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A NOVEL PROCEDURE TO MINIMIZE THE ACOUSTIC AND ENVIRONMENTAL IMPACT OF EVTOL VEHICLES FOR INTRA-CITY MISSION PROFILES

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ABSTRACT

The paper applies a novel procedure to minimize the emitted noise or maximize vehicle performance for advanced air mobility applications. It considers a hexacopter configuration during the whole flight envelope for a typical intra-city mission profile. For a given flight trajectory conceived as a sequence of steady states segments, a trim solver, suitable for vehicle configurations with redundant controls, is applied in each segment to evaluate the optimal combination of control settings and vehicle attitude optimizing selected target functions like, for instance, noise and performance, while guaranteeing the desired flight condition. To this aim the trim solver is coupled with an aerodynamic solver based on the blade element momentum theory method and an acoustic solver based on the compact source version of the Farassat 1A formulation.

Keywords: *Advanced air mobility, noise reduction, eVTOL, trim procedure*

1. INTRODUCTION

Due to the exponential growth of city overcrowding and pollution, academia and industries are making a great effort to develop eco-friendly alternatives to standard urban mobility. Among them is urban air mobility (UAM), e scenario that is conceivable thanks to significant technological advances, including electric propulsion and batteries. Yet, to allow public acceptance and entry into the service of UAM, some critical issues should be addressed [1], such as environmental pollution and acoustic nuisance (mainly during take-off and landing operations).

In recent years, a great amount of research activities have been carried out to investigate viable strategies and technologies aimed at reducing the noise emitted by conventional vehicle designs, while maximizing aerodynamic performance to reduce fuel and electric energy consumption [2].

In typical eVTOL designs, as those commonly exploited for UAM applications, the propulsive system consists of more than one rotor, suitably tilted during the different flight envelope stages, eventually complemented by fixed wings to lift generation. In this perspective, to reduce the acoustic emissions of these concepts, several strategies can be exploited, from optimising each single rotor's geometrical characteristics [3] to defining optimal installation parameters to maximize the destructive interference of the signals radiated by each rotor [4] or the shielding effect of the vehicle airframe [5]. Even though great progress has been achieved so far, these strategies have the drawback of requiring the re-design of the whole configuration through costly optimization processes.

Recently, the authors proposed a novel procedure to minimize the emitted noise or maximize the aerodynamic performance of multi-rotor systems [6]. This approach overcomes the limitation of re-engineering the whole vehicle, by introducing strictly acoustic and aerodynamic

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constraints since the earliest design phases, and is applicable as an easy retrofitting of already existing concepts. This strategy is based on the observation that typically eVTOL vehicles are conceived as multi-rotor systems, for which the number of available controls is generally greater than those required to trim the vehicle. In addition to the possible methods available in the literature for the control redundancy management [7, 8], recently the author proposed an alternative approach based on recasting the trim procedure into a constrained cost function minimization problem, which provides the optimal combination of control settings and vehicle attitude that guarantees the desired flight condition while achieving targeted design objectives [6]. It has already been successfully applied to minimize the acoustic emissions in terms of tonal and broadband components for specific flight condition cases [9, 10].

Here, the method is applied to minimize the noise emitted by a hexacopter configuration during the whole flight envelope for a standard intra-city mission profile. Starting from a given flight trajectory conceived as a sequence of steady-state segments, the trim solver is applied in each trajectory segment to evaluate the optimal combination of control settings and vehicle attitude to minimize the emitted noise while guaranteeing the desired flight condition. To this aim, the trim solver is coupled with an aerodynamic solver based on the blade element momentum theory method [11] and an acoustic solver based on the compact source version of the Farassat 1A formulation [12].

2. MINIMUM OBJECTIVE FUNCTION TRIM METHOD

For multi-rotor configurations with redundant controls the trim solution, in terms of attitude and control settings, can be achieved by the control identification method presented and validated through comparison with literature results in [6].

