

Impact of Optimized Variable Rotor Speed and Active Blade Twist Control on Helicopter Blade-Vortex Interaction Noise and Environmental Impact

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Abstract

Combined variable rotor speed and active blade twist helicopter technologies have the potential to reduce the environmental and acoustic impact of modern rotorcraft. This paper explores the aeroacoustics, environmental and ground noise impact of combined variable rotor speed and active blade twist helicopter rotors, optimized for simultaneous mitigation of source noise and NO_x emissions. An integrated approach is employed including free-wake aeroelastic rotor modeling and time-domain aeroacoustic formulations fundamentally based on Acoustic Analogy. The overall method is incorporated into a multi-disciplinary design space exploration and surrogate-model-assisted optimization algorithm. The developed framework is deployed towards devising optimal variable rotor speed and active blade twist control for a representative twin-engine light helicopter operating in a realistic descent trajectory. The obtained rotor control schedules achieve overall ground noise reductions of up to 7 dB with concurrent NO_x reductions of 11%, relative to the conventional rotor. The proposed approach provides new insight into rotor wake behavior and blade-vortex interactions, as well

as environmental impact and ground noise footprint of combined variable rotor speed and active blade twist helicopter concepts.

Keywords: *Helicopters, Blade-vortex interactions, Aeroacoustics, Environmental impact, Ground noise footprint, Multi-disciplinary optimization.*

Nomenclature

Roman Symbols

AUM	All-up mass	[kg]
c_b	Blade chord	[m]
C_L	Rolling moment coefficient = $L / (\rho \pi \Omega^2 R^5)$	[-]
C_M	Pitching moment coefficient = $M / (\rho \pi \Omega^2 R^5)$	[-]
$C_n M^2$	Normal force coefficient = $F_N / (0.5 \rho a^2 c_b)$	[-]
C_T	Thrust coefficient = $T / (\rho \pi \Omega^2 R^4)$	[-]
$EAOASPL$	Energy averaged overall sound pressure level	[dB]
F_N	Blade section normal force	[N/m]
h	Density altitude	[m]
L	Rotor rolling moment	[Nm]
M	Rotor pitching moment	[Nm]
$\vec{M}$	Relative Mach number vector	[-]
N	Number of data points on acoustic sphere	[-]
$N_{Pearson}$	Pearson's product moment of correlation	[-]
NO_x	Nitrogen oxide emissions	[kg]
NO_x^{rate}	Rate of NO_x formation	[kg/sec]

$NRMSE$	Normalized root mean square error	[%]
$OASPL$	Overall sound pressure level	[dB]
R	Main rotor radius	[m]
$\vec{r}$	Radiation distance vector	[m]
T	Rotor thrust	[N]
V_x	Flight speed	[m/s]
V_z	Climb rate	[m/s]
Greek Symbols		
a	Speed of sound	[m/s]
a_s	Wind-tunnel rotor shaft angle	[deg.]
θ_{tw}	Blade twist angle	[deg.]
ρ	Air density	[kg/m ³]
σ	Standard deviation	[-]
ψ	Blade azimuthal position	[deg]
Ω	Rotor rotational speed	[rad/s]
Superscripts		
$(\cdot)^{Opt}$	Optimized quantity	

1. Introduction

Rotorcraft activity is expected to develop sharply in the near future [1], which is foreseen to affect the associated environmental and acoustic impact if no technological improvements are achieved. The International Civil Aviation Organization (ICAO) has recommended the so-called “Balanced

Approach” [2] for aviation noise control around airports, which includes: (a) reduction of noise at source, (b) land-use planning and management, (c) noise abatement operational procedures and (d) operational restrictions. Landing and take-off (LTO) cycles are directly associated with increased NO_x concentration around airports [3]. Additionally, helicopter noise is pronounced in descent where blade tip vortices are in close proximity to the elastic rotor blades [4], thus generating intense blade-vortex interaction (BVI) noise [5].

The demanding future environmental requirements [6] suggest that pollutant and acoustic emissions should be resolved in a multi-disciplinary fashion, targeting the concurrent mitigation of the intercoupled generating mechanisms. The most effective means to reduce aeroacoustic and pollutant emissions is through suppressing adverse aerodynamic effects in the vicinity of the main rotor. The diverse operational conditions across rotorcraft missions dictate that there is a requirement of active rotor morphing technologies to effectively abate the environmental and acoustic impact of modern helicopters [7].

Conventional helicopter rotors usually rotate at constant speed; however in specific operating conditions, trim can potentially be achieved at rotational speeds different than the nominal, therefore improving performance and operability [8], [9]. Steiner [10] examined the performance benefits arising from the implementation of variable rotor speed (VRS) on a UH-60 helicopter, demonstrating 12% and 17% power reductions in hover and cruise near 60 m/s, respectively. Bowen-Davies and Chopra [11] showed that at low-thrust requirements in low-speed cruise, power reduction of up to 20% can be achieved with a rotor speed of 76% on the UH-60 helicopter, using the University of Maryland Advanced Rotorcraft Code (UMARC) [12]. Misté *et al.* [8] presented fuel savings of about 7-8% within a $\pm 15\%$ range of the nominal UH-60 rotor speed. The impact of VRS on rotor noise generation has been recognized [13]. Overall, the use of slowed rotors mitigated source noise generation due to the reduced magnitude of blade relative Mach number vector in the direction of noise radiation. However, the impact of VRS on the break-down of low- and higher-harmonic noise components during descent has not been thoroughly quantified.

