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Multidisciplinary optimization of a MAV propeller for noise reduction

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ABSTRACT

The following research aims at reducing the noise of a MAV's propeller without impacting its efficiency. To ensure reasonable computational time, low fidelity methods are used for each discipline: Lifting line for aerodynamics, beam model for structure and Ffowcs-Williams and Hawkings analogy for acoustics. Validation tests are performed to evaluate reliability of these methods on a reference configuration: a GWS80x45 propeller in hover. More complex CFD tools are also used at some points of the optimization process to check for the coherence and fidelity of the results. The open-source SU2 solver and a Lattice-Boltzmann Method solver serve this purpose. Finally, results are compared to an experimentation conducted by ISAE (Institut Supérieur de l'Aéronautique et de l'Espace) in an anechoic chamber.

1 INTRODUCTION

Micro-Unmanned Air Vehicules (MAV) are developing incredibly fast worldwide. They tend to be in every aspects of everyday life. Those are used for surveillance as well as in agriculture, firefights or delivery services. It is becoming crucial to reduce their noise. In that aspect, blade noise represents the most part of this disturbance. A part of this noise is due to pressure variations induced by aerodynamic around rotating blades, so it is possible to adapt blade geometry to reduce the noise. However, this geometric modification should not degrade performance of the blade: in an aerodynamic point of view, traction force must be kept constant, and efficiency of the blade should not decrease. At least two disciplines, aerodynamic and acoustics are involved, and a third discipline: mechanics, could be also considered to take into account deformation due to aerodynamic forces, and to ensure structural robustness, so a multidisciplinary optimization (MDO) is then necessary to solve this problem. Low-fidelity simulation tools are used for each discipline in order to have acceptable run times for the optimization. These disciplinary tools are integrated in GEMS[1] (Generic Engine for MDO Scenarios). GEMS is a platform developed by IRT St Exupery which allows performing multidisciplinary optimization. Thanks to the flexibility of this tool, a large number of MDO schemes can be tested and compared. This global process is integrated into OPTIMIND, an in-house workflow manager, to handle the connection between the different tools and to provide a user-friendly GUI. The GWS80x45 blade was selected for this as many experimental and computational data for this geometry were available. This allow validating the results provided by our low-fidelity tools before starting the optimizations. Furthermore, this blade offers room for improvement. The main goal here is to find the best methodology. For this reason both Mono and Multi-Disciplinary optimizations were launched to see the impact of each discipline on the solution.

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2 THE MULTIDISPLINARY OPTIMISATION (MDO) METHODOLOGY

The Multidisciplinary Optimization (MDO) proposes solutions to design complex systems. When more than one discipline are involved in an optimization problem, it cannot be solved efficiently by performing sequential optimizations for each discipline. A more global approach combining all the disciplines must be adopted, taking into account coupling between disciplines. In this approach one global optimization algorithm is used to solve the whole problem. Different strategies, often called MDO formulations, exist: MDF, IDF and many other. The most common methods are MDF and IDF:

- MDF: Multi discipline feasible: equilibrium between disciplines is computed at each iteration of the optimization algorithm, the advantage of this method is that the computed solution is "feasible" all along the optimization process,
- IDF: Individual discipline feasible: equilibrium between disciplines is defined as a constraint of the optimization algorithm: iterations run faster but equilibrium between disciplines is obtained only at the convergence.

As usual in optimization, a "universal" method suited for any kind of problem does not exist. The best method depends on the problem studied. In the end three points are crucial to efficiently lead a MDO study:

- Definition of the optimization problem: objective(s), constraints,

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- Optimization algorithm and MDO strategy used,
- Workflow management: communication between disciplinary tools, and integration in the optimization loop.

GEMS is used for the first two items. It offers a large choice of optimization algorithms and MDO formulations. It is a very flexible tool which allows testing several problem formulations easily. The in-house tool OPTIMIND is used for workflow management. It allows wrapping and linking disciplinary tools easily in order to integrate them in the optimization loop handled by GEMS.