This method minimizes an objective function, $\mathcal{O}(\boldsymbol{z},\boldsymbol{u})$, depending on the flight state parameters, $\boldsymbol{z}$, and the commands, $\boldsymbol{u}$, under the constraint to comply with the steady-state flight mechanics equations of trimmed flight. To this aim, the Lagrange multipliers, $\boldsymbol{\lambda}$, are introduced and the original minimization problem is recast into the following one

$$\mathcal{H}(\boldsymbol{z},\boldsymbol{u},\boldsymbol{\lambda}) = \mathcal{O}(\boldsymbol{z},\boldsymbol{u}) + \boldsymbol{\lambda}^T \boldsymbol{f}(\boldsymbol{z},\boldsymbol{u}) = min \quad (1)$$

where the $\boldsymbol{f}$ vector collects the equilibrium equations of trimmed flight. The solution of Eq. (1) requires the solution of the following system of equations:

$$\frac{\partial \mathcal{H}}{\partial \boldsymbol{z}} = 0\,; \qquad \frac{\partial \mathcal{H}}{\partial \boldsymbol{\lambda}} = 0\,; \qquad \frac{\partial \mathcal{H}}{\partial \boldsymbol{u}} = 0 \quad (2)$$

Thus, for a given steady-state flight condition, the system consists of 5 equations given by $\partial\mathcal{H}/\partial\boldsymbol{z} = 0$, N equations given by $\partial\mathcal{H}/\partial\boldsymbol{u} = 0$, and 9 equations provided by $\partial\mathcal{H}/\partial\boldsymbol{\lambda} = 0$, with $5 + N + 9$ unknowns, $(\boldsymbol{z},\boldsymbol{u},\boldsymbol{\lambda})$. Thus, Eqs. (2) yield a consistent nonlinear system that can be solved through the standard Newton-Raphson method. Although simple to implement, the drawback of this approach is the need to evaluate the Hessian matrix of $\mathcal{H}$. For this purpose, a standard finite difference algorithm can be exploited to evaluate the derivatives numerically, or, if available, the solution can be derived analytically. Alternatively, the computational burden of such an approach could be alleviated by using other solution approaches, such as the SLSQP (sequential quadratic programming) [13].

For a given set of kinematic variables and commands, the trim solver combines aerodynamic/propulsive loads, evaluated through a component build-up procedure, with the gravitational and inertial loads. The rotor blade is modeled as a hinged, rigid structure, with lead-lag and flap motion in addition to rotation about the feathering axis. The aerodynamic loads are determined by a quasi-steady Blade Element Momentum Theory, with section aerodynamic loads evaluated through a lookup table approach.

The trim problem is solved through two nested iterative loops, one for the solution of Eq. (1) and the other for the rotor dynamics equations solution through a harmonic balance approach. Specifically, starting from current states $(\mathbf{x},\mathbf{u})$, the aerodynamic loads of each rotorcraft component are evaluated, including those from rotors given as output of the harmonic balance problem. Then, these are used to define a new value of the functions in Eq. (1) and hence of the unknowns to be applied in the next step of the trim loop. This procedure is iterated until convergence. Once the convergence is reached, the spanwise distribution of the blade section aerodynamic loads is determined.

As already stated, the designer can arbitrarily define the objective function in terms of suitable measures of targeted performance as long as they depend on any of the flight variables and the flight parameters involved in the problem. If the selected target function is an acoustic metric, the trim solver has to be suitably coupled with an aeroacoustic solver. In particular, the blade section aerodynamic loads, coming from the trim procedure, become the input of the aeroacoustic solver used to evaluate the vehicle radiated noise. The aeroacoustic solver is based on the compact-source version of the Farassat 1A boundary integral formulation [12]. Indeed, since the latter requires the knowledge only of section loads, it can be easily coupled with the blade element theory method implemented within the trim solver described above for the evaluation of aerodynamic loads. For rotors in a subsonic regime, this formulation yields the aeroacoustic pressure field as a superposition of a thickness noise term depending on the blade geometry and kinematics, and a loading noise term associated with the blade aerodynamic loads. Both can be suitably expressed as a combination of line integrals along the spanwise quarter-chord line of the rotor blades [14].