Variable blade pitch [14] is implemented either through individual blade control (IBC) [15] or collectively, through higher harmonic control (HHC) inputs [16] or collective active blade twist (ABT)

variations [17]. Brooks and Booth [18] investigated the impact of HHC on BVI noise and aeroelastic response of a dynamically and Mach scaled, four-bladed, articulated rotor in low-speed descent. BVI noise reductions of up to 5.6 dB were achieved through 4/rev HHC excitations, although with low-harmonic noise penalties of 6 dB. A Bo 105 helicopter featuring 2/rev IBC control system was tested [19], with BVI noise reductions of up to 5 dB for descent slope angles between 4-8 deg. Booth and Wilbur [20] assessed the aeroacoustics of active blade twist variation. A 5/rev excitation led to 2.8 dB BVI noise reduction at an advance ratio of 0.14; however, low-frequency noise was increased by up to 5 dB. Anobile *et al.* [21] presented the synthesis of a 2/rev active twist controller for noise alleviation. BVISPL reduction of 6 dB was achieved in the retreating side, although with a limited increase in low-frequency noise. Cesnik *et al.* [22] emphasized the importance of multi-disciplinary treatment of the aeroelastic and aeroacoustic aspects associated with active twist morphing.

VRS combined with ABT offers the potential of further enhancing helicopter operability and environmental impact, through control of rotor blade unsteady aerodynamics. Han *et al.* [23] assessed the performance of a UH-60A helicopter rotor employed with combined VRS and ABT. In 250 km/h cruise, the individual variation of rotor speed and blade twist offered power reductions of 17.8% and 10.4%, respectively, whilst the combined variation raised this figure to 20.9%. Goulos and Bonesso [24] evaluated the performance and environmental impact of a Bo 105 helicopter featuring a VRS and ABT rotor. A global optimization strategy was developed to obtain optimum rotor speed and blade twist control schedules for minimum engine fuel flow. The accrued rotor control schedules were deployed in the simulation of realistic, three-dimensional operations. Fuel flow and NO_x rate reductions of up to 5% and 8% were computed, respectively. Despite that the impact of individual variation of rotor speed and blade twist on helicopter rotor noise and NO_x emissions has been discussed, the aeroacoustics of combined VRS and ABT helicopter concepts have not yet been investigated. Furthermore, no quantifications with respect to the trade-off between noise and NO_x emissions have been found in the literature relevant to combined VRS and ABT concepts.

The overall scope of this work is to investigate the potential impact of combined VRS and collective ABT helicopter configurations, in terms of improved environmental and acoustic impact.

Rotor speed variation is accomplished through the engine full authority control system (FADEC) by transient adjustment of fuel flow. This concept has been preferred instead of a variable transmission due to the added weight and complexity that would be introduced. In terms of ABT, it is noted that the linearly distributed twist of the Bo 105 helicopter rotor blades is varied collectively, therefore no higher-harmonic twist actuation is considered in this study. Emphasis is given on the aerodynamic and aeroacoustic aspects of the novel concept, considering both low and higher frequency noise components. A three-step integrated procedure is deployed comprising mathematical modeling methods for helicopter flight dynamics, engine performance, unsteady airloads, aeroelasticity, pollutant emissions, rotor aeroacoustics and ground noise impact. An efficient design space exploration and multi-disciplinary optimization framework is developed, targeting the concurrent mitigation of NO_x and source noise emissions. The derived VRS and ABT optimal control schedules are applied on a helicopter model representative of the Airbus Helicopters Bo 105, operating in a realistic descent trajectory. The proposed approach sheds light on rotor wake behavior, blade-vortex interactions and source noise generation, as well as environmental impact and ground noise footprint of combined VRS and ABT helicopter concepts.

2. Mathematical approach

A comprehensive flight performance framework is coupled with a free-wake aeroelastic rotor model and a rotor aeroacoustic model. The three-step integrated procedure is utilized within a design space exploration approach for the investigation of the impact of VRS and ABT on the trade-off between source noise and NO_x emissions. A surrogate-model-assisted optimization strategy is applied along a realistic descent trajectory to devise optimized VRS and ABT schedules for the simultaneous reduction of environmental and acoustic impact of a representative twin-engine light helicopter.