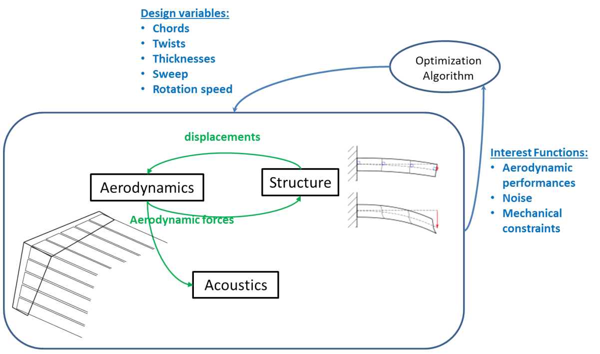

Figure 1: The Multidiscplinary Optimization procedure.

2.1 *Aerodynamic solver:* QuickCFD.py

QuickCFD computes aerodynamic loads and performance of lifting surfaces with complex geometrical properties including arbitrary camber, sweep, dihedral and twist. It relies on an adaptation of the general numerical lifting-line method based on a fully three-dimensional vortex lifting law developed by Phillips and Snyder [2]. The accuracy of this method was shown to be comparable to that obtained from panel methods at a small fraction of the computational cost.

2.2 *Structure solver:* MECHA-BLADE

MECHA-BLADE is an in-house program developed to carry out mechanical calculations on turbomachinery blades. The code is based on the variational formulation approach proposed by Rao [3, 4] which takes into account pre-twisted cantilever beams with an asymmetric airfoil cross-section mounted at a stagger angle on a rotating disc. The use of this semi-analytical approach aims at providing fast and relatively accurate calculations, particularly in an optimization context or in preliminary design stages where a large amount of sensitivity analyses for several parameters are required. In practice, the blade is discretized into several cross sections from which the mass and stiffness matrices are calculated. The natural frequencies and mode shapes are then determined using an eigenvalue extraction routine. A modal approach is then used to complete the structural analysis and determine the displacement and stress response of the blade subjected to both centrifugal and aerodynamic forces. The figure 2 shows the model flow chart.

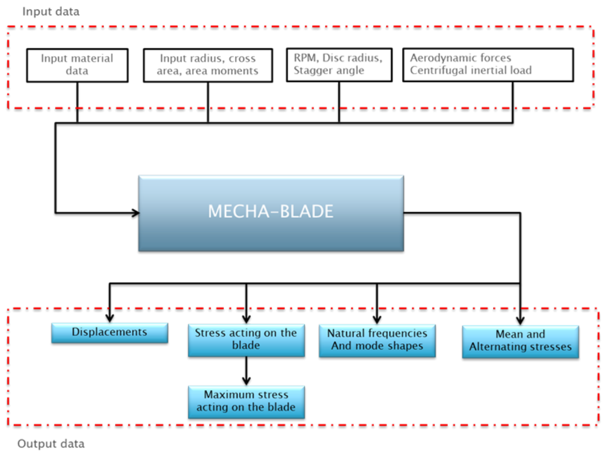

Figure 2: Model flow chart of the MECHABLADE program.

2.3 *Ffowcs-Williams & Hawkings solver:* pyFfonc.py

The acoustic propagation is done through the pyFfonc.py program. It solves the Ffowcs-Williams and Hawkings aeroacoustic analogy using Farassat's 1A formulation[5] as described by Casalino[6]. The inputs are the drag, lift and induced velocity on a blade of the propeller, the latter being divided into several panels. The acoustic power is then computed by summing the radiated noise all around the propeller.

3 Validation of the method

3.1 *QuickCFD validation*

Figure 3: The GWS80x45 reference propeller.

Since many experimental and computational data are available for GWS80x45 geometry, this configuration was used to validate QuickCFD results. The propeller is represented in Figure 3. Figure 4 compares Drag and Lift forces repartition along blade radius with the results of a Blade Element (BEMT) computation performed at ISAE. QuickCFD seems to be quite accurate to compute lift forces. However the computed drag is inferior to the BEMT value. This can be explained by the fact that only induced drag component is computed by QuickCFD, friction or viscous pressure drag

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are not taken into account. In order to validate this hypothesis and to ensure that the induced drag computed by QuickCFD is correct, a comparison of induced velocity was done. The results are presented in Figure 5. A good agreement between BEMT data and quickCFD results is reached.

