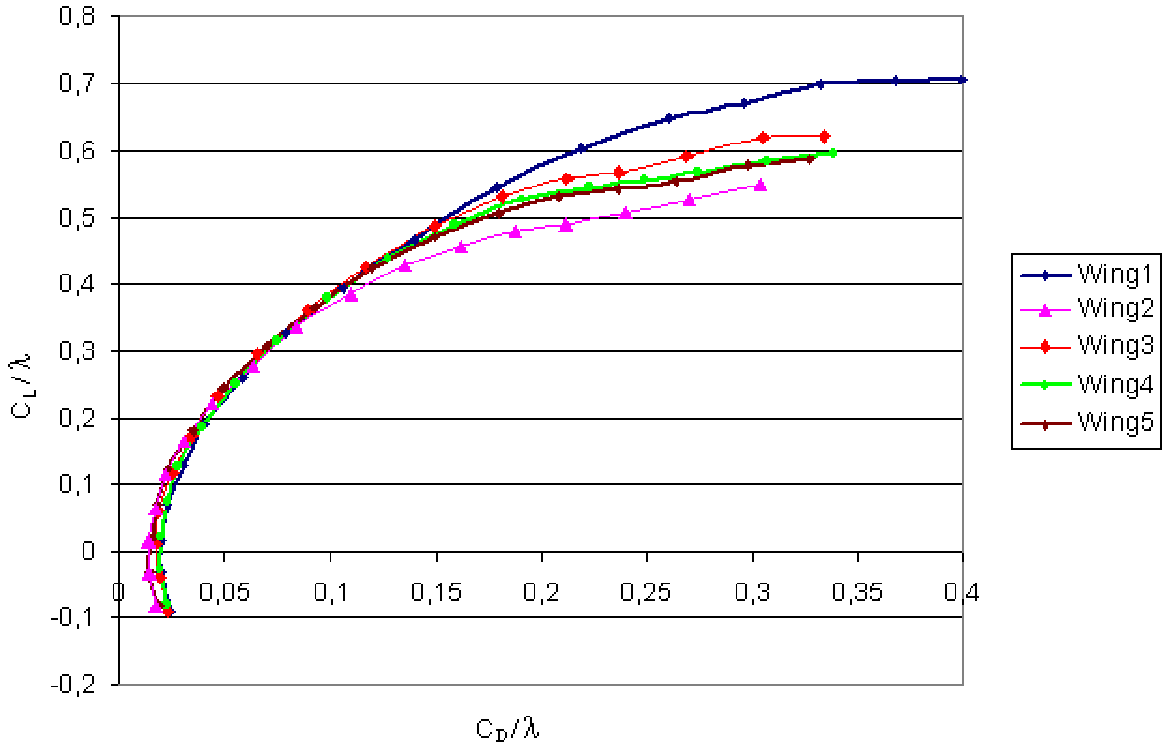


Figure 3. “Real” polar curve for the wings investigated.

One can see that for the low C_L/λ (C_L/λ <0.2) elliptical wing has the lowest C_D/λ comparing to other wings. In the region of intermediate C_L/λ all the wings have nearly the same C_D/λ, and at high C_L/λ the wings with lower λ are preferable. From this, as MAVs fly at intermediate C_L/λ, so one can choose any of MAV's wing shape on the basis of other requirements without drag increase.

It should be mentioned that the results obtained are valid not only for the wings investigated. Processing of the results from Ref. 1 leads to the same conclusions.

The knowledge of the polar curve and the value of $L/D(C_L)$ is needed for the task of trajectory length maximization. But for the task of flight time maximization one must know the value of $C_L^{1.5}/C_D$ (let's call it "Energetic Efficiency" or EE). The results for "energetic efficiency" are given in Fig. 4.