3. NUMERICAL RESULTS

The configuration considered herein consists of a hexacopter vehicle (schematically depicted in Fig. 1) with a maximum take-off weight of 3000 kg, six coplanar and identical three-bladed rotors, each with a radius, R = 3 m, in a vertex-first configuration. The blades have a linear twist of 12°, a mean chord c_w of 0.2711 m, and the airfoil shape is the VR7 profile. In the reference system depicted

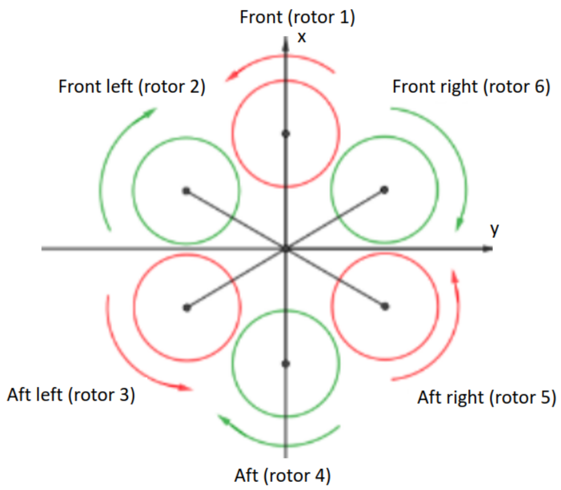


Figure 1. Schematic representation of the hexacopter configuration.

in Fig. 1, the rotors hubs coordinates are listed in Tab. 1.

The mission profile herein considered is schematically depicted in Fig. 2. The transient phases between the

	x [m]	y [m]	z [m]
Rotor 1	6.5	0.0	2.0
Rotor 2	3.25	-5.63	2.0
Rotor 3	-3.25	-5.63	2.0
Rotor 4	-6.5	0.0	2.0
Rotor 5	-3.25	5.63	2.0
Rotor 6	3.25	5.63	2.0

Table 1. Coordinates of the rotor hubs.

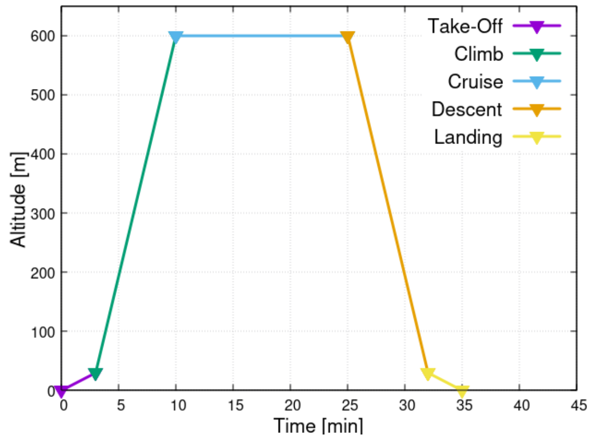


Figure 2. Mission profile.

different segments are ignored (they are assumed to be of short duration and, thus, scarcely affecting the overall nuisance generated).

The steady-state flight operative conditions in each segment of the mission profile are detailed in the following:

- Take-Off (TO): vertical flight from an altitude of 0 m to 30 m at 6 m/s;
- Climb (CL): from an altitude of 30 m to 600 m at 20 m/s, with a flight path angle equal to 12°;
- Cruise (CR): horizontal flight at an altitude of 600 m at 60 m/s;
- Descent (DS): from an altitude of 600 m to 30 m at 20 m/s, with a flight path angle equal to -12°;
- Landing (LN): vertical flight from an altitude of 30 m to 0 m at 6 m/s;

In each segment of the flight envelope, the trim procedure is applied considering two different objective functions to be minimised:

- Strategy A, minimum torque condition: the objective function is the sum of all the dimensionless rotors' torque, defined as:

$$\mathcal{O}_t = \sum_{i=1}^{N_r} \hat{M}_{z_i}$$

where $\hat{M}_{z_i}$ denotes the dimensionless torque of the i-th rotor and N_r is the number of rotors;

- Strategy B, minimum noise condition: the objective function is the mean Overall Sound Pressure Level (OASPL) evaluated in a selected set of microphones, defined as:

$$\mathcal{O}_{ac} = \frac{1}{N_{mic}} \sum_{i=1}^{N_{mic}} OASPL_i$$

where N_{mic} is the number of microphones.

In particular, in the reference system shown in Fig. 1, the microphones lie over a circle in the xy plane, centred at the origin and having a radius equal to $40R$.

Note that for the evaluation of the radiated noise objective function (here accounting for the tonal contribution only), the frequency analysis required to evaluate the acoustic metric includes a windowing process of the signal recorded during a three-rotor-revolution period to deal with the presence of arbitrary rotor angular velocities. In particular, the Hann windowing is applied, and an energy correction factor is used to maintain the total energy content of the signal.

