STUDY OF A PROPULSION SYSTEM FOR A MINI UAV. MUDRONE PROJECT, ENSMM, BESANÇON.

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Abstract

Within the framework of the international universities mini UAV competition, the ENSMM (National Superior School of Mechanics and Microtechnics of Besançon) presents its µdrone project. It is based on the concept of a streamlined rotor with rotary wing. This article deals with different parts of the propulsion system namely coaxial-ducted rotor, brushless motor and propeller designing.

The coaxial rotor seems to be the best choice for a VTOL UAV in light of the high thrust-to-absorbed-power efficiency. Furthermore, research into brushless motor design along with the optimization of the duct resulted in the attainment of an acceptable level of noise. Moreover, the fact that propeller design should account for flight conditions was respected.

1 Introduction

1.1 International universities mini UAV competition

Set up by the ONERA — National Agency of Aerospatial Study and Research — and subsidized by DGA — General Delegation for Armament —, International universities mini UAV competition started in 2002 for an initial duration of 3 years. Opened to Engineers Schools and Universities, it seeks to demonstrate technical feasibility and operational interest of mini UAV with a less than 70 cm wingspan. One of the goals is to evaluate the degree of maturity of the technologies, especially miniaturization. Indeed, mini UAV components' size and weight reduction remains a major technology challenge. Intended to equip infantryman in 2010, these mini UAV will essentially be in charge of surveillance missions. The final flying test, which consists of a reconnaissance mission in a fighting town, will take place in May 2005. A 15k€ price will be given to the winner.

1.2 µdrone ENSMM project

The project submitted in June 2003 by the National Superior School of Mechanics and Micromechanics of Besançon (ENSMM) was ranked 3rd out of 20 Engineers School and Universities taking part in the competition. This mini UAV project named µdrone is based on an original concept, a propulsive system equipped with a coaxial-ducted rotor. This choice of aerodynamic shape was justified by stability and minimal sensibility to environmental stress criteria such as gusts. An electrical motorization was chosen because it guarantees flexibility, discretion and autonomy.

In order to assure a full autonomy and consequently the UAV automatic piloting, an avionic platform made up with different collectors and arithmetic units will constitute the aboard navigation system. An objective search and obstacle avoiding device by ultrasound telemetry, together with an acquisition and video processing specific system will finally equip the UAV to provide a sturdy and high-performance guiding and observation ability. A ground station will enable to keep communication with the UAV continuously in sight of all flying parameters analysis and thus insure security functions in allowing an operator to take back UAV partial or total control with a radio command.

The first part of the project has been performed by a team of 6 third-year-engineer-students trained by 7 engineers or researcher-teachers and had led up to the CAD shown below:

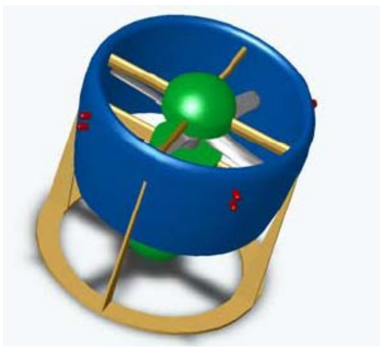

Figure 1: µdrone CAD r2003

The skills required pertain to many disciplines: aerodynamics, flying mechanics and propulsion, energy, microtechnology, computing, automatic control, artificial intelligence and transmission. Engineering-students working on this project have followed different teaching options organized around 5 major subjects: Automatic control and Production, Materials and Surfaces, Mechanics, Microtechnics and Optronics.

In February 2004, a second team of 24 engineer-students trained by 11 researcher-teachers or engineers had taken over to assure project continuity. Going back to the first study concepts made in 2003, different complementary studies have been made during February-June 2004 period. It concerns:

- Coaxial propulsive line,
- Single propeller propulsive line,
- Vibratory analysis of different structure elements,
- Behavior modeling,
- Enslaving by command law,
- Avionic and navigation,
- Transmissions between UAV and ground station,
- Navigation software competition,
- Environment observation,
- Obstacle detection and avoiding by ultrasound telemetry.

