Reducing the noise of Micro–Air Vehicles in hover

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-
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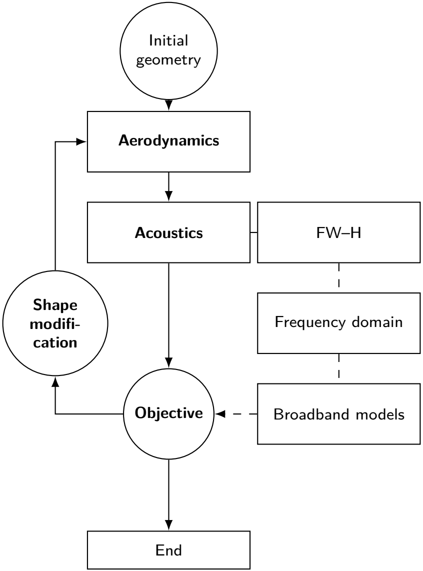
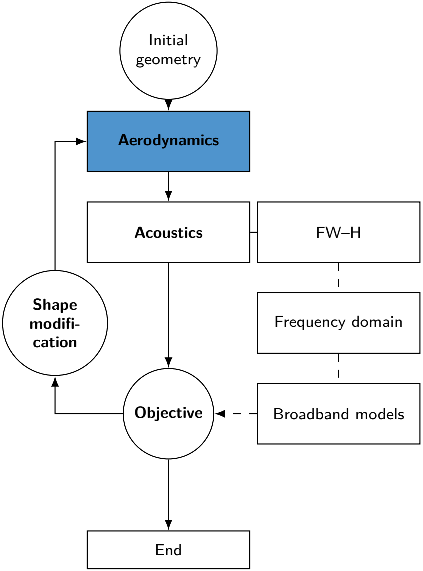
Context :
- intensive use of Micro Air Vehicles
- sound perceived as “annoying”

Motivations :
- improve discretion
- allow sound recordings

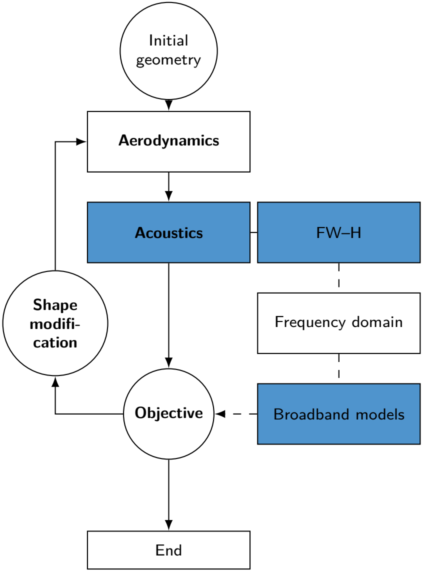
Objectives of the method :
- effective optimization procedure
- reduce noise
- maintain endurance


Initial geometry
Aerodynamics
Acoustics
FW–H
Frequency domain
Broadband models
Shape modifi-cation
Objective
End



Aerodynamics

- Aerodynamic coefficients : Xfoil [Drela and Giles, 1987]
- Blade Element and Momentum Theory [Winarto, 2004]
- Steady loading



Aerodynamics

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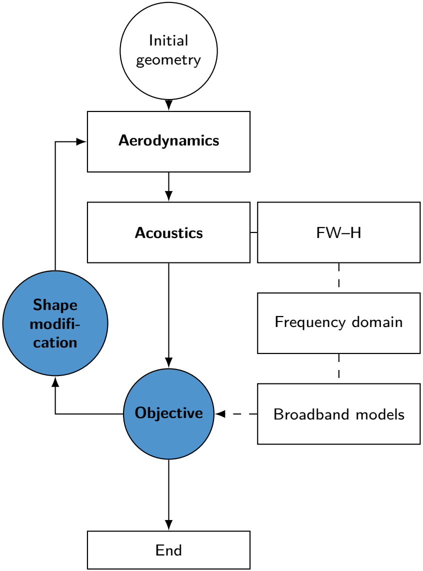
- Steady loading