2.1. Helicopter flight performance model

The comprehensive framework “HECTOR” (Helicopter Omni-Disciplinary Research Platform) is utilized to calculate flight dynamics, engine performance and pollutant emissions for the investigated operating conditions. HECTOR has been extensively analyzed by Goulos *et al.* [1], [25]–[27], therefore the individual modeling methods will be briefly described. Elastic rotor blade flap, lag and torsion characteristics are attained through the minimum potential energy method proposed by Goulos *et al.* [25] and enhanced by Castillo-Pardo *et al.* [28]. The structural formulation is coupled with the Leishman-Beddoes unsteady nonlinear blade element aerodynamics model [29], the Peters-He finite state induced flow model [30] and the Goulos’ dynamic wake curvature model [27]. The aforementioned modules are integrated within a globally-convergent Newton-Raphson algorithm to acquire rotor thrust C_T , rolling moment C_L and pitching moment C_M coefficients for any designated set of flight conditions.

The engine performance model is implemented in TURBOMATCH [31], a gas turbine simulation software developed and continuously improved within Cranfield University. TURBOMATCH performs a zero-dimensional aero-thermal gas path analysis, solving for the mass and energy balance between the various engine components. For the purposes of this work, the engine is assumed to operate at steady state off-design conditions. NO_x emissions are modeled through HEPHAESTUS, a generic platform developed by Celis *et al.* [32] for the estimation of pollutant emissions of civil aero-engines. This is implemented through a stirred reactor concept along with a set of simplified chemical reactions, accounting also for the design specifications of the combustion system. Goulos *et al.* [33] and Ortiz-Carretero [34] enhanced and extensively validated HEPHAESTUS to also cater for turboshaft engine emissions. Specifically, the model predictions were compared with measured data derived by the Federal Office of Civil Aviation (FOCA) for a wide range of engine power settings [35].

2.2. Rotor airloads model

A free-wake and aeroelastic rotor model, developed by Castillo Pardo [36], is employed for the calculation of the high-resolution unsteady airloads required for noise predictions. The model features a minimum potential energy method, similar to the one used in HECTOR, for the evaluation of blade coupled flap-lag-torsion vibration characteristics [28]. The matrix/vector based analytical formulation presented in [26] is used for modeling flexible rotor blade kinematics. The structural blade model is coupled with the Leishman-Beddoes indicial response method [29] for the prediction of unsteady blade aerodynamics.

The pseudo-implicit predictor-corrector relaxation scheme, proposed by Bagai and Leishman [37], is employed for the modeling of unsteady rotor inflow. This free-wake method predicts the convection of wake tip vortex filaments, hence rendering the aeroelastic rotor model able to capture the complex blade-vortex interaction phenomena in the vicinity of the main rotor [38]. The semi-empirical analytical model developed by van der Wall *et al.* [39] is utilized to capture the first-order effects associated with rotor-fuselage aerodynamic interactions. The aforementioned models are incorporated into a globally-convergent trim algorithm based on Broyden's numerical scheme, solving for the rotor collective and cyclic pitch controls for designated flight conditions and rotor thrust C_T , rolling moment C_L and pitching moment C_M coefficients, as calculated by HECTOR.

2.3. Rotor aeroacoustics model

The Integral Computational AeRoacoustics Unified Software (ICARUS) developed and validated by Vouros *et al.* [40], [41] is deployed for the prediction of helicopter rotor source noise and ground acoustic footprint. ICARUS has been validated for the baseline HART-II rotor [42], which is a 40% geometrically and dynamically scaled model of the Bo 105 helicopter rotor employed in this work. The software constitutes a numerical implementation of Farassat's Formulation 1A [43], [44], which is effectively an integral solution of the fundamental Ffowcs Williams-Hawkings equation (FW-H) for noise propagation [45]. FW-H equation originally classifies noise in thickness, loading and high-speed impulsive acoustic components. Formulation 1A neglects high-speed impulsive noise, on the basis that

blade tip Mach number does not reach supersonic values along typical civil helicopter missions; hence significant HSI noise is typically avoided.

The chord-wise compact thickness noise formulation proposed by Lopes [46] is utilized for the prediction of thickness noise. Similarly, the compact loading noise expression developed by Brentner *et al.* [47] is employed for the prediction of loading noise, including BVI acoustic components. The utilization of compact acoustic formulations leads to considerable reductions in terms of computational time, enabling the incorporation of rapid on-the-fly rotor source noise predictions into the simulation of complete helicopter missions. Furthermore, the acoustic formulations of this model are directly compatible with the lifting-line aerodynamic calculations of the free-wake airloads model. It is noted that the accuracy of this compact formulation is lower when source-observer distance is comparable to the blade chord length [48], [49]. Overall, the compact formulations employed within this work satisfy the trade-off between predictive accuracy and computational efficiency in the context of holistic design space exploration and multi-disciplinary optimization.