Work carried out during first semester 2004 leads to a CAD evolution depicted below:

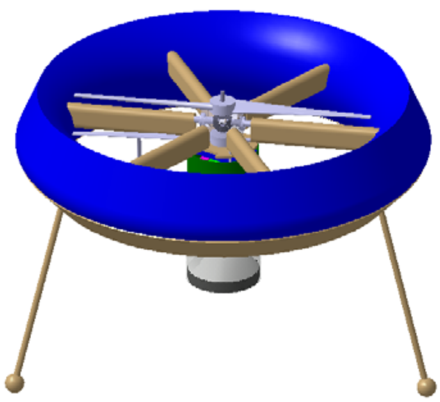

Figure 2: µdrone CAD r2004

Since September 2004, a third phase of the project is in progress to provide production of a first µdrone prototype near the end 2004.

2 Propulsive system

2.1 Engine

The motopropulsor group must be enough powerful to allow the UAV to move fast, be as light as possible and quiet. All of these constraints can be satisfied with the integration of two brushless rolling cage motors (cf. table 1). Their characteristics agree specially a direct link between motor shaft and propeller axe. A low pressure fan (low noise level) assures continue motor freshening in order to keep its performances invariable.

Motor Type	Brushless	Brushless LRK
Weight (g)	331 (with 50 for controller and 45 for gearbox)	264 (with 36 for controller)
Power (W)	750 max	500 to 850 (20s)
Amperage (A)	56	20 to 40 continue
Number of cells	10 to 30	8 to 30
Maximum yield	85	84 to 86 %
Kv (Rd/Min/V)	2633	5 values from 310 to 1120

Table 1: motors characteristics

In the ENSMM's configuration, two 500W (228g) motors put into the duct make the mini UAV naturally steadier (cf. figure 3). These two motors work at the same speed and provide a power comparable to the one of a single motor two times weightier (in the same series).

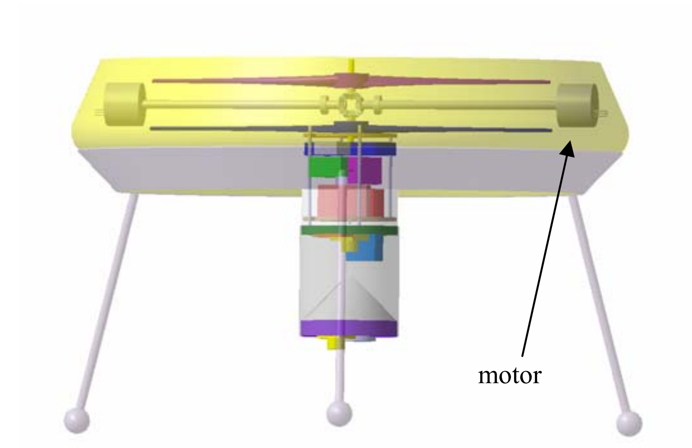

Figure 3: site of the two motors

2.2 Batteries

The number of cells is determined according to many criteria such as autonomy, power reserve, motor characteristics, life (number of cycles charge/discharge, etc…). The range of technologies for these elements is huge. In the framework studied, the more appropriate are Lithium Polymer batteries, which have higher performances than former technologies (NiCd and NiMH) for quantity of stored energy by weight unit (cf. table2).

Batteries type	NiCd (SANYO CP-2400 SCR)	NiMH (GP SANYO 3300 SCHR)	LiPo NPM-2000
Technology	NiCd	NiMH	LiPo
Capacity (Wh)**	2,35 x 1,1 = 2,585	3,465 x 1,1 = 3,811	2,1 x 3,5 = 7,35
Weight (g)	47	62	40
Densité massique mWh/g	55	61	194
Voltage (V)	1,2	1,2	3,7
Max discharge current (1 C = 1 Capacity)	30C	15C	15C à 75C*
Volume (cm^3)	10	10	17
Volume density mWh/cm^3	258	381	457

Table 2: batteries characteristics
* Parallel LiPo cells can easy reach 75C, this gives for a NPM-2000 cell a maximum discharge current of 150 Amperes.
** Cells voltage are given for a current equivalent to 50 % of the maximum discharge current.

In the configuration retained by the ENSMM, batteries are disposed into the duct (cf. figure 4), improving in this way natural system stability (out of guideline).