Acoustics

- Ffowcs–Williams & Hawkings [Casalino, 2003] : tonal noise
  - ↪ velocity and loading (BEMT)
- Broadband noise models [Roger and Moreau, 2010] :
  - ↪ trailing–edge noise : boundary–layer data (Xfoil)
  - ↪ interaction noise : turbulence statistics
  - ↪ separation noise



Aerodynamics

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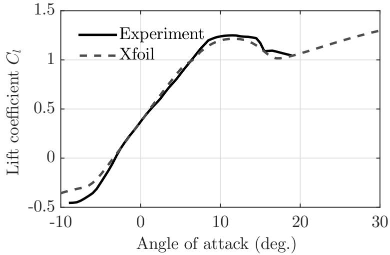
  - ↪ separation noise

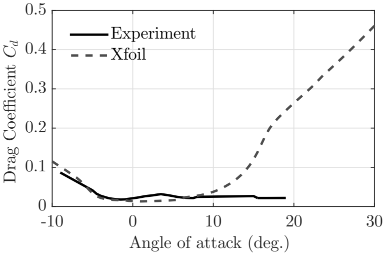
Optimization

- Multi–objective :
  - ↪ lower OASPL
  - ↪ lower aerodynamic power
- Shape modification :
  - ↪ systematic evaluation
  - ↪ evolutionary algorithms (NSGA–II)

Estimating the aerodynamic coefficients

E–387 airfoil section at Reynolds number $Re = 100,000$. Experiments from [Lyon et al., 1998]





Xfoil lift prediction

Accurate and efficient but avoid high angles of attack

Xfoil drag prediction

Severe overestimation of drag

Trailing edge noise

$$S_{pp}\left(\overrightarrow{x},\omega\right) = \left(\frac{\omega c x_3}{2\pi c_0 S_0^2}\right)^2 \frac{L}{2} \left|\Lambda_{TE}\left(\frac{\omega}{U_c},\frac{\bar{k}x_2}{S_0}\right)\right|^2 \underbrace{\Phi_{pp}\left(\omega\right) l_y\left(\omega\right)}_{\text{input}}$$

- Φ_{pp} : wall pressure spectrum at trailing edge. Model : [Kim and George, 1982]
- l_y : spanwise coherent length. Model : Corcco, in [Rozenberg et al., 2010]

Turbulence interaction noise

$$S_{pp}\left(\overrightarrow{x},\omega\right) = \left(\frac{\rho_0 k c x_3}{2 S_0^2}\right)^2 \pi U_0 \frac{L}{2} \left|\Lambda_{TI}\left(x_1,\frac{\omega}{U_c},\frac{k x_2}{S_0}\right)\right|^2 \underbrace{\Phi_{ww}\left(\frac{\omega}{U_c},\frac{k x_2}{S_0}\right)}_{\text{input}}$$

- Φ_{ww} : cross–correlated upwash velocity fluctuation spectrum. Model : von Kármán, in [Amiet, 1975]

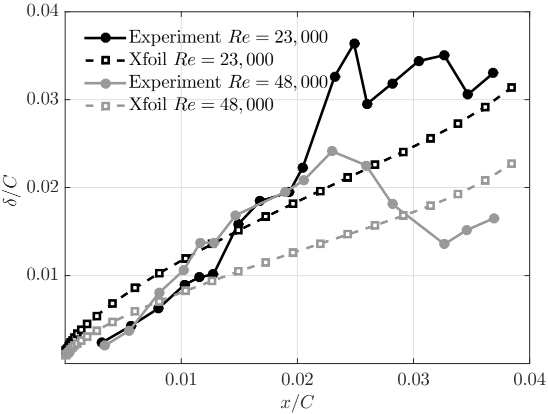
Main input data for trailing edge noise model