Source noise prediction is carried out across the surface of a designated acoustic sphere surrounding the rotorcraft and fixed to the main rotor hub. The acoustic pressure time history for a full rotor revolution is evaluated through the compact thickness and loading noise expressions of Formulation 1A. The time-resolved acoustic signal is then spectrally analyzed via fast Fourier transformation (FFT) to obtain a frequency-domain expression of rotor aerodynamic noise at each sphere-observer. The overall sound pressure levels (OASPL) are calculated via integration of the FFT signal in the frequency spectrum. The OASPL metric is selected instead of BVISPL or weighted metrics, to capture the impact of VRS/ABT on the entire noise spectrum. The highest annoyance to human hearing occurs at frequencies between 1-5 kHz which is the frequency range where BVI noise usually occurs. However, apart from the directly-sensed impact of noise annoyance on human hearing, health-related impacts shall also be considered. Low-frequency noise between 20-100 Hz, is related to adverse physiological (cardiovascular and respiratory) as well as psychological effects on human health [50]. This can be of special importance in populated areas located near airports. Therefore, the original version of the OASPL metric has been selected for the elementary noise evaluations to resolve both the low and higher-frequency noise spectrum with no bias.

The propagation losses during the sound wave travel from the acoustic sphere to the ground observer are accounted for in the frequency domain, assuming no losses within the sphere volume. It is noted that for ground observers located at distances closer than the radius of the acoustic sphere, ground noise levels are calculated directly through Formulation 1A without including far-field propagation effects. Atmospheric absorption is assessed using the method proposed by Sutherland et al. [51] and standardized by ISO 9613-1 and ANSI S1.26-1995. The method is based on the calculation of the absorption coefficient resolving propagation frequencies, flight temperature and pressure, and relative humidity. Geometric spreading is accounted using the inverse square law for spherical spreading outside the acoustic sphere of 150 m radius. This work focusses on the impact of combined VRS and ABT on noise generation whilst resolving the first-order effects of variations in the propagation distance along the trajectory. For the standardized descent trajectory to be later explored, no significant variations of atmospheric properties are expected within the designated altitude range. For the quantifications of this work, the impact of meteorological and ground effects would identically apply on both conventional and conceptual configurations, so no significant variation would be expected in the relative deltas. However, it is advised that future studies include the impact of temperature and wind velocity gradients, as well as the impact of ground reflections.

2.4. Design space exploration approach

A dedicated multi-disciplinary optimization strategy is developed comprising the models presented in Sections 2.1-2.3. The overall objective of the optimization approach is to obtain optimum rotor speed and blade twist control schedules of the main rotor in terms of simultaneous minimization of both noise and NO_x emissions. The method caters for the inherent non-linearity associated with rotorcraft aerodynamics, aeroelasticity, aeroacoustics and engine and combustor performance by utilizing an effective numerical strategy capable of evaluating multiple design iterations. The system's response is analyzed in terms of two principal disciplines, emitted NO_x and emitted noise. A cumulative metric of source noise levels, representative of the entire acoustic sphere is employed, evaluated through energetically averaging the values of $OASPL$ for all the acoustic sphere observers:

$$EAOASPL = 10 \log_{10} \left(\frac{1}{N} \sum_{i=1}^N 10^{\frac{OASPL(i)}{10}} \right) \quad (\text{Eq. 1})$$

where $EAOASPL$ is the energetically averaged $OASPL$ in dB and N is the number of observers across the surface of the acoustic sphere. The $EAOASPL$ metric has been successfully deployed in trajectory optimization for helicopter ground noise mitigation [52], [53]. The rate of nitrogen oxide NO_x^{rate} constitutes the second objective of the optimization procedure to effectively explore the trade-off between environmental and acoustic impact of helicopters in descent.

A Design Space Exploration (DSE) method is developed to obtain the system's response to variations of design parameters and operational conditions. The DSE comprises two main modules; (a) the Design of Experiments (DOE) to populate the design space and (b) the generation of Response Surface Models (RSMs) to estimate the system's non-linear response. A DOE is a systematic approach to get the maximum amount of information out of a given sample [24]. A full-factorial design is employed to populate the design space. Factorial sampling enables the use of different weighting for each design and operational variable based on the relative importance between them. Additionally, it allows future expansion of the design space without altering the original set of solutions.

Response Surface Models (RSMs) are structured using Gaussian Process Regression [54] (Kriging interpolation) across the sample data obtained from the DOE. The employment of RSMs instead of direct HECTOR/Free-wake/ICARUS simulations reduces the computational cost associated with the multiple system evaluations required by the optimization algorithm. The classical Leave-One-Out Cross-Validation (LOOCV) method [55] is employed to evaluate the predictive accuracy of the developed RSMs. An overview of the DSE strategy developed in this work is presented in Fig. 1.