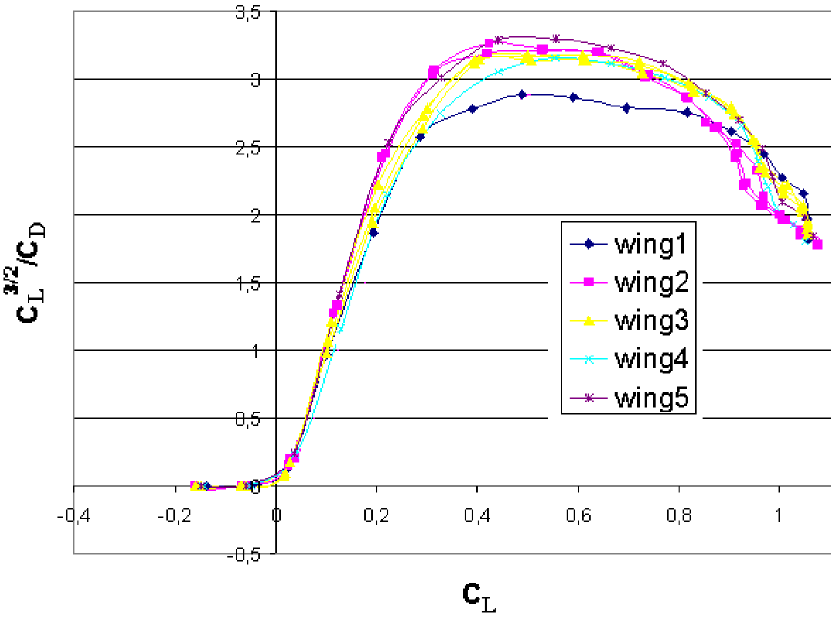


Figure 4. "Energetic efficiency" for the wings investigated

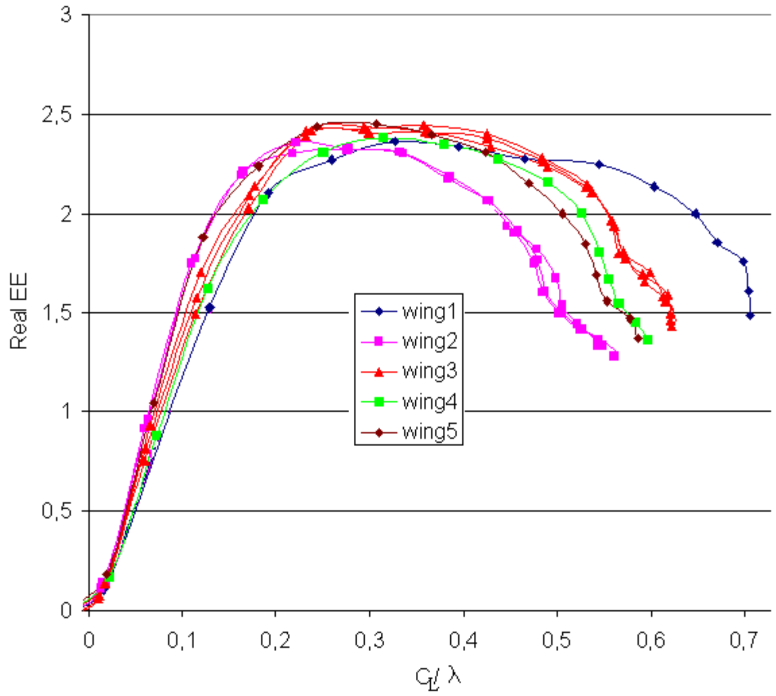


Figure 5. "Real energetic efficiency" for the wings investigated.

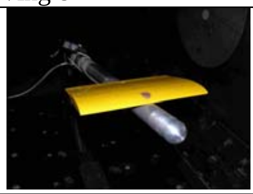
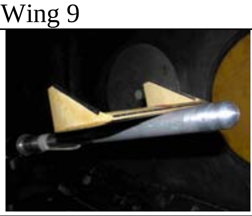
But as in the previous case, for the fixed wing span one must use another parameter, which is proportional to $C_L^{1.5}/C_D/\lambda^{0.5}$ (let's call it "real EE") as the function of (C_L/λ). The results for this function are given in Fig.5.

One can see that for small values of lift force the elliptical wing is preferable for flight time maximization. For the moderate values of the lift force all the wings give practically the same characteristics, and for high lift force the less λ (or the higher area) the better.

Also it should be mentioned that the values of C_L that provide the maximum L/D and EE are rather close to each other for the same wing.

