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Résumé :

Cet article introduit une évaluation des techniques de designes, à la fois pour les performances propulsives et pour le comportement structural d'un proprotor souple en composite pour les drones. Un modèle numérique a été développé en utilisant une combinaison du modèle aérodynamique basé sur Blade Element Momentum Theory (BEMT), et le modèle d'élément fini dune poutre anisotrope, afin d'évaluer le couplage entre et les caractéristiques aérodynamiques et structurals d'une pale de proprotors souples. Le modèle numérique a ensuite été validé par des mesures de la performance statique et la reconstruction de la forme par Laser Distance Sensor (LDS). Les résultats de la validation du modèle couplé aérodynamique et structure permettent de conclure que l'approche numérique développée par les auteurs est valide comme un outil fiable pour designer et analyser le proprotor de drones en matériaux composites. La technique expérimentale est également capable de fourir des données fiables de la géométrie et de la performance des pales.

Abstract :

This paper is concerned with the evaluation of design techniques, both for the propulsive performance and for the structural behavior of a composite flexible proprotor. A numerical model was developed using a combination of aerodynamic model based on Blade Element Momentum Theory (BEMT), and structural model based on anisotropic beam finite element, in order to evaluate the coupled structural and the aerodynamic characteristics of the deformable proprotor blade. The numerical model was then validated by means of static performance measurements and shape reconstruction from Laser Distance Sensor (LDS) outputs. From the validation results of both aerodynamic and structural model, it can be concluded that the numerical approach developed by the authors is valid as a reliable tool for designing and analyzing the drone proprotor made of composite material. The proposed experiment technique is also capable of providing a predictive and reliable data in blade geometry and performance for rotor modes.

Mots clefs : Tilt-body drones ; Pale flexible ; Scanner tridimensionnel ; Intéraction Fluides-structure

1 Introduction

Tilt-body drones has been developed to be multifunctional in order to offer a wide range of services. It can fly in both of hover and forward flight. In 2008, Shkarayev and Moschetta introduced the efforts on the aerodynamic design of a tilt-body drones named mini-Vertigo, which had a tilt-body configuration[1]. The results were realized in the design of a tilt-body drone prototype which was successfully tested in flight. A key issue to solve for optimal operation is the problem that a stiff proprotor cannot operate efficiently for both hover and forward flights. Nixon proposed a passive blade twist control method for conventional proprotor of tilt-rotor aircraft using extension twist coupling[2].

Unfortunately most of large scale adaptation techniques are not transferrable to small scale rotor based drones. In the present study a passive twist control is considered as a potential way to improve the overall flight efficiency of drone proprotor. The proprotor blade made of composite material is preferred to be used. It is due to their potential benefits such as aeroelastic tailoring, ability to manufacture, more refined aerodynamic designs, significant enhancements in fatigue performance and damage tolerance of the blade. The blade is expected to be deformed in torsions under different airloads and structural load. This paper is aimed at developing an evaluation of design techniques of a composite flexible proprotor.

2 Numerical Model

2.1 Aerodynamic Model (FPROP)

The aerodynamic model based on BEMT is used as a tool to compute the aerodynamic loadings. In forward flight modelling, the BEMT proposed by Adkins is adapted, meanwhile ; a classical BEMT is used for hover case. The detailed equations used for both are described in [3] and [4], respectively. In this model, the flow angle is iteratively computed until the convergence criteria are reached. In the classical approach of low order proprotor analysis, lift polar is a linear function. Hence, in order to consider non-linear airfoil characteristics prevalent in low Reynolds number regime ($Re < 70,000$), XFOIL, an airfoil design and analysis code developed by Drela [5] was integrated into the design iterative process. The turbulence effect was eliminated by using flat plate [6]. In this respect, the Ncrit parameter, used to define the turbulence level in XFOIL, can be set as 0.1 for both flight modes. A 2-bladed rotor with rectangular planform ($R = 0.1m, c = 0.02m$), flat plate blade profile with thickness $t/c = 2.5\%$ and blade pitch of 25° was used for validation(hover case), in Fig. 1(a). Meanwhile, the propeller APC 8x6 was used to validate the FPROP for forward flight case. The inflow velocity was $16m/s$. From the validation result as shown in Fig. 1(b), it is found that the developed BEMT method with the integration of XFOIL shows better agreement with the experimental measurement compared to the linear model QPROP. A slight increase in torque observed in the experimental result can be due to the heavy material (aluminium) used in the blade.