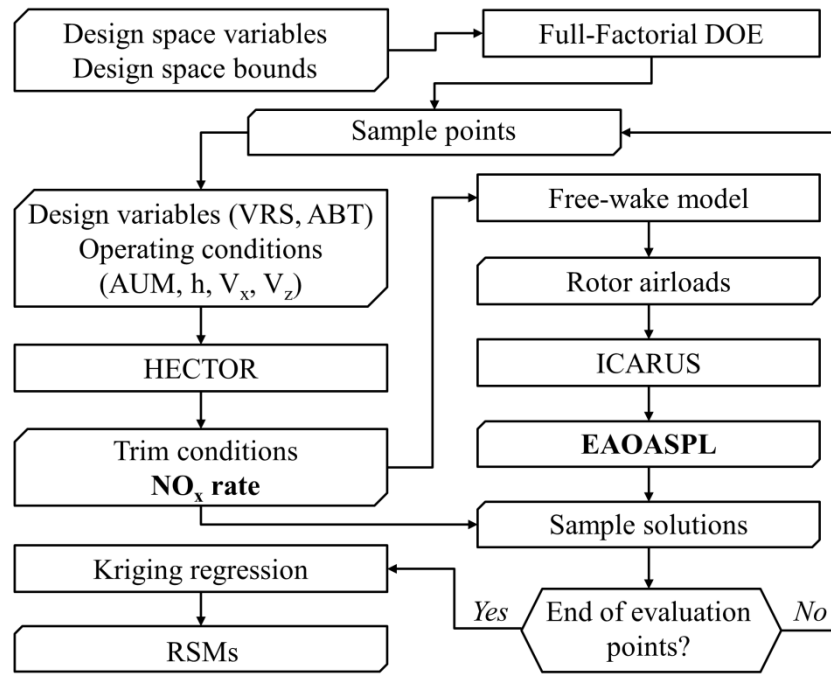


Fig. 1. Overview of the DSE approach.

2.5. Optimization strategy

The designated design space can be systematically explored to establish optimum VRS and ABT control settings for the concurrent mitigation of environmental and noise impact of VRS and ABT concept. The optimization algorithm employed in this work is the Non-dominated Sorting Genetic Algorithm II (NSGA-II), originally developed by Deb *et al.* [56]. NSGA-II is an elitist evolutionary algorithm which performs sorting of the population into a hierarchy of non-dominated Pareto fronts. The elite solutions of each generation are directly transferred to the next generation, which prevents back-tracking of the algorithm.

NSGA-II is a global optimization approach, which, compared to gradient-based methods, is considerably less sensitive of getting trapped within design space regions containing local optimum solutions [24]. The output of the multi-disciplinary optimization process is a Pareto front, which is a set of optimal (non-dominated) solutions. The Pareto-optimal set of solutions is utilized to investigate the trade-off between the objectives of the optimization process. Consequently, one or more specific point(s) of the Pareto optimal front can be selected based on problem requirements and design intent.

3. Results and discussion

A DSE approach comprising full-factorial DOE and Kriging-based RSMs is utilized to approximate the sensitivity of the system to variations of rotor speed and blade twist. The system's behavior is explored to identify trade-offs between noise and NO_x emissions. The derived RSMs are deployed towards devising optimized rotor control schedules along a representative descent trajectory. The impact of optimized VRS and ABT on source noise, ground noise impact and NO_x emissions is quantified.

3.1. Surrogate modeling and cross-validation

The six-dimensional design space is composed of the following design and operational parameters referring to the Airbus Helicopters Bo 105 helicopter: (a) variable rotor speed, (b) active blade twist angle, (c) rotorcraft all-up-mass, (d) density altitude, (e) flight speed and (f) rate of climb. The design space is discretized using 2,916 sample points based on full-factorial sampling design. The sampling grid structure and design space bounds are provided in Table 1. Additionally, reference values, representative of realistic descent conditions, have been assigned to all the parameters. The three-step integrated procedure introduced in Sections 2.1-2.4 is employed to calculate $EAOSPL$ and NO_x^{rate} at each evaluation point.

Table 1. Discretization of the design space based on non-uniform full factorial sampling.

Parameter	Min value	Max Value	Nodes	Reference	Unit
All-up-mass AUM	1600	2400	3	2000	kg
Density altitude h	0	500	3	250	m
Flight speed V_x	20	40	3	30	m/s
Climb rate V_z	0	-5	3	-4	m/s
Rotor speed Ω	75	100	6	100	%
Blade twist angle θ_{tw}	2.4	16.4	6	8.0	deg

The RSMs are generated using Kriging-based interpolation, implemented through quadratic regression combined with exponential auto-correlation, which were selected on the basis of optimizing the RSM accuracy. The predictive accuracy of the derived RSMs is quantified through Leave-One-Out Cross-Validation (LOOCV) [55]. LOOCV assesses the ability of the surrogate model to predict unknown data using a dataset of known data on which training is run. In the present implementation, each and every point of the original DOE is treated as unknown data, thus excluded from the training dataset. A dedicated RSM is then constructed and its prediction is compared to the unique value of the specific excluded data point. This process is repeated for every DOE sample point. The quality of the original RSMs is assessed in terms of Pearson's product moment of correlation $N_{Pearson}$ [24] along with the gradient of the associated linear regression line. A perfectly linear correlation corresponds to $N_{Pearson} = 1.00$ and a regression gradient of 45.00 deg.

Table 2. Statistical properties of the LOOCV for the objectives of interest.