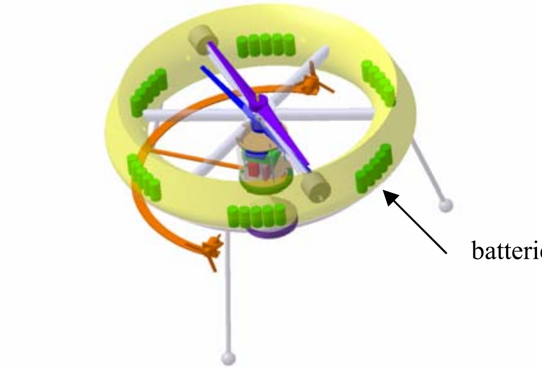

Figure 4: Batteries' site

2.3 Coaxial propellers

Coaxial propeller properties are studied and recognized for a long time. They were first used in 1933 on an Italian competition plane Macchi-Castoldi. Many countries have worked on this principle but it is Russia (especially when it was USSR) which realizes most of the planes and helicopters with coaxial rotors. Their main advantages [01], [02] in relation to single propeller are:

- an efficiency increased of 16 to 22%,
- a size decreased of 35 to 40% regarding a single propeller system with the same take off weight and the same available power,
- an important reduction of inertia moments.

Since both propellers do not provide an equal thrust (even if they have the same diameter), the size decrease is not 50% but 35% to 40%. Froude disc theory [03] allows to determine thrust ratio between the two propellers in agree with experimental data [04], [05], [06]:

$$\frac{T2}{T1} = 0{,}88 \quad (1)$$

Studies have shown that both propellers must have the same speed. Therefore a transmission by gears has been chosen. Furthermore, it reverses one propeller rotation direction in relation to the other. Use of spiro-conics gears (cf. figure 5) improves yield and lows noise level.

Figure 5: spiro-conics gears

The inter-propeller gap is the result of a compromise between theory and physic constraint. Ideally, propellers must be in the same plan to exactly cancel out their torques but they turn in opposite directions and their blades bend. Moreover, power is conveyed by the gearbox between propellers. Because of these points, they must be separate with a minimal gap.

Documents [04], [05], [06] as well as experiments (cf. table 3) have allowed to assess the optimal inter-propeller gap (H): it is propeller diameter (D) divide by 10.

$$H = \frac{D}{10} \quad (2)$$

	Inter-propeller gap	
	3 cm (D/10)	5 cm
Rotation speed in Rd/min	Thrust in Newton	Thrust in Newton
5500	8,1	5,3
7040	14	10,9
7670	17,3	14

Tableau 3: thrust versus rotation speed for two inter-propeller gap

Then again, propellers rotation generates vortex creation in blade extremities which are origins of many disadvantages. The next paragraph deals with a way to reduce them.

2.4 Duct

Vortex creation is an energy loss converted into noise pollution. So as to ward off this double issue, UAV can be equipped with a duct. A deal must be find again because inside diameter has to be the nearest of blades but not too, the latter lengthening under centrifugal force.

Furthermore, this wall can speed up air if its shape is optimized. For this, inside section decreases between air admission and exit, thanks to the Venturi effect [03]. A Matlab [08] program has been created to design inside shape and first calculations show that best results are reached for a equation profile as follow:

$$y = A \times e^{-\frac{x}{c}} \quad (3)$$

Prandtl observations [03] also show the necessity to correct the exit profile to make it lightly divergent, in order to keep a laminar flow. Once more, a deal will be finding because this phenomenon consumes energy.

Outside duct profile must be almost insensitive to wind to withstand to gusts but agree with dimensional competition criteria. That is why a "flying saucer" profile has been retained (cf. figure 6). Improvements will be brought after tests in an airfoil.

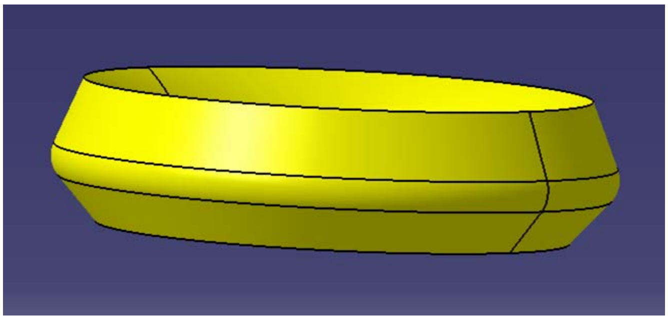

Figure 6: duct diagram

2.5 Moving decoupling

Mini UAV performances optimization leads to decouple sustentation and translation functions. So a platform has been designed to assure this function (cf. figure 7). It consists of small propellers directed by servo commands to move the vehicle in any way with a short reaction time.

