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One Idea of Propeller for Low Reynolds Numbers

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Abstract

The main idea is to make larger the propeller relative chord length (with respect to diameter) with the dimensions decrease. So, at several dimension this propeller will look like the marine screw. The analysis of the small marine screw design applicability for MAVs is discussed.

1 Introduction

One of the difficulties for MAV dimensions miniaturization is propeller dimensions. One can see that the propeller diameter with respect to wing span of MAVs becomes greater and grater with the wing span decrease (see fig. 1). So, for some wing span the propeller diameter can be equal to the wing span if the existing technology of propeller design is used. Of cause, this situation is unacceptable if we have the limitations on the maximal aircraft size. From this, some other ways for propeller design of very small MAVs must be found. One of the proposals is to use "marine screw"-like propellers.

2 Problem statement

Very useful for the propeller performance description are dimensionless characteristics: thrust coefficient C_T, power coefficient C_P and efficiency η as function of advanced ratio J:

$$J = \frac{V}{nd}, \quad C_T = \frac{T}{\rho n^2 d^4}, \quad C_P = \frac{P}{\rho n^3 d^5}, \quad \eta = \frac{C_T J}{C_P},$$

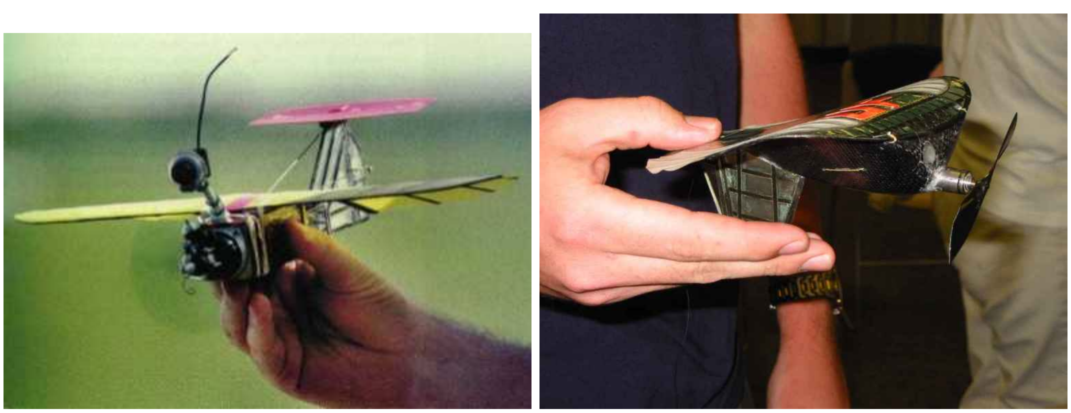

Figure 1: University of Florida MAVs

where V — air velocity at infinity, n — frequency of propeller rotation, ρ — air density, d — propeller diameter, T — propeller thrust, P — propeller power.

It is well known that for the fixed Reynolds number Re these coefficients are independent of dimensions and velocities. The behavior of these characteristics at low Reynolds numbers was investigated, for example, in [6].

Imagine that one have the propeller tuned for some flight regime (for example, the best efficiency for defined propeller diameter, flight velocity and thrust) and want to use this propeller dimensionless geometry for the other propeller diameter and flight conditions.

If one simply change the propeller size proportionally in all dimensions, then, for the same advanced ratio the thrust changes as forth power of diameter and the power changes as fifth power of diameter. But the same advanced ratio at changing the propeller diameter assume either that flight velocity is changed or frequency of propeller rotation is changed.

In the case of constant velocity the frequency must be changed inversely proportional to the diameter, so the thrust is totally changed as second power of propeller size. (If we resize the airplane in such way, the drag, lift and power required also change as second power). So, in this case some possibility of thrust and drag equivalence exists. Here we not take into account the effects of low Reynolds numbers.

But in the case of resizing dimensions and decreasing the flight velocity or in other cases one can't obtain the equivalence of thrust and drag at fixed propeller advanced ratio. So, in this case one must change either the advanced ratio or propeller geometry.

First of all, one can change the angles of profile installation along the blade and doesn't change the chords length. This way enable to optimize the propeller's characteristics in rather close limits.

Second, one can increase the number of blades. In this case the propeller efficiency can slightly decrease.

Third way is the increasing the chords length. From aerodynamical point of view for the small Re one blade is better than two blades of the same total chord. (There even exist the examples of propeller with one blade, see fig. 2.) In MAV practice from time to time one can see that the aircrafts has propeller with cut blades, see fig. 3. This method increases relative chord of propeller blade.

Increasing the chord of blade one make the propeller more and more like the marine screw. And at some moment can appear the idea of using the marine screw geometry for the MAV propeller.

3 Analysis

Let's make some comparisons. As an example of "marine screw" can be taken the screws investigated in [4]. A set of screws was tested in water tunnel (see fig. 4).