Objective	$N_{Pearson}$ [-]	Gradient [deg]	NRMSE [%]	σ [%]
<i>EAOASPL</i>	0.996	44.991	0.817	0.818
NO_x^{rate}	0.999	45.004	1.199	1.200

The statistical properties of LOOCV for *EAOASPL* and NO_x^{rate} are provided in Table 2. The predictive accuracy of the derived RSMs is quantified through the normalized root-mean-square error *NRMSE* which is approximately 1% for both objectives. The corresponding standard deviation σ of the calculated error is again in the order of 1% for both variables, indicating that the RSM error is uniformly distributed throughout the investigated design space. Overall, it is confirmed that the developed RSMs accurately replicate the non-linear behavior of the physical process.

3.2. Trade-off between source noise and NO_x emissions

In Fig. 2 (a), the sensitivity of source noise and NO_x emissions to combined variations of rotor speed Ω and blade twist θ_{tw} is explored at $AUM = 1600 \text{ kg}$. The rest of flight conditions retain their reference values as described in Table 1, leading to a flight path angle of -7.6 deg. Relative metrics have been adopted for the quantifications of this work. Specifically

$$\Delta NO_x^{rate} [\%] = 100 \cdot \frac{NO_x^{rate, Opt} - NO_x^{rate, Nom}}{NO_x^{rate, Nom}}$$

represents the normalized change of NO_x^{rate} with

respect to the corresponding value at nominal Ω and θ_{tw} . The dimensional values in noise reduction were preferred from normalized ones, since this is the convention typically used in noise abatement studies. Therefore, $\Delta EAOASPL = (EAOASPL^{Opt} - EAOASPL^{Nom})$ represents the difference in dB relative to nominal rotor control settings at the specified flight conditions.

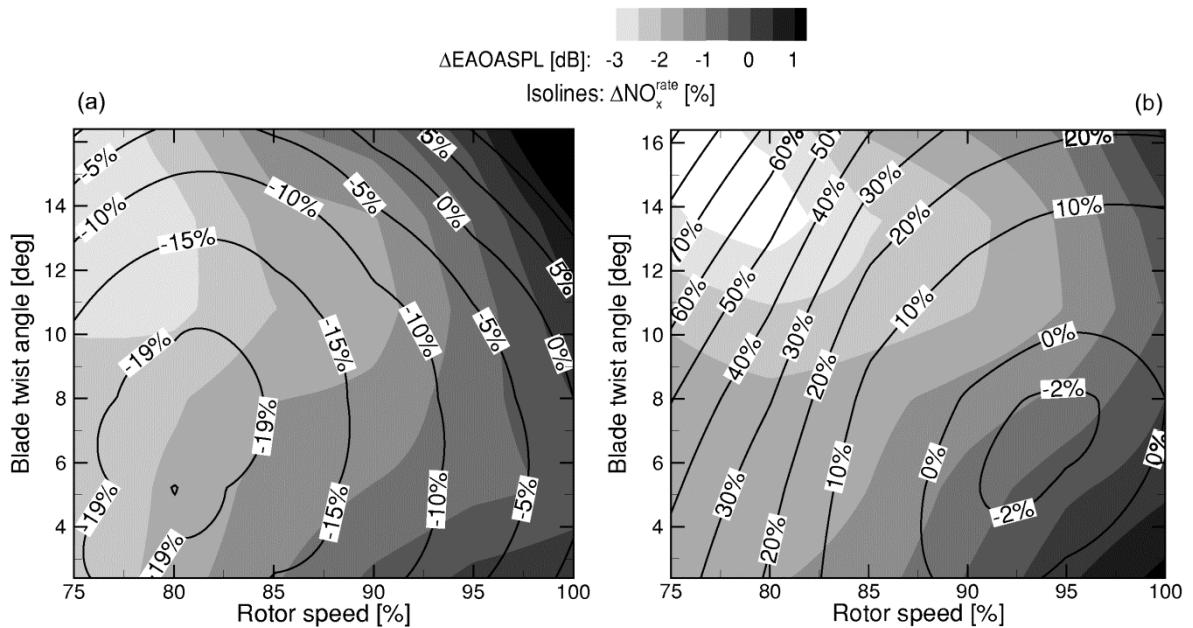


Fig. 2. Impact of combined VRS and ABT variation on source noise and NO_x emissions at $h = 250 \text{ m}$, $V_x = 30 \text{ m/s}$, $V_z = -4 \text{ m/s}$: (a) $AUM = 1600 \text{ kg}$; (b) $AUM = 2400 \text{ kg}$.

The noise contours illustrate that $EAOASPL$ is minimum at low Ω and high θ_{tw} in these flight conditions. Decrease in Ω results in reduced acoustic radiation Mach numbers and consequently, increased Doppler amplification factor. According to the derivations of Formulation 1A of Farassat [43], this moderates the contribution of both thickness and loading noise components. Increase in θ_{tw} leads to a re-distribution of aerodynamic loading, moving the peaks of blade loading radially inboards. As discussed in [42], the most severe BVIs are concentrated at the outboard blade regions due to the small miss-distance between trailed tip-vortices and rotor blades around the aforementioned regions. Hence, re-distribution of aerodynamic blade loading towards the inboard direction of the blade span leads to reduced circulation around the tip which reduces tip-vortex strength and eventually BVI noise.