2.2 Structural Model (FBEAM)

The structural analysis is based upon the use of anisotropic beam finite element model to determine the blade deflections during operation. The FBEAM consists of an integrated set of programs, which perform a two-dimensional cross-sectional analysis of the blade, followed by a one-dimensional finite element of a proprotor blade. A global coordinate system is used for the description of the blade geometry and the calculation of the loads. BECAS [7], a cross-sectional analysis tool which is developed at Denmark Technical University (DTU) was incorporated in this structural analysis program. The motivation of employing BECAS is due to the fact that BECAS has ability to determine the cross section stiffness properties while accounting for all the geometrical and material induced couplings.The linear relation between generalized forces F and the resulting strains and curvatures q is written in a matrix form as follows :

$$Kq = F \tag{1}$$

where K is the sectional stiffness matrix. The final form of elastic energy and kinetic energy are written in Eq. 2.

$$K_e = \int_0^L B^T S B dz; \qquad M_e = \int_0^L N^T M_s N dz \tag{2}$$

where M_s sectional mass matrix, B is the strain-displacement matrix and N is the polynomial matrix. The details of equation used in these relationships are described in [8]. Global stiffness of the blade is obtained through spanwise integration. As for the one-dimensional finite element, the classical Timoshenko beam theory is used for considering finite element analysis. With the obtained shape function, the principle of virtual displacements is used to derive the elemental stiffness. For structural model validation, a static analysis on a rectangular planform with dimension (190.5mmx12.7mmx3.175mm) was performed. Material properties of graphite-epoxy are :
$E11 = 129GPa; E22 = 9.4GPa; E33 = 9.4GPa; G12 = 5.16GPa; G13 = 4.3GPa; G23 = 2.54GPa;$

$\mu = 0.3 \; and \; \rho = 1550 kg/m^3$. The ply angle with respect to pitch axis was 30°. The result obtained in FBEAM was validated by MSc. Nastran, in Fig. 3.

2.3 Coupled-aero-structure (FAE)

In order to compute the blade deformation, the coupled-aero-structure (CAS) model is developed. To begin with, the basic geometry (zero deflections) is assumed. Then the FBEAM calculates the blade deformations. The deformed blade shape is used to update the aerodynamic model. The aerodynamic loads are transferred to the beam nodes as concentrated forces. A new structural analysis is performed to calculate the deformed shape of the blade under the influence of aerodynamic and centrifugal loads. The aero-structural interaction is repeated until equilibrium between deformation and loadings is achieved. The approach described above was applied to the constant chord untwisted 2-bladed system for drones-sized proprotor made of laminate composite. The deflection results in bending and torsion. The effects of camber changes are not included in this study due to limitation in the modeling. Iteration 1 denotes the deflection due to centrifugal loads only and the rest include the aerodynamic loads. The difference between single-step (SS) simulation and coupled-aero-structure simulation was investigated and the result is illustrated in Fig. 4. The slight effect on deformation is observed.