The next set of experiments was conducted to obtain the influence of the profile with thickness, flexible wing surface and winglets on the MAV aerodynamics. Wings investigated are given in Table 2.

Table 2

Wing 1	Wing 7	Wing 8	Wing 9
			
flate plane	profile	profile, flexible	profile, winglets

All the wings have the same aspect ratio λ=1.5, so one can compare them directly. "Flexible" wing had rigid leading edge and trailing edge, and 50% in the middle of profile was flexible. Polar curves for these wings are given in Fig. 6. One can see that profile with thickness provide better characteristics. Also, the flexible wing gives some advantage in comparison with the rigid one. Winglets are effective only if C_L>0.3, and for C_L=0.6 the drag coefficient reduction in the case of winglets is about 20%.

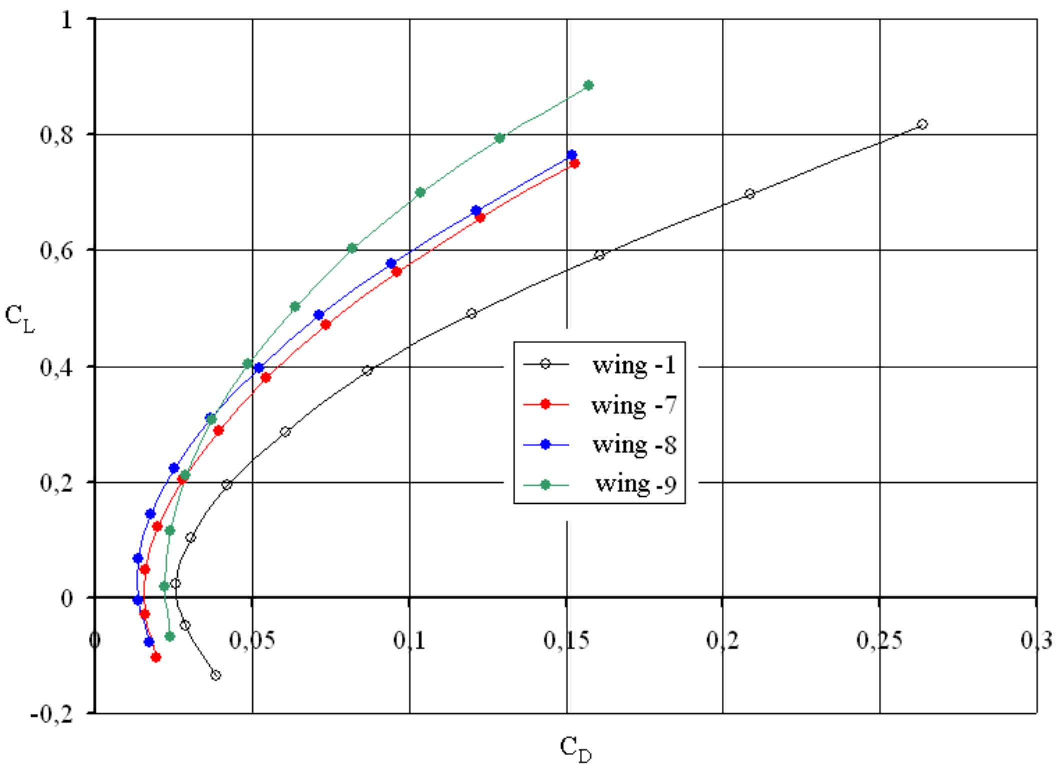


Figure 6. Polar curves for wings 1,7,8,9

Also the influence of the flow from propeller on wing characteristics for the wing with winglets was investigated. The result of this investigation is shown in Fig. 7. The axis of the propeller was parallel to the axis of the wing. The conclusion is that the maximal C_L and angle of attack increase in the presence of the flow from the propeller. Also if we compare the polars with and without the propeller flow by shifting one relative to another till the coincidence of C_{D0}, we will find the coincidence of all the polars until the separation region.