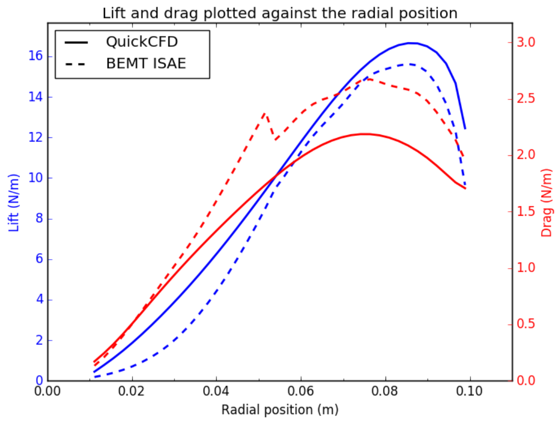

Figure 4: Comparison of QuickCFD results with experimental data for GWS80x45

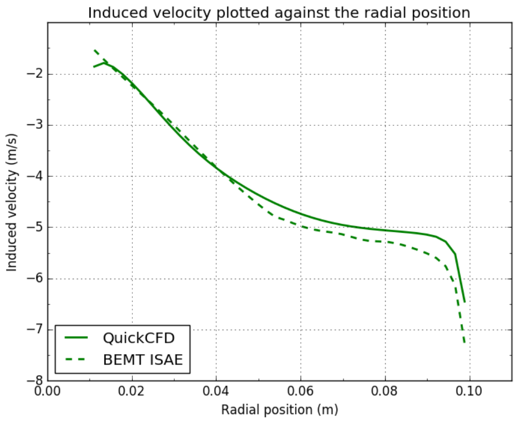

Figure 5: Comparision of induced velocity computed by QuickCFD with experimental data

The evolution of the lift force with respect to the rotation speed of the propeller was also compared to existing results: experimentations or computations with STAR CCM+, LBM methods (PowerFlow) or BEMT (Blade Element Momentum Theory). The propeller is composed of two blades as shown in Figure 3 even if the QuickCFD computation only considers one blade. A summary of the results is given by Figure 6, QuickCFD results are conform with the reference data. To conclude, these validation tests demonstrate that QuickCFD is able to compute aerodynamic forces with good accuracy, and can be used for optimization studies.

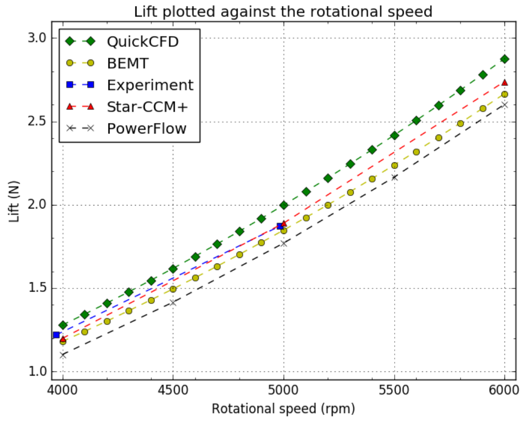

Figure 6: Evolution of lift with rotation speed

4 Optimization study

The design parameters for this study are the geometrical parameters of the blade: chord length, sweep, dihedral and chord values along blade radius. Spline curves are used to control the evolution of these geometric laws so as to obtain smooth geometries. The number of control points used to define these splines is chosen by the user. More control points offers more flexibility to explore different shapes but it also involves slower convergence for the optimization. The rotation speed of the blade is also controlled during the optimizations to adjust traction level.

This study is divided in three steps in order to understand well the influence of parameters on each discipline and the influence of discipline coupling on the optimization process. These steps are:

1. Mono disciplinary (Aerodynamic) optimization: The goal of this study is to maximize the efficiency of the blade in hover with a constraint of minimal thrust to respect. This first study shows what are the most influent parameters on the aerodynamics of the blade and the result of this optimization provides an "ideal" goal for the two following optimizations.