3 Experimental Setup

Optical measurement techniques have been developing for a couple of years in applications of aerodynamics, materials and structure, such as Holographic Interferometry (HI), Electronic Speckle Pattern Interferometry (ESPI), Projection Moiré Interferometry (PMI) and Digital Image Correlation (DIC) [9]. In 1998, Fleming obtained the 3-D deformation of rotor blade using PMI technique [10]. However, it has low sensitivity for in-plane deformation and moderate for out-of-plane deformation. By contrast, DIC has a relatively high sensitivity that can reach 1/30,000 of the test field [11]. In 2011, Lawson demonstrated the deformation of a rotating blade using DIC [12]. The technique was found to have many advantages including high resolution results, non-intrusive measurement, and good accuracy over a range of scales. However, DIC needs a preprocessing which is to apply a stochastic speckle pattern to the surface by spraying it with a high-contrast and non-reflective paint. This complex painting will probably affect the stiffness of blade. Hence, in this study, LDS was developed to measure blade deformation and validate the above numerical models. Two LDSs are driven by track systems to scan the blade from blade root to tip with an incremental distance 2mm. The LDS used in experiment is KEYENCE LK-G502. The distance of reference is 500mm, and the range of measuring can be between -250mm to 500mm. The sampling frequency of this laser was selected as 10,000Hz. In order to determine the overall uncertainty U_{laser} of the experimental result, the bias and precision limits, B_{laser} and P_{laser}, must be combined. This is accomplished using the Root-Sum-Square (RSS) method,

$$U_{laser} = (B_{laser} + P_{laser})^{1/2} \tag{3}$$

A reference surface was measured first to determine the precision limits, then the total uncertainty is obtained, ± 0.1%. LDS records the Z coordinates which is the distance from the position detected on blade surface to reference plane. Meanwhile, square wave in time domain is measured by RPM sensor. Then, average RPM and angular speed at each blade section can be extracted from the square wave. Furthermore, with the azimuth of feathering, polar coordinates is possible to be transferred to Cartesian coordinates X and Y. Combining coordinates X, Y and Z, a polynomial surface fitting is performed to obtain the bending and torsion of rotating blade. To evaluate the flexible blade performance, the thrust and torque were measured using two transducers.

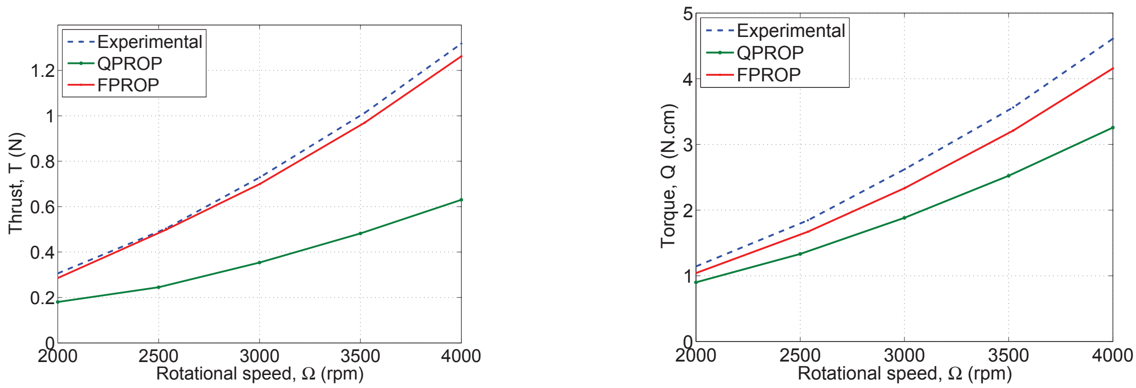
4 Results Validation

The validation results in performance are shown in Fig. 5. As can be seen, the FPROP agrees well with experimental data of thrust. However, it over-predicts the torque. Fig. 6 shows the good agreement between the FAE simulation and the experimental data as obtained from LDS measurements. This is the result obtained for the blades clamped at collective pitch 35°. The fluctuations that can be observed through scattered plot of deformations are the results by the preliminary post-processing method. In this method, the deformation was extracted through the data interpolation at each section. Since the vibration of rotating blade probably generated uncertainty to the LDS data in spanwise, hence, the deformation exhibits unsmoothness in the plots.