Boundary layer lenth scales

Main input data for interaction noise model

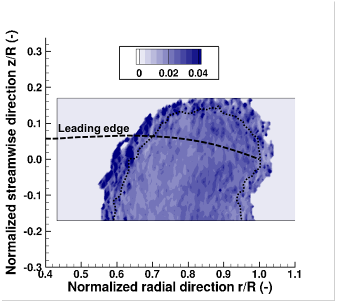
Turbulence lenth scale

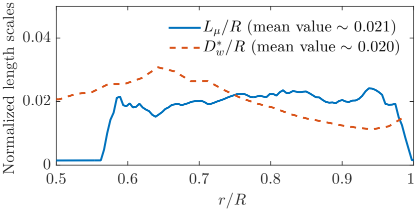
Estimating the boundary layer lenth scale



- Boundary layer thickness
- NACA 0012, 6° angle of attack
- Reynolds numbers $Re = 23,000$ and $Re = 48,000$
- Xfoil prediction
- Experiments by [Kim et al., 2009]

Estimating the turbulence lenth scale





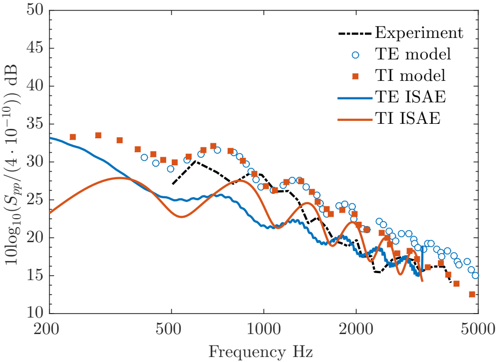
Wake width D_w^* scales as Taylor micro–scale L_μ [Fukano et al., 1977] :

$$D_w^* = d_{AS} + \delta_p^* + \delta_s^*$$

- d_{AS} : airfoil section thickness near trailing edge
- δ_p^* : boundary layer displacement thickness (pressure side)
- δ_s^* : boundary layer displacement thickness (suction side)

Validating the models

Wing translating at ~ 40 m/s with NACA 0012 airfoil section. From [Moreau and Roger, 2007]

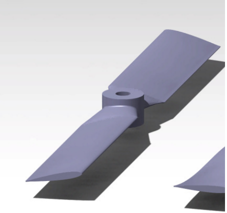


Main input data for interaction noise model

- low frequencies underestimated
- high frequencies overestimated

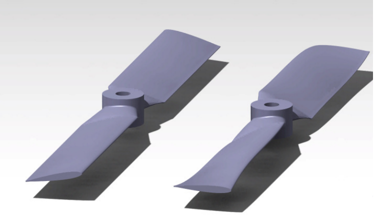
Case #1 :

- constant twist
- constant chord
- NACA 0012 airfoil section



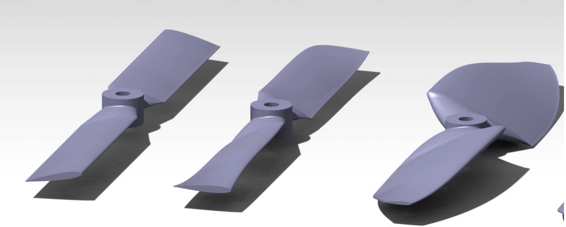
Case #2 :

- optimized twist
- constant chord
- NACA 0012 airfoil section



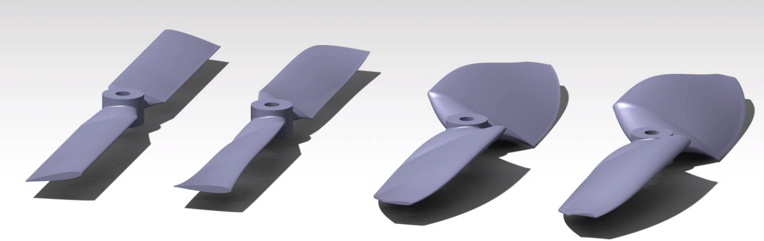
Case #3 :

- optimized twist
- optimized chord
- NACA 0012 airfoil section



Case #4 :

- optimized twist
- optimized chord
- optimized airfoil sections



Optimization procedure :

Twist :

- combination method
- 4 control points along the radius (twist imposed on the 4^{th}) ;
- 5 values at each control points
- 5^3 evaluations
- multi–objective : lower noise and lower aerodynamic power