The blades are assumed to have a fixed pitch set equal to 11° (reference value). Thus, the only available controls are the six rotors' angular velocities. The control settings obtained through the application of strategies A and B are shown in Tab. 2 and Tab. 3, respectively.

The differences in control settings are negligible in all the mission phases except for the cruise. This means that, except for the cruise segment, the controls that minimize noise emissions and rotors' torque are the same. Instead, for the cruise condition, the control settings obtained by minimizing the torque or the noise are significantly different, even if both the minimization processes lead to a set of control settings where the angular velocity of rotor 1 is significantly lower than the others.

For the cruise segment the comparison of the noise and performance objective functions obtained through strategies A and B is reported in Tab. 4. A significant improvement of the value of the specific objective function minimized is obtained: when the torque is the objective function to be minimised, the dimensionless rotors' torque is reduced up to 45% with respect to that obtained through strategy B. On the contrary, when the target function is noise minimization, the average OASPL is reduced by 13 dB. This outcome is confirmed by Fig. 3 which shows the comparison of OASPLs evaluated at the selected set of microphones through the application of strategies A and B.

As already stated, the only active controls used up to this point are the rotor angular velocities, as typically assumed for multirotor control procedures. This means that the collective blade pitch angles are set a priori based on structural and aerodynamic considerations. An alter-

	TO	CL	CR	DS	LN
ω_1 [rad/s]	51.4	42.1	16.5	33.9	36.1
ω_2 [rad/s]	51.5	43.0	37.3	34.9	36.1
ω_3 [rad/s]	51.5	44.9	42.5	36.9	36.2
ω_4 [rad/s]	51.6	45.8	39.4	37.9	36.3
ω_5 [rad/s]	51.5	44.9	31.8	36.9	36.2
ω_6 [rad/s]	51.5	43.0	46.2	34.9	36.1

Table 2. Control settings during the whole mission profile as obtained by application of strategy A.

	TO	CL	CR	DS	LN
ω_1 [rad/s]	51.4	41.9	23.6	33.8	36.0
ω_2 [rad/s]	51.5	43.0	38.1	34.8	36.1
ω_3 [rad/s]	51.5	45.1	39.6	37.2	36.3
ω_4 [rad/s]	51.6	45.6	40.3	37.8	36.3
ω_5 [rad/s]	51.6	45.0	37.0	36.9	36.2
ω_6 [rad/s]	51.5	43.2	40.0	35.1	36.2

Table 3. Control settings during the whole mission profile as obtained by application of strategy B.

	$\mathcal{O}_t$	$\mathcal{O}_{ac}$
Strategy A	1.45	72.47
Strategy B	3.14	59.32

Table 4. Comparison of the objective function for the cruise condition as obtained by application of strategies A and B.

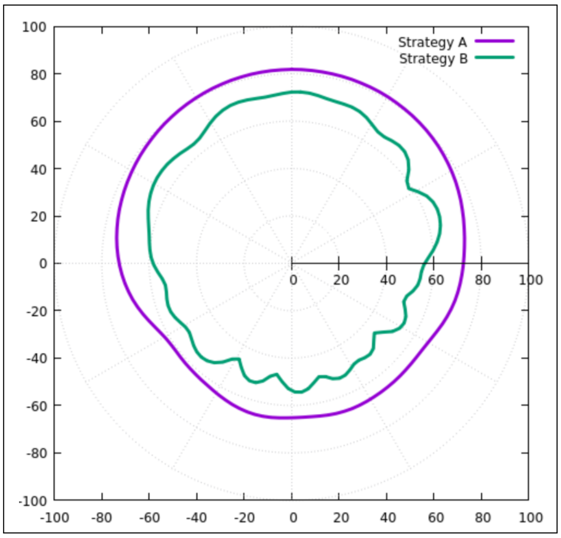


Figure 3. Comparison between the OASPL's directivities obtained for the minimum noise and minimum torque cases.

native approach might be considering the blade pitch angles as additional controls. But, being the use of variable blade pitch propellers unrealistic for standard configurations, the idea is to define an optimal pitch angle to be exploited for the whole flight envelope. To evaluate the optimal pitch, the trim procedure is applied considering 12 available commands for a selected flight condition. Once determined, the optimal pitch is kept fixed for the whole mission profile, and the trim procedure is applied with the angular velocities as the only available commands.