Characteristic data for these experiments were: frequencies of rotation - 1700–5000 RPM, water flow velocity — 9–14 ft/s, screw diameters — 2–2.5 in, Pitch/Diameter — 1.4–2.0.

So, maximal Reynolds number (for characteristic chord length of 2 sm and velocity at the end of the blade) is about $Re = 10^5$. One must keep in mind that in main part of data points from [4] Re is lower than 10^5.

Maximal value of efficiency obtained in these experiments is about 60–70% (see fig. 5).

Also one can see from fig. 2 that the maximal thrust coefficient C_T (denoted on the graph as KT) corresponding to $J = 0$ is about $C_T = 0.5$. For the model airplane 2-blade propeller this value is about $C_T = 0.1$ [1].

It should be mentioned that the propellers analyzed were for hobby boats, i.e. hardly have the best performance available. So, they should be compared with the propellers of the "same nature" i.e. small propellers for hobby aircrafts. For example, propeller U80 has maximal efficiency of about

Figure 2: Examples of one blade propellers

40–50% for $Re = 50000$ [2]. Data from [1] also show that efficiency of small propellers is low enough, see fig. 6.

Also one should compare the above data with the propeller performance of BlackWidow MAV [3] (see fig. 7). The propeller data are: diameter — 3.81 inch, pitch — 6.04 inch ($P/D = 1.58$), frequency 5000 RPM, velocity blade tip $V_{\text{tip}} = 25$ m/s, $Re = 50000$, efficiency — 80%.

4 Discussion

At the times of "aviation childhood" and "aviation youth" there was the division of air propellers and marine screws, see. fig. 8 [5]. As we can see above, with the decreasing the dimensions of MAV it is better to make the propeller blade wider and angle of blade installation bigger. This enables to obtain more thrust at nearly the same or better efficiency.

Also it should be noted that the propellers for hobby boats and aircrafts are not with the best efficiency, and example of Black Widow propeller shows that the proper design can improve the performance.

Figure 3: MAV propeller with cut blades

Figure 4: Screws tested in [4]

The reason of usage of "aircraft propellers" can be explained by the fact that for propeller efficiencies of 90% and more the part of efficiency losses due to the thrust is comparable with losses due to friction drag and it is well known that larger diameter for the same thrust gives better efficiency.

But in the case of restrictions on aircraft dimensions (and especially for MAVs) the part of efficiency losses due to friction becomes much more larger that for higher efficiencies. In this case it's better to use the propellers with wider blades. So, an some size the propeller can looks like "marine screw" (one can say that even a Black Widow propeller looks a little like marine screw).

The design methodology for marine screw is well developed for boats and other water vehicles. Moreover, a lot of good screw designs were made. For a set of MAV applications it can be preferable to use the existing marine designs.

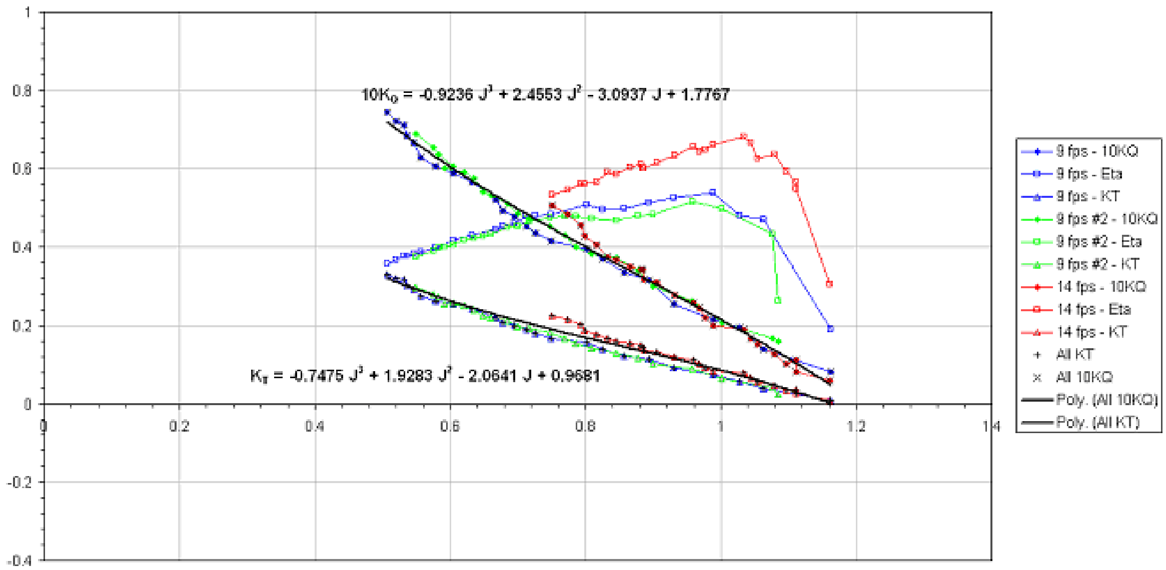

Figure 5: The corrected propeller performance curves for propeller 1457 [4]