Optimization procedure :

Twist :

- combination method
- 4 control points along the radius (twist imposed on the 4^{th}) ;
- 5 values at each control points
- 5^3 evaluations
- multi–objective : lower noise and lower aerodynamic power

Chord and twist :

- combination method
- 4 control points along the radius (twist imposed on the 4^{th}) ;
- 5 values at each control points
- 5^7 evaluations
- multi–objective : lower noise and lower aerodynamic power

Optimization procedure :

Twist :

- combination method
- 4 control points along the radius (twist imposed on the 4th) ;
- 5 values at each control points
- 5^3 evaluations
- multi–objective : lower noise and lower aerodynamic power

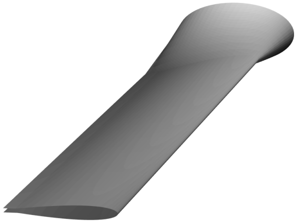
Chord and twist :

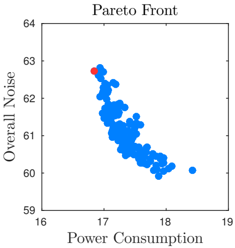
- combination method
- 4 control points along the radius (twist imposed on the 4th) ;
- 5 values at each control points
- 5^7 evaluations
- multi–objective : lower noise and lower aerodynamic power

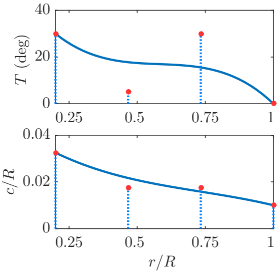
Airfoil section :

- 3 radial positions yielding Reynolds number and angle of attack
- CST parameterization with 12 coefficients
- Matlab's Genetic Algorithm
- population : 100
- generations : 55
- mono–objective : higher lift–to–drag ratio
- multipoints : average in Reynolds number and angle of attack

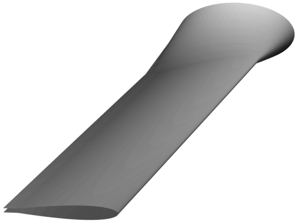
Combination method :

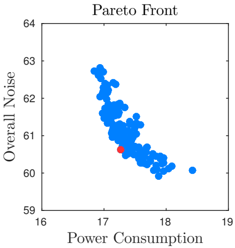


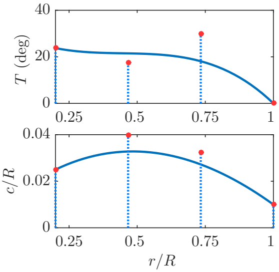




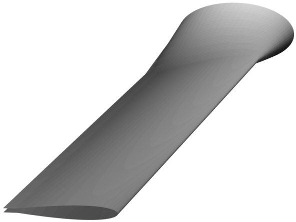
Combination method :

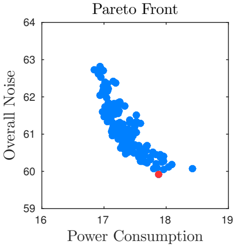


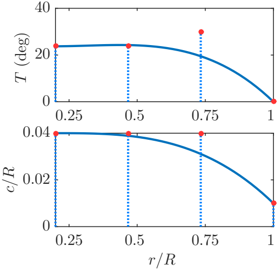




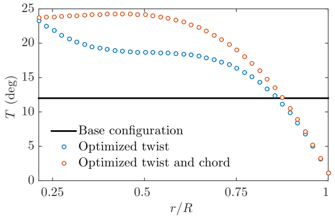
Combination method :