To this purpose, strategies A and B are applied in the takeoff condition, to evaluate the corresponding optimal collective angles, considering six angular velocities and six collective angles as available controls. The noise minimization leads to an increase of the collective pitch angle, with an optimal value of $12.7°$ (upper bound of the design space due to aerodynamic constraints), and equal for all the rotors. Instead, the minimization of the rotor torque results in a decrease of the pitch angle, with an optimal value of $9.3°$ (only slight differences are obtained among the rotors, less than 2%). The angular velocity control settings obtained through strategies A and B in combination with the optimal pitch angle setting are shown in Tab. 5 and Tab. 6, respectively.

The objective function obtained through the two strategies when applying the corresponding optimal pitch

	TO	CL	CR	DS	LN
ω_1 [rad/s]	60.0	48.7	36.7	38.5	40.7
ω_2 [rad/s]	60.0	49.5	38.8	39.3	40.7
ω_3 [rad/s]	60.0	51.4	43.2	41.3	40.7
ω_4 [rad/s]	60.0	52.2	45.6	42.2	40.7
ω_5 [rad/s]	60.0	51.2	43.2	41.3	40.7
ω_6 [rad/s]	60.0	49.5	38.8	39.3	40.7

Table 5. Control settings during the whole mission profile as obtained by application of strategy A with the optimal pitch setting.

	TO	CL	CR	DS	LN
ω_1 [rad/s]	47.5	37.7	31.4	31.4	33.1
ω_2 [rad/s]	47.4	40.4	32.0	32.3	33.2
ω_3 [rad/s]	47.5	42.6	35.1	35.3	35.5
ω_4 [rad/s]	47.5	41.3	42.2	35.6	33.2
ω_5 [rad/s]	47.4	42.8	35.4	34.4	33.3
ω_6 [rad/s]	47.5	40.3	31.4	33.3	35.3

Table 6. Control settings during the whole mission profile as obtained by application of strategy B with the optimal pitch setting.

angles are compared in Fig. 4 and Fig. 5 for the noise and torque objective functions, respectively. For the sake of completeness, the objective functions obtained by assuming the reference pitch angles are also depicted.

Concerning the rotor torque minimization, using an optimal pitch angle improves the target functions throughout the whole flight envelope. Instead, When the objective function is the emitted noise, the average OASPL is reduced in all the mission profile phases except for the cruise. In the latter case the average noise is 4 dB higher than that obtained by setting the reference pitch. In fact, since the optimal collective pitch angle is identified for a single flight condition, not necessarily it remains the optimal value for all the mission profile phases. Nevertheless, the average OASPL is still lower than the OASPLs resulting from a torque minimization strategy. These results confirm that even if an improved target function can be achieved by setting the same reference pitch angle for all the analyses, the application of a suitably determined optimal collective pitch can provide even better outcomes.

Finally, Fig. 6 shows comparisons between the OASPL directivities evaluated through the two strategies

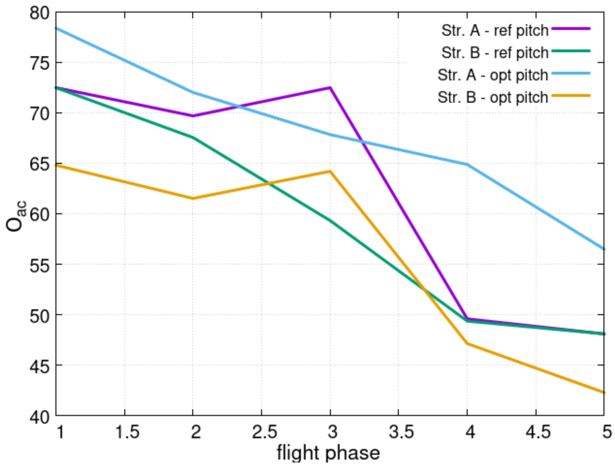


Figure 4. Comparison of the objective function $\mathcal{O}_{ac}$ obtained by application of strategies A and B with the reference and optimal pitch angle.