2. Aero-acoustic optimization: For this optimization, the noise generated by the blade is taken into account. Two strategies can be investigated: a bi-objective optimization can be performed or noise can be treated as a constraint of the optimization algorithm. Comparing results obtained with those of the pure aerodynamic optimization helps understanding the influence of design parameters on both disciplines.

3. Full MDO study: Aerodynamic- Acoustic-Structure: The goal of this final study is to add structure discipline in the process with a coupling between aerodynamic and structure by considering the blade displace-

ment induced by aerodynamic loads. This part of the study was not done yet due to a lack of time but it is necessary and will be performed in the future.

Results of the three studies are analyzed and compared to see the benefit of a multi-disciplinary approach for our problem.

4.1 *Aerodynamic optimization*

- Objective: **minimize Drag force (N)**

- Constraint: **maintain Lift force up to 2.08 N** (Reference value for GWS80x45 at 5000 rpm)

- Design variables: 7 control points were used to define spline curves controlling Chord, Twist, Dihedral and Seewp evolution along blade radius: **28 design variables**

- Algorithm: In order to have a fast convergence, we chose a gradient-based algorithm: **SLSQP**, available in GEMS, allows performing gradient based optimization, with one ore several constraints. GEMS also provides a finite differences module to compute aerodynamic gradients.

The aerodynamic optimization converges in 30 iterations as shown by Figure 7. The comparison of the aerodynamic forces (computed by QuickCFD) between baseline and optimized blade is given in Table 1: Drag force decreases by 28%, Lift force is kept at the same level. Figure 8 compares baseline and optimized geometries: as we can see globally sweep and mean chord decreased, whereas Twist increased near the root of the blade. These geometric modifications involved an increase of the rotation speed to keep the Lift force constant.

QuickCFD	Baseline	Optimized	delta (%)
Drag (N)	0.3264	0.2350	**-28.02**
Lift (N)	2.087	2.087	**2.26e-7**
Torque (N/m)	0,0177	0,0129	**-27.34**
Rot. speed (rpm)	5000.0	6206.12	**24.12**

Table 1: Aerodynamic optimization summary

In order to validate results of this aerodynamic optimization, calculations were done on baseline and optimized geometries using PowerFlow: surface repartition of aerodynamic forces is represented by Figure 10. Table 2 presents results for Torque and Lift: PowerFlow gives almost the same results than QuickCFD for Lift, Torque levels computed by PowerFlow are higher but we obtain the same relative difference between baseline and optimized blade than in QuickCFD, which confirms better performances of the optimized shape, and enforces reliability of this first aerodynamic optimization results

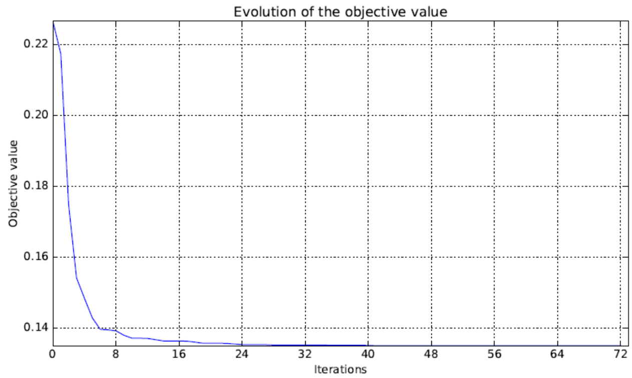

Figure 7: Aerodynamic optimization convergence history

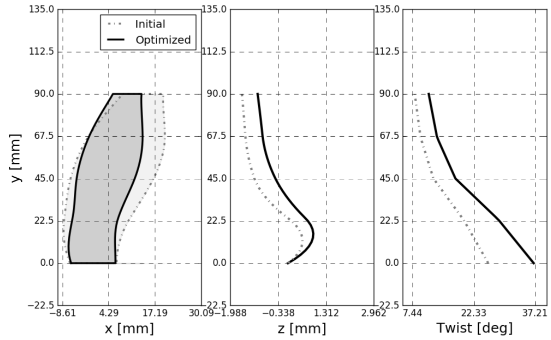

Figure 8: Aerodynamic optimized geometry: left: XY planform, center: Dihedral, right: Twist