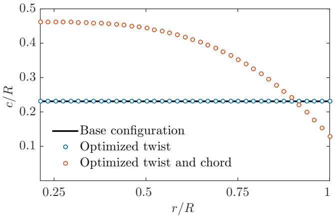




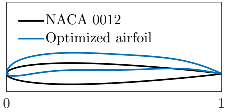
Twist $\in$ [5 ;30] degrees



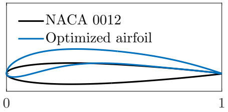
Chord $\in$ [0.1 ;0.45] r/R



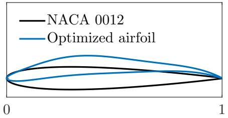
$r/R = 0.1,\ Re = 32,000$



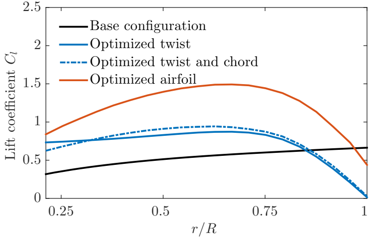
$r/R = 0.5,\ Re = 82,000$



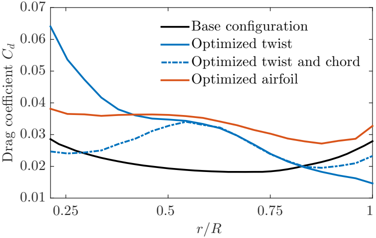
$r/R = 1.0,\ Re = 42,000$



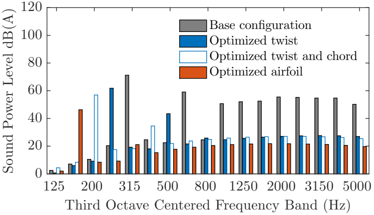
Lift coefficients



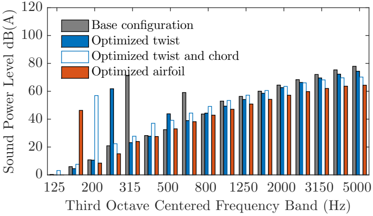
Drag coefficients



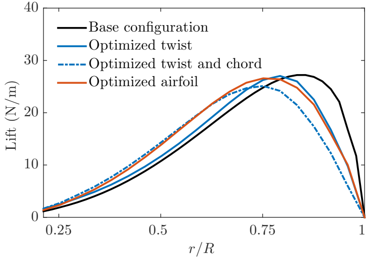
Trailing edge noise



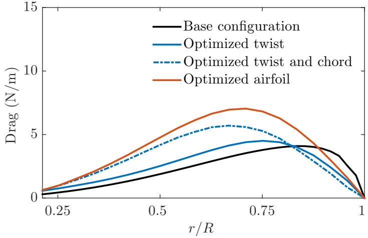
Turbulence interaction noise



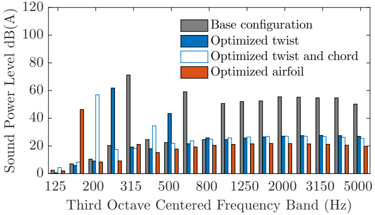
Lift



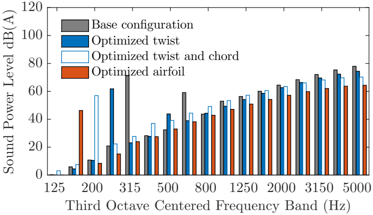
Drag



Trailing edge noise

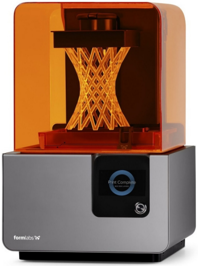


Turbulence interaction noise



Rapid prototyping :

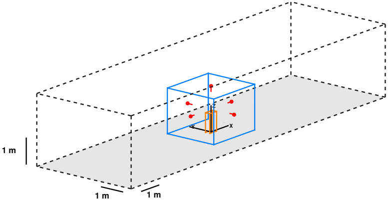
3*D*–printer : FormLabs Form 2

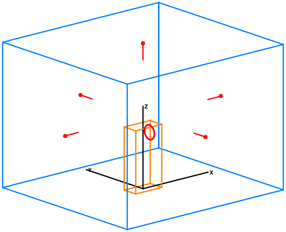


SLA technolgy, 50 μm vertical resolution

Credits : Usine Nouvelle ©

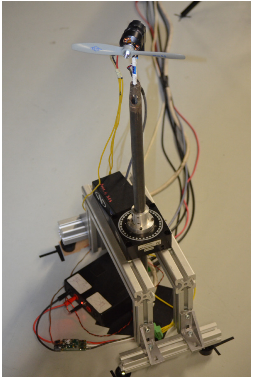
Experimental set–up :