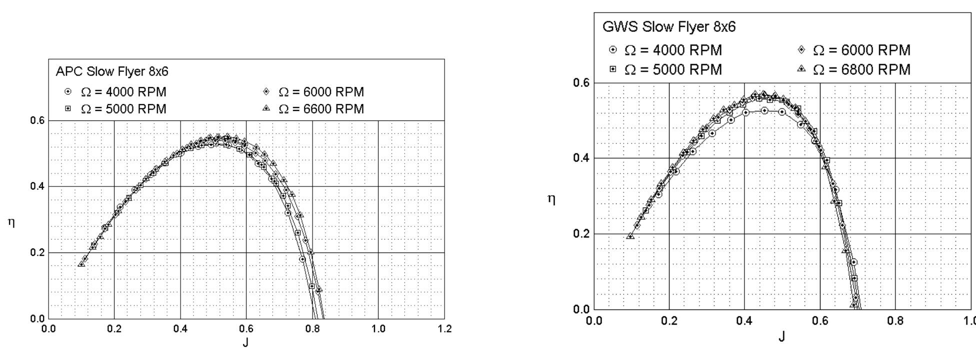

Figure 6: Examples of propeller efficiency, Re =40000–70000 [2]

5 Conclusion

The main conclusion from the above analysis is that it can be preferable to use the propellers with wide blades at higher angles of installation in MAV designs. It can provide higher thrust at nearly the same efficiency. Very good initial point for such propellers design can be the shapes of marine screw.

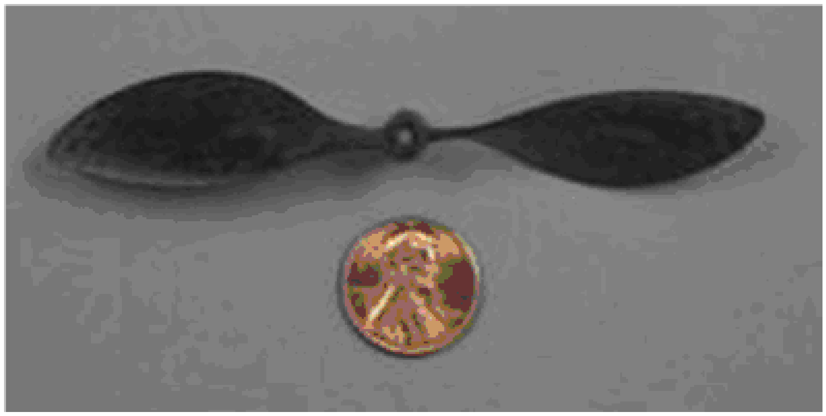

Figure 7: Black Widow MAV propeller

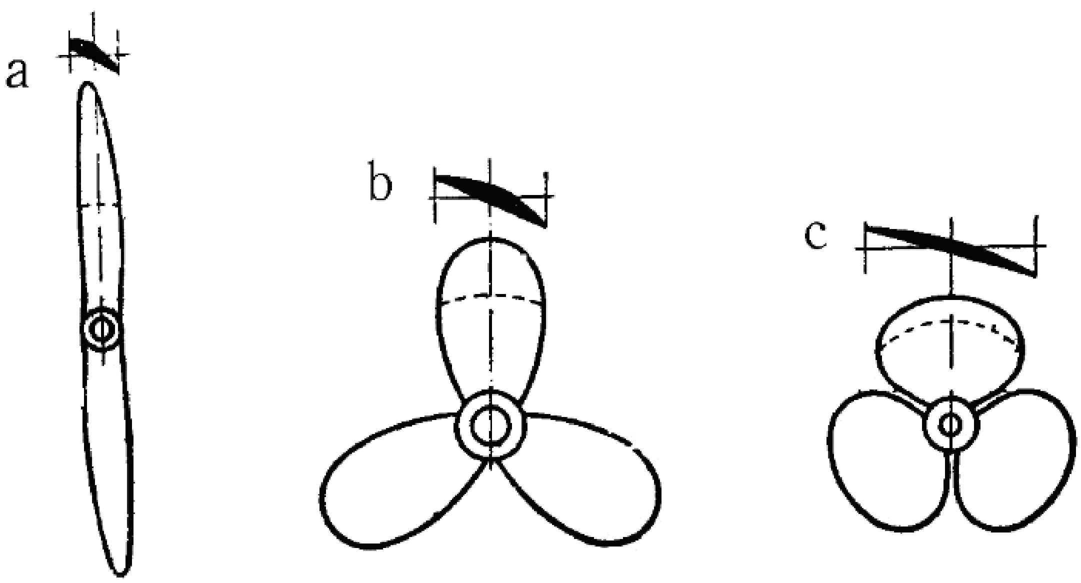

Figure 8:

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