5 Conclusions

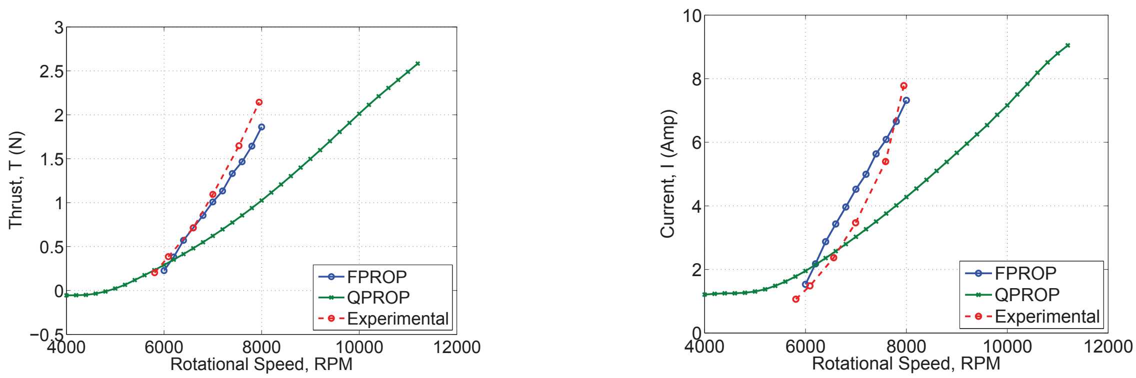
As conclusion, the evaluation of design techniques, both for the aerodynamic performance and for the structural behavior of a composite flexible proprotor has been presented in rotor modes. The numerical model has capability of prediction in proprotor aerodynamics and structure. The model presents coupling between anisotropic beam finite element model and an aerodynamic model that takes into consideration of low Reynolds number. The numerical model has also been experimentally validated by LDS technique and transducers of thrust and torque. It can be concluded that the developed numerical model is a reliable tool for designing and analyzing the proprotor made of composite material. Additionally, the developed structural model which uses cross-sectional analysis enables a more complex blade with highly-twisted and/or arbitrarily-shaped blades to be efficiently analyzed. As perspectives, an investigation of static aeroelasticity on the drone-sized flexible proprotor will be carried out using the validated numerical model. In future, the study will focus on propeller modes and optimization to enhance the proprotor efficiency. Likewise, based on inverse method, the loads on blade are expectedly able to be deducted from blade deformation.

Appendix



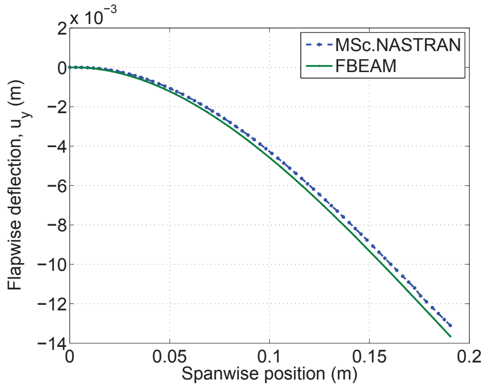
(a) Thrust (b) Torque

FIGURE 1 – Comparison of BEMT simulation and corresponding measurements for hover (V=0)

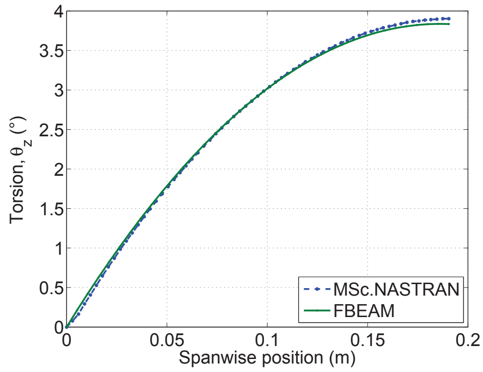


(a) Thrust (b) Torque

FIGURE 2 – Comparison of BEMT simulation and corresponding measurements with inflow (V=16m/s)