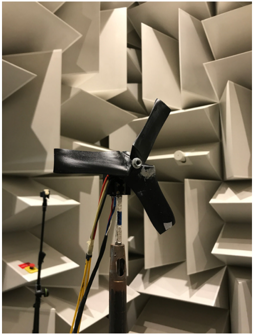




- $(l_x \times l_y \times l_z) = (14.9 \times 4.5 \times 1.8)\ \text{m}^3$
- sound power level computed according to ISO 3746 : 1995 standard
- 5 measurement points
- Brüel & Kjær 1/2″ free–field microphone
- Nexus frequency analyzer (3.125 Hz of frequency resolution)
- Measurement distance : $\sim$ 1 m ($\sim$ 5 rotor diameters)

Experimental set–up :



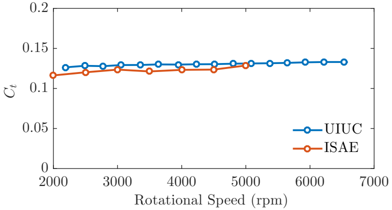


Validation of the aerodynamic balance : Graupner SlimProp 9x6 propeller, UIUC online database

Thrust coefficient

$$C_t = \frac{T}{\frac{1}{2}\rho(\omega R)^2 \pi R^2}$$

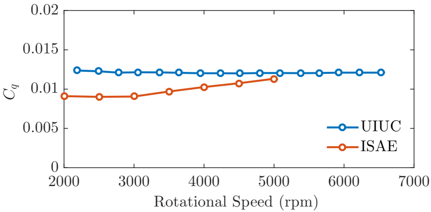
- T : thrust
- ρ : ambient density
- R : tip radius



Torque coefficient

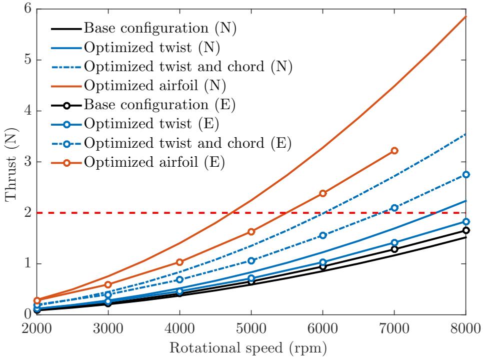
$$C_q = \frac{Q}{\frac{1}{2}\rho(\omega R)^2 \pi R^3}$$

- Q : torque
- ω : rotational frequency



- underestimated torque
- leads to overestimation of Figure of Merit

Thrust from numerical tool and experiment

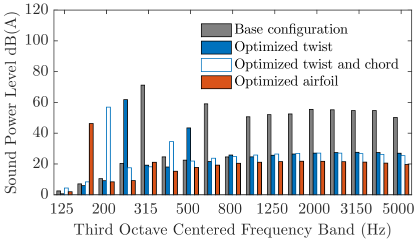


Rotational speed (and BPF) for a 2 N thrust

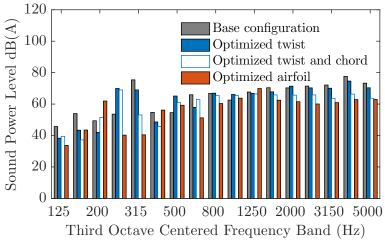
	Numerical	Experimental	Deviation
Base configuration	9310 rpm (310 Hz)	9800 rpm (325 Hz)	5%
Optimized twist	7630 rpm (255 Hz)	8400 rpm (280 Hz)	9%
Optimized chord and twist	6010 rpm (200 Hz)	6650 rpm (220 Hz)	10%
Optimized airfoil	4880 rpm (165 Hz)	5450 rpm (180 Hz)	10%