The $\Delta NO_x^{rate}[\%]$ isolines are superimposed to illustrate the trade-off between noise and NO_x emissions under variations in Ω and θ_{tw} . The production of NO_x emissions is dependent on the engine operating point which is determined by two fundamental disciplines: (a) rotor aerodynamic performance and (b) engine thermodynamic performance. In terms of main rotor aerodynamics and performance, reduction of Ω results in reduced rotor dynamic pressure which eventually leads to reduced blade profile drag [57]. However, a simultaneous raise in blade local pitch angle by collective pitch is necessary to restore rotor thrust to meet trim requirements. This inevitably leads to increased blade loading [24]. It is noted that excessive increase in blade loading can negatively affect the aerodynamic performance of rotor blade elements and eventually, increase rotor power requirements.

As regards engine performance, Walsh and Fletcher [58] showed that at a given rotational speed of the gas generator (GG), there is a unique free-power turbine (FPT) speed that minimizes specific fuel flow (SFC) and maximizes power generation, as also shown by Goulos and Bonesso [24]. A variation in FPT speed relative to the unique value leads to reduced thermal efficiency and increased SFC. Hence, it is the trade-off between engine thermodynamic deficit and rotor aerodynamic benefit which determines the overall impact of VRS on fuel consumption and NO_x .

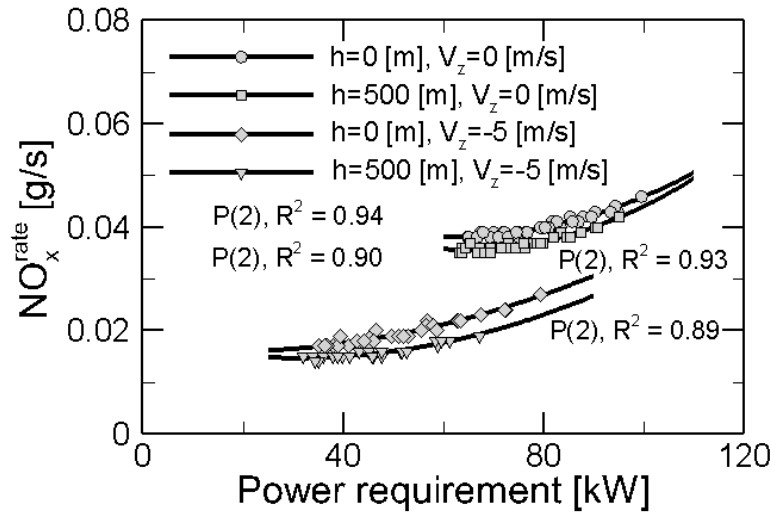


Fig. 3. Correlation between rotor power requirement and NO_x rate for $V_x = 30 \text{ m/s}$ and $AUM = 1600 \text{ kg}$.

Fig. 3 presents the correlation between rotor power requirement and NO_x emissions. A fixed $AUM = 1600 \text{ kg}$ and $V_x = 30 \text{ m/s}$ is used for all four parametric curves. Each curve demonstrates a specific combination of h and V_z , whilst the individual points of each curve represent the different combinations of Ω and θ_{tw} in the DSE procedure. It is shown that families of correlated points are formed using a 2nd order polynomial regression with coefficients of determination ranging between $R^2=0.89$ and $R^2=0.94$ for the four curves. These refer to $AUM = 1600 \text{ kg}$, but similar response was found for the rest AUMs. The associated mean-value-normalized standard deviations are between 4.4% and 9.7% for the four curves and is attributed to the variation of rotor speed and blade twist in the DSE procedure. The accrued correlation suggests that the main driving factor for NO_x generation is rotor aerodynamic performance, therefore NO_x is used as surrogate for rotor power in the interpretation to follow. Variations in θ_{tw} predominantly affect rotor induced power which is dominant in low-speed flight. In low-speed flight, increased θ_{tw} leads to a re-distribution of induced flow, bringing radial loading variation closer to optimal loading conditions.

Fig. 2 (b) presented the behavior of $\Delta EAOASPL$ and $\Delta NO_x^{rate}[\%]$ at $AUM = 2400 \text{ kg}$ and reference flight conditions of Table 1. It is shown that at high AUM , $\Delta NO_x^{rate}[\%]$ reduction margins are more limited compared to the $AUM = 1600 \text{ kg}$ case. In agreement with [11], [24], [59], higher performance benefits can be accrued at low-and-light operating conditions. The minimum allowed Ω is required to minimize noise, primarily due to Doppler amplification effects. Moreover, high θ_{tw} is required to off-load the highly loaded blade tip regions due to the increased AUM .