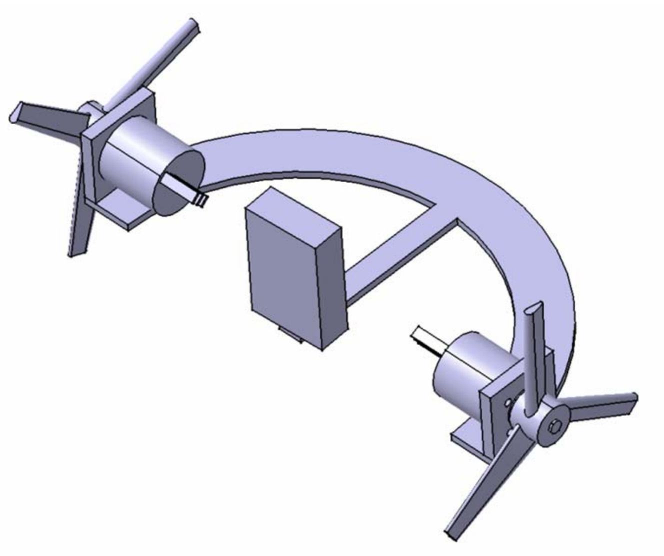

Figure 7: translation system CAD

3 Propeller optimization

Two solutions have been initially studied for the µdrone propulsive line: a single propeller system and coaxial propeller system. Commercial model propellers quickly appears to be unsuited to specific needs of the mini UAV: sizes, thread/diameter ratio, yield, fixing type, reverse thread, etc… Moreover, mini UAV needs a high thrust propeller at low or none speed lead. Use of not adapted propeller implies a power overconsumption and a considerable propeller diameter. With the intention of providing a solution to this issue, propeller modeling computer programs have been made with the Matlab software [07], [08] to realize a propeller model dedicated to mini UAV specific needs. There were two essentially points to respect for this study:

- a less than 5% error with experimental measures,
- quick computing time.

Why not buy existing software ? As these software are expensive and none of them, a priori, could meet this work specific needs, a program dedicated to this function has been developed.

In the bibliography, there are three main propeller modeling theories (classified by accuracy rising rank):

- Rankin-Froude theory,
- blade element theory,
- swirl propeller theory.

Only the last two theories can be used for a complete propeller sizing. Two programs were realized based on these theories, the second being most use for vertical flight but was proved to be unsuited for stationary flight.

The Matlab propeller modeling principle consists of an above research of a succession of profiles at different blade radius. These profiles are then studied thanks to the Javafoil software [09] (a virtual airfoil). Thus profiles aerodynamic coefficients are obtained. From these data, propeller characterizing files are written. It is the longer part of the work.

Once files are obtained, programs give thrust, consumed power versus rotation speed. It is also possible to modify size parameters as the designer wish: chord, blade number, etc…

As two systems have been in competition for the µdrone, programs were adapted to single and coaxial propellers system. It permits to verify that the coaxial propeller system performances is superior to the single propeller. The figure 8 illustrates it from results found for Aeronaut 11*6.5'' propeller.

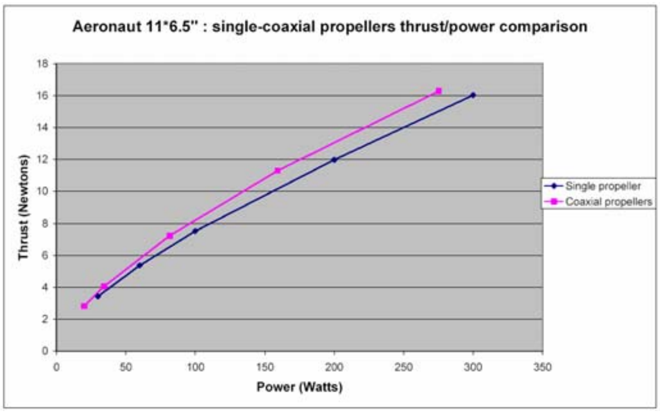

Figure 8: Aeronaut 11*6.5'': single-coaxial propellers thrust/power comparison

In case of low power, both systems have equivalent performances but as power increases, coaxial propellers system performances become higher.