Acoustic power levels from numerical tool and experiment

N : trailing edge noise



Experiment

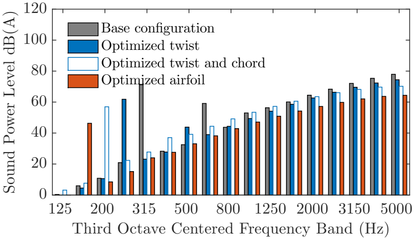


Comments

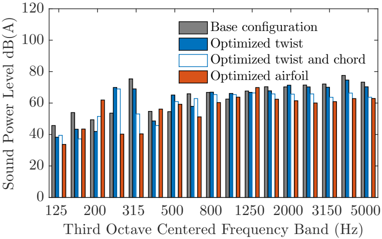
- lower BPF, shifted towards low frequencies
- lower broadband noise levels

Acoustic power levels from numerical tool and experiment

N : turbulence interaction noise



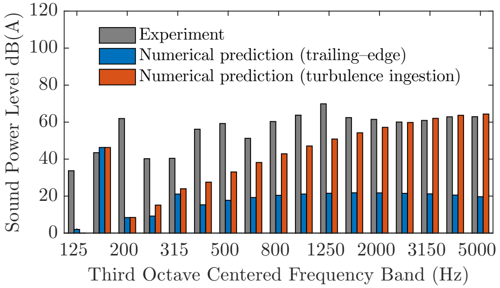
Experiment



Comments

- lower BPF, shifted towards low frequencies
- lower broadband noise levels

Acoustic power levels from numerical tool and experiment (final optimization)



Comments

- higher BPF (and subharmonics) : unsteady loading and installation effects
- fine agreement at higher frequencies

Final evaluation

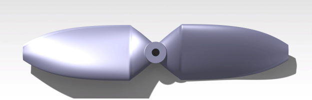
	A_p (N)	A_p (E)	L_{wA} (NTE)	L_{wA} (NTI)	L_{wA} (E)
Base configuration	19.6 W	25.2 W	72.0 dB(A)	85.0 dB(A)	83.3 dB(A)
Optimized twist	17.2 W	22.1 W	61.9 dB(A)	81.2 dB(A)	81.3 dB(A)
Optimized chord and twist	17.9 W	23.1 W	57.0 dB(A)	77.1 dB(A)	76.6 dB(A)
Optimized airfoil	16.9 W	21.3 W	46.6 dB(A)	71.1 dB(A)	74.5 dB(A)

Comments

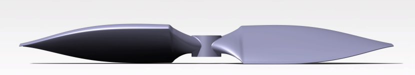
- Aerodynamic power reduction : 4 W (15%)
- Acoustic power reduction : 9 dB(A) (10%)

Side view

Top view



Front view



Final evaluation

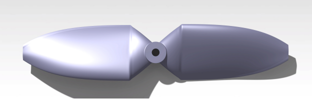
	A_p (N)	A_p (E)	L_{wA} (NTE)	L_{wA} (NTI)	L_{wA} (E)
Base configuration	19.6 W	**25.2** W	72.0 dB(A)	85.0 dB(A)	**83.3** dB(A)
Optimized twist	17.2 W	22.1 W	61.9 dB(A)	81.2 dB(A)	81.3 dB(A)
Optimized chord and twist	17.9 W	23.1 W	57.0 dB(A)	77.1 dB(A)	76.6 dB(A)
Optimized airfoil	16.9 W	**21.3** W	46.6 dB(A)	71.1 dB(A)	**74.5** dB(A)

Comments

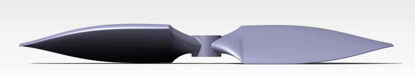
- Aerodynamic power reduction : 4 W (15%)
- Acoustic power reduction : 9 dB(A) (10%)

Side view

Top view



Front view



Results :

- development of an aeroacoustic modeling environnement with low–fidelity models
- development of an optimization framework for aeroacoustic blade optimization
- development of an experimental methodology for acoustic measurements
- encouraging results (low fidelity models)

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- tip radius
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- funding agency (Direction Generale de l'Armement)
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Back–up slides.