4.2 *Aeroacoustic optimization*

- Objective: **minimize weighted sum of Torque and Acoustic Power**:

$$Obj = w * \frac{T}{T_0} + (1 - w) * \frac{Pa}{Pa_0} \quad (1)$$

- Constraint: **maintain Lift force up to 2.08 N** (Reference value for GWS80x45 at 5000 rpm)

- Design variables: same parameters than Arodynamic optimization: **28 design variables**

- Same algorithm than the one used for Aerodynamic optimization: **SLSQP**

Aero-Acoustic optimization converges in 10 iterations as shown by Figure 11, comparison of aerodynamic forces

PowerFlow	Baseline	Optimized	delta (%)
Torque (N/m)	0,0426	0,0319	**-25.01**
Lift (N)	2,0276	2,1249	**4.8**

Table 2: Aerodynamic optimization: PowerFlow results

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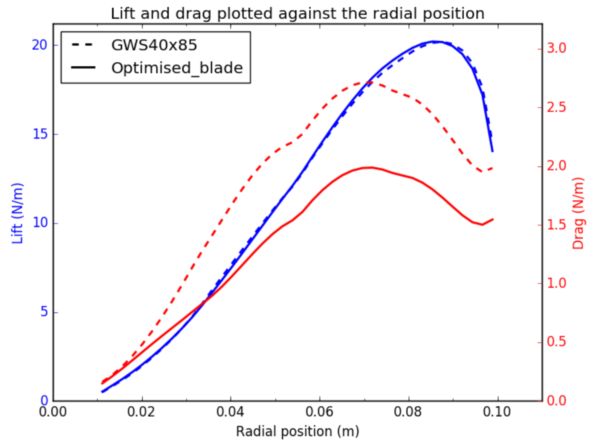

Figure 9: Aerodynamic optimization: radial forces comparison

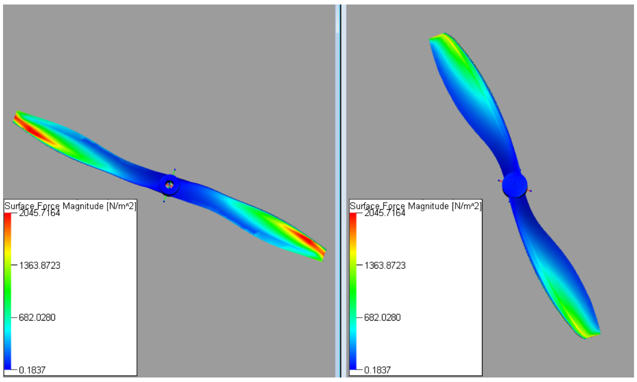

Figure 10: Aerodynamic forces computed by PowerFlow: left: Optimized, right: Baseline

(QuickCFD) and noise levels (PyFfonc) between baseline and optimized blade is given in Table 3: Similarly to pure Aerodynamic optimization, Drag force decreases by 28%, Lift force is kept almost at the same level. Figure 12 compares baseline and optimized geometries: the optimized geometry seems quite similar to the one obtained by Aerodynamic optimisation: both shapes are compared in Figure 14: the only differences are the twist and chord distribution near blade root. Optimized blade reduces the noise by **1dBA**, which represent a reduction of **20.41%** of the acoustic power.

4.3 Full multdisplinary optimization

Due to a lack of time this study could not been performed yet. Nevertheless, a fonctionnal structural tool was developed: MECHA-BLADE. It will soon be integrated in GEMS to perform aeroelastic computations. The previous two optimisation studies (Aerodynamic and Aero-Acoustic) will then be performed with MECHA-BLADE-QuickCFD coupling, to see its impact of structure on optimization results. In a second time optimization problem are to be improved to take into accound structural aspects: to limit vibrations or structural constraints level in the blade for instance.