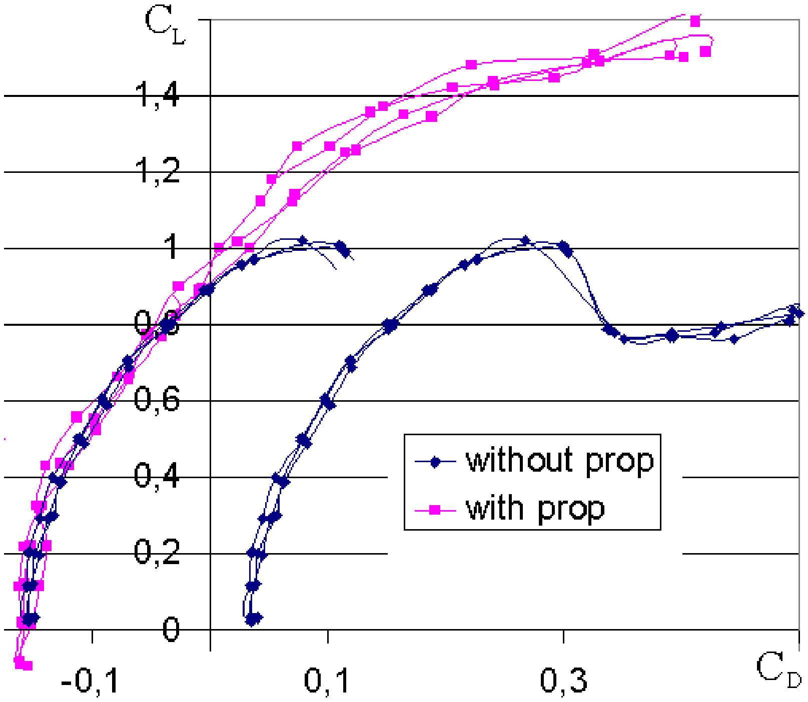


Figure 7. Polars for wing with and without flow from propeller. Polar without propeller (right blue) is shifted to the polar with propeller for the comparison

The next step was the experiments with a real MAV design (see Fig. 8). It is interesting to compare the data of the whole MAV and its wing (see Fig. 2, wing 3). One can see that the maximum of *L/D* in the case of MAV decreases at about 30%.

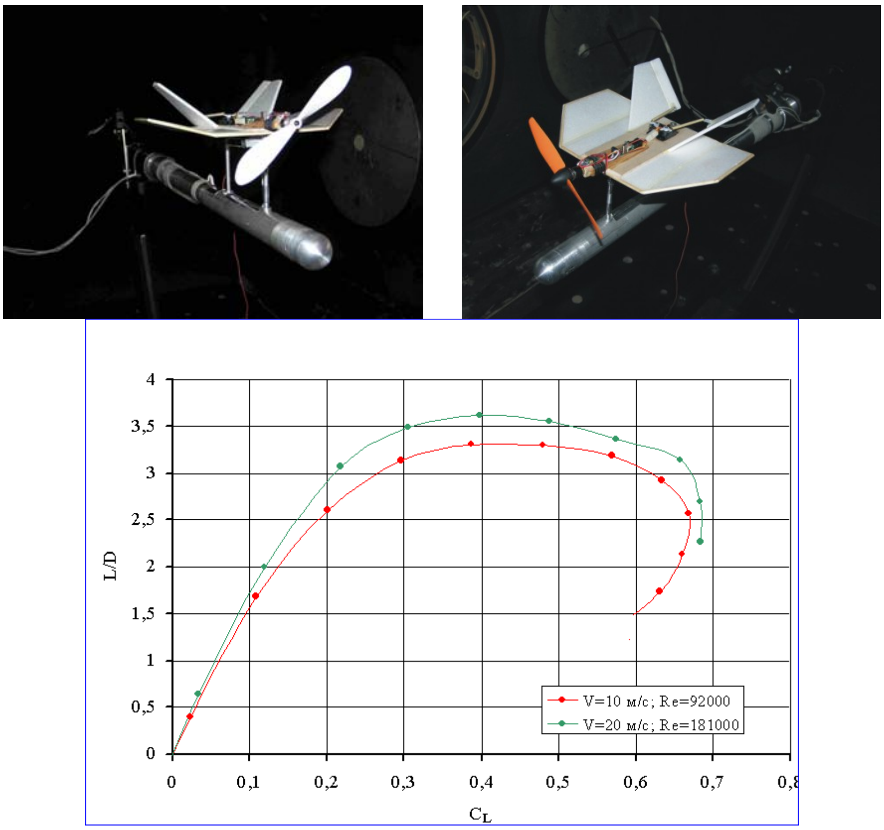


Figure 8. MAV “KORSHUN” with various propellers in wind tunnel and L/D for MAV “KORSHUN”

At least, the test of selecting the tunings (control surfaces deflections, rotational frequency of propeller) which provide the level flight without acceleration was made.