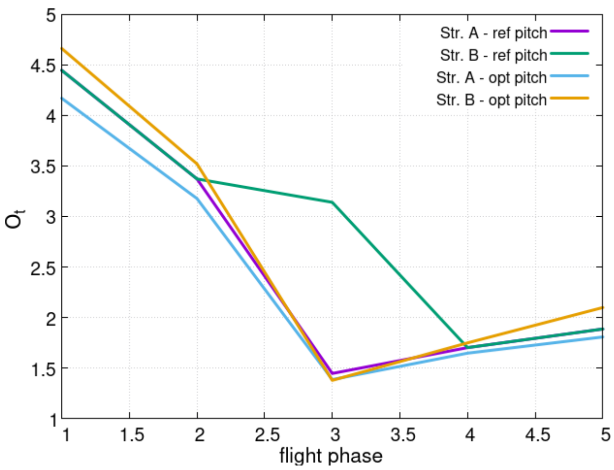
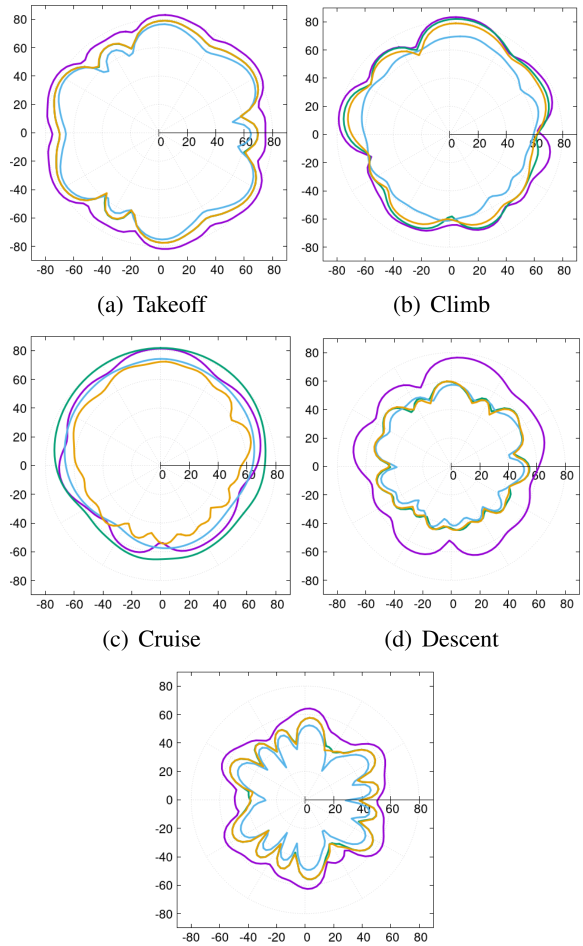


Figure 5. Comparison of the objective function $\mathcal{O}_t$ obtained by application of strategies A and B with the reference and optimal pitch angle.



(a) Takeoff (b) Climb

(c) Cruise (d) Descent

(e) Landing

Figure 6. Comparison between the OASPL directivities obtained through the two strategies, with the optimal and the reference pitch angle. Purple line: strategy A - optimal pitch; Green line: strategy A - reference pitch; Light blue line: strategy B - optimal pitch; Orange line: strategy B - reference pitch;

by the two pitch settings for the whole mission profile.

The reduction in noise emission already observed in Fig. 5 is here confirmed. The decrease in the average OASPL is almost equally distributed among all the observers, with no microphones measuring an undesirable significant increase in noise. As already pointed out, the only exception is the cruise condition, where an increase of noise in all the microphones is observed with respect to that radiated in the case of noise minimization assuming the reference pitch angle.

4. CONCLUSIONS

This paper proposes a novel procedure to determine the trim condition of multi-rotor systems suitably exploiting the control redundancy to optimize selected target functions, here related to noise emissions and aerodynamic performance. The configuration herein investigated is a hexacopter with a typical intra-city mission profile, which is conceived as a sequence of steady-state conditions. To demonstrate the capability of the proposed approach to achieve an effective improvement of the selected objective function, two different strategies are applied and compared which rely on the minimization of the acoustic emissions and the rotors' torque, respectively. The numerical investigations demonstrate that the minimization of both rotor torque objective function and acoustic metric objective function is successful when the rotor angular velocities are the set of controls to be identified. Furthermore, if the blade pitch angle is set a priori without involving any noise constraint, the improvements are limited. Instead, if the pitch angle is set through a preliminary trim analysis involving both the collective pitch angles and the angular velocities as active commands, the improvement strongly increases with a reduction of noise up to 8 dB, and a reduction of rotors' torque up to 5%.

5. ACKNOWLEDGMENTS

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