QuickCFD-PyFfonc	Baseline	Optimized	delta (%)
Drag (N)	0.3224	0.2342	**-27.1**
Lift (N)	2.057	2.0574	**-0.01**
Torque (N/m)	0,0176	0,0126	**-27.84**
Rot. speed (rpm)	5000.0	6196.12	**23.92**
Noise (dBA)	67.28	66.28	

Table 3: Aero-Acoustic optimization summary

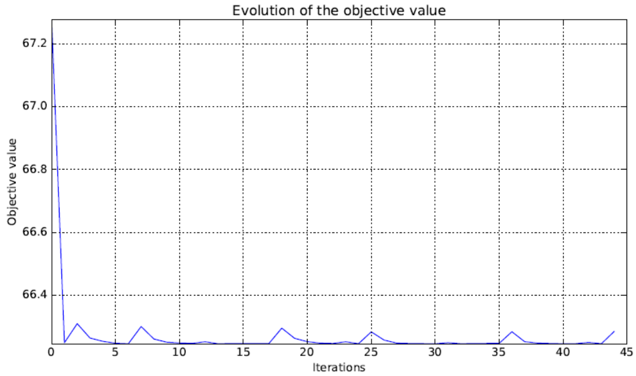

Figure 11: Aero-Acoustic optimization convergence history

5 Conclusion

A multi-disciplinary/multi-objective method for the aeroacoustic optimization of MAV propeller's blade has been developed in this study. It was tested on a well known propeller, the GWS80x45. First aeroacoustic optimizations showed some very interesting results such as a decrease of the drag force on the propeller of about 27% for an acoustic radiation reduced by 1dB. A full aero-structure-acoustics optimisation has still yet to be performed. The new blade design

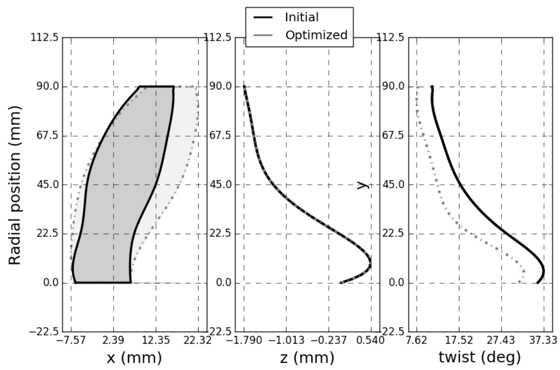

Figure 12: Aero-Acoustic optimized geometry: left: XY planform, center: Dihedral, right: Twist

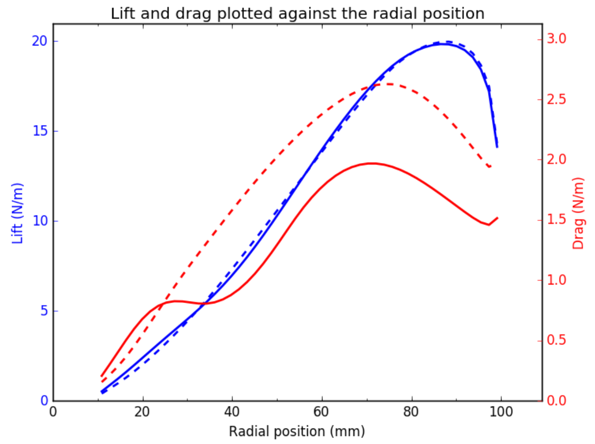

Figure 13: Aero-Acoustic optimization: radial forces comparison

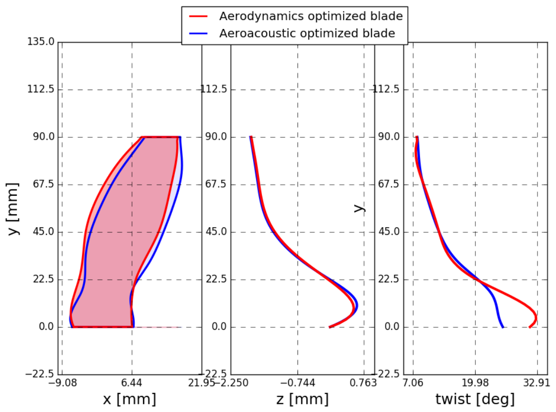

Figure 14: Comparison between Aerodynamic and Aero-Acoustic optimized geometries

will then be 3D-printed and tested in an anechoic chamber to confront with the experiment.

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