Due to time constraints and a lack of resources, only single propeller programs have been validated by experimental measures. They have shown a good adequacy between theoretical and experimental results (error from 0.3 to 4.8 % on the thrust evolution versus rotation speed) (cf. figure 9). Calculated absorbed power gives a good idea of real consummate power, allocating a yield to the propulsive line.

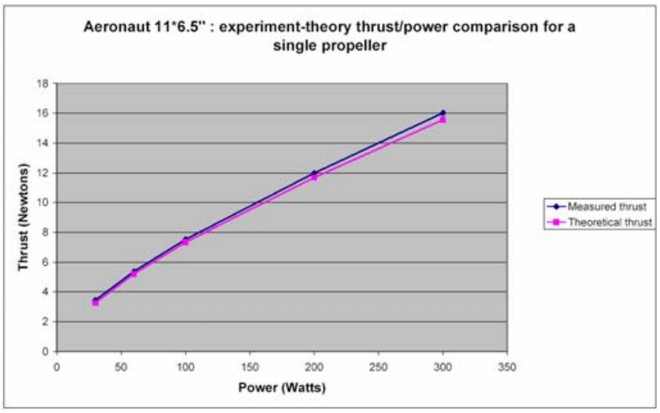

Figure 9: Aeronaut 11*6.5'': experiment-theory thrust/power comparison for a single propeller

From these programs, propellers sizing consisted in choosing profiles, then calculating optimal size parameters which provide the higher feasible thrust on consummate power ratio, and this for a propeller diameter as small as possible.

4 Conclusion

Following studies and realizations in progress, information supplied in this document can not correspond exactly with solutions retained for µdrone final release.

Nevertheless, at present stage of the project, many parameters are already known for certain, such as motorization, propulsive options just as most part of the onboard electronics. The same goes for the duct and the fuselage.

Manufacturing of the two prototypes will begin at the end of September 2004. In this way, from January 2005, a test campaign will be launched so as to develop them.

Acknowledgements

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References

[01] HUNSINGER Ewald, OFFERLIN Michaël, BARREAU Matthieu. *L'hélice: la génération de la force de propulsion* [On-line]. Strasbourg (France): ASCSA [dernière consultation le 02.06.04].
Available from Internet:
<URL: http://inter.action.free.fr/publications/helices/helice.html>

[02] PETROSYAN Eduard. *Aerodynamic features of coaxial configuration helicopter* [On-line]. Moscou (Russie): Kamov Company [dernière consultation le 02.06.04].
Available from Internet:
<URL: http://www.kamov.ru/market/news/petr11.htm>

[03] PARASCHIVOIU Ion. *Aérodynamique subsonique, Vol. 1.* Canada: Editions de l'Ecole Polytechnique de Montréal, 1998. 573p. ISBN 2-553-00684-5.

[04] BROCARD Gilles. *La propulsion électrique des modèles réduits d'avions et de planeurs, tome 1.* 2004.

[05] Dr. Of Sc. BOURTSEV Boris N. and Ing. SELEMENEV Sergey V. The flap motion and the upper rotor blades to lower rotor blades clearance for the coaxial helicopters. *Nineteenth European rotorcraft forum*. Italie: 1993. 18p.

[06] COLEMAN Colin P. *A survey of theoretical and experimental coaxial rotor aerodynamic research*. USA: NASA, 1997. 25p. Technical paper 3675.

[07] MOKHTARI Mohand. *MATLAB 5.2&5.3 et SIMULINK 2&3 pour étudiants et ingénieurs*. Allemagne: Springer-Verlag Berlin Heidelberg, 2000. 662p. ISBN 3-540-66649-4.

[08] SIGMON Kermit. *MATLAB, Aide mémoire*. France: Springer-Verlag France, 1999. 99p. ISBN 2-287-59681-X.

[09] Javafoil: aerodynamics for model Aircraft
Available from Internet:
<URL: www.mh-aerotools.de/airfoils/>