IV. Flight experiments

First of all, test flights with the tunings obtained in the wing tunnel were conducted. As it was expected, MAV flew horizontally with the velocity corresponding to the flow in the wind tunnel.

The next experiment was flight with silk threads on the upper surface and the on-board camera for the flow visualization during the level flight and some maneuvers. The results obtained show that the flow separation without reattachment occurs only on the wing tips.

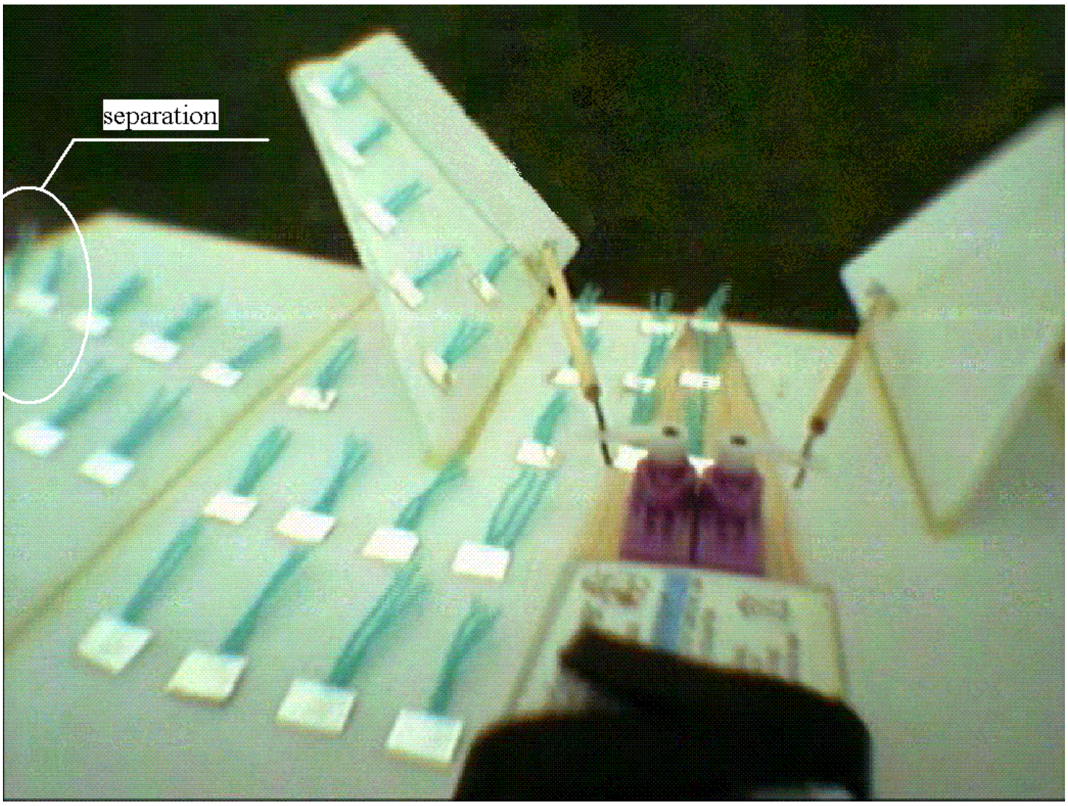


Figure 9. Flight experiment with silk threads

V. Conclusions

The results obtained allow to make some conclusions.

1. XFoil program can be used to determine the location of a separation bubble.
2. All the wing with the same wing span give nearly the similar characteristics in the region of moderate C_L.
3. Profiled wing, flexible wing can improve the MAV characteristics. Winglets are effective for C_L>0.3.
4. Wind tunnel experiment results are in coincidence with real flight.
5. A separation without re-attachment on the MAV with the working powerplant occurs only on the wing tips.

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References

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