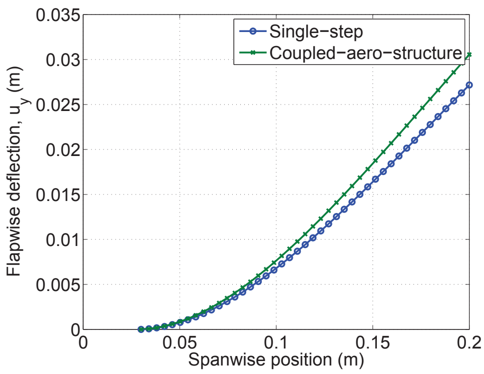


(a) Bending

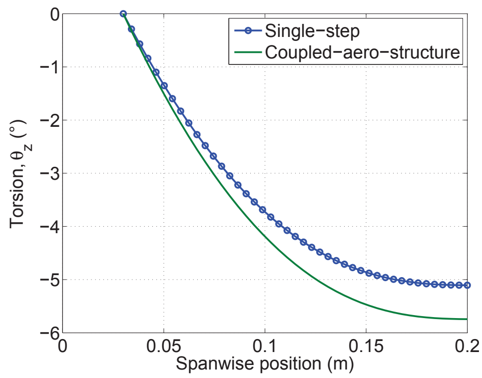


(b) Torsion

FIGURE 3 – FBEAM validation by MSc. NASTRAN

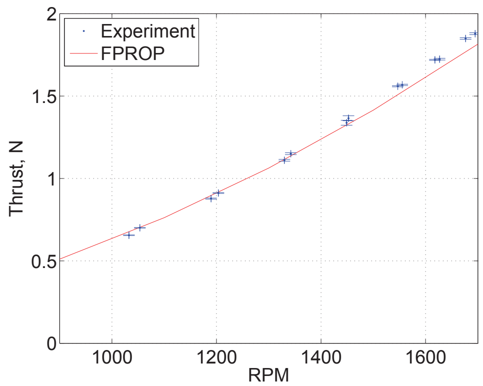


(a) Bending

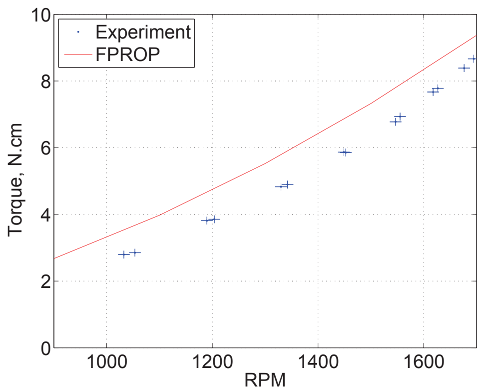


(b) Torsion

FIGURE 4 – The effect of SS and CAS simulation on the blade deformations

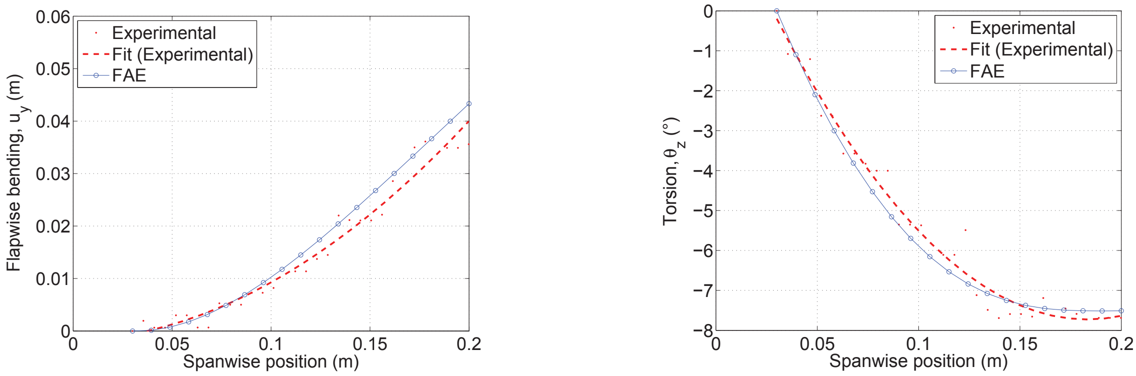


(a) Thrust



(b) Torque

FIGURE 5 – Thrust and torque of rigid and flexible proprotor at different rotational speed (V=0)



(a) Bending (b) Torsion

FIGURE 6 – Comparison of FAE simulation with the corresponding measurements

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