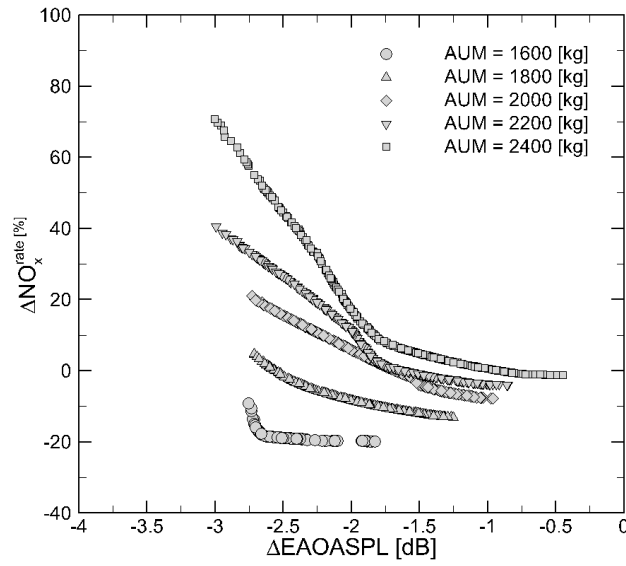


Fig. 4. Trade-off between source noise and NO_x emissions on optimized VRS and ABT helicopter configuration at $h = 250 \text{ m}$, $V_x = 30 \text{ m/s}$, $V_z = -4 \text{ m/s}$.

It has been shown that combined VRS and ABT technologies have the potential to reduce $EAOASPL$ and NO_x emissions. That gives space for multi-disciplinary optimization aiming at simultaneous mitigation of acoustic and environmental impact of helicopters in BVI conditions. The optimization strategy presented in Section 2.5 is deployed for the generation of Pareto optimal fronts in a parametric manner for a series of AUM options, as shown in Fig. 4. The rest of operating parameters retain their reference values as presented in Table 1. It is observed that the highest noise benefits can be achieved at high AUM . On a highly loaded rotor, the circulation peaks are located closer to the blade tips, compared with a lightly loaded rotor [53]. Hence, ABT can more efficiently off-load the tips

by moving the circulation peaks inboards. The highest NO_x benefits are attained at lightly-loaded rotor disc conditions, as also reported in [24]. It is noted that comparisons between RSM-derived results and original model simulations were made for selected states across the design space with minimal deviations between the original model predictions and the RSM-derived optimizer deltas.

3.3. Descent trajectory definition

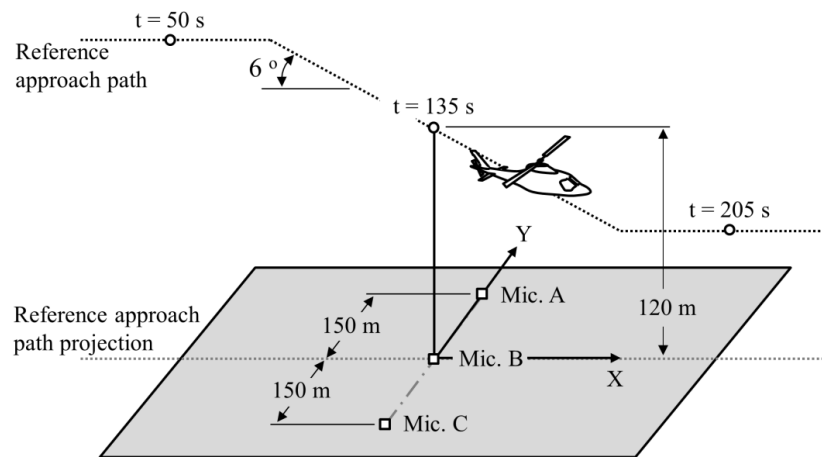


Fig. 5. Descent flight path definition, selected trajectory control points and ground microphone locations, reproduced after [60].

The descending flight path for helicopter noise certification approved by the EASA and specified in Annex 16, Volume I of ICAO [60] is replicated for the assessments of this work. A reference flight path angle of -6° is prescribed and three microphones (A, B and C) are located at specific co-ordinates on the ground level, as depicted in Fig. 5. Microphone measurements are taken at the time-instant when the helicopter flies at altitude $h = 120\text{ m}$ above Microphone B. Sideline microphones A and C are mounted at lateral distance of 150 m from Microphone B in the port and starboard direction, respectively.

According to [61], the helicopter should be descending at a reference climb rate equal to the certified best rate of descent speed. In this study, a horizontal flight speed $V_x = 40\text{ m/s}$ along with a climb rate $V_z = -4.2\text{ m/s}$ is selected for the descending part of the flight path. For continuity of the

trajectory, a level-flight section with $V_x = 40 \text{ m/s}$ is added prior to the beginning of descent and a low-altitude/low-speed level-flight section with $V_x = 20 \text{ m/s}$ is added after the end of the descending flight segment. Three representative trajectory waypoints at time instants $t = 50 \text{ s}$, $t = 135 \text{ s}$ and $t = 205 \text{ s}$ are selected for analysis of aerodynamic and aeroacoustic phenomena in the vicinity of the rotor, corresponding to each one of the three segments of the trajectory. The resulting time-variations in density altitude, flight speed and flight path angle are provided in Fig. 6 (a)-(c), respectively. Steady helicopter motion is considered throughout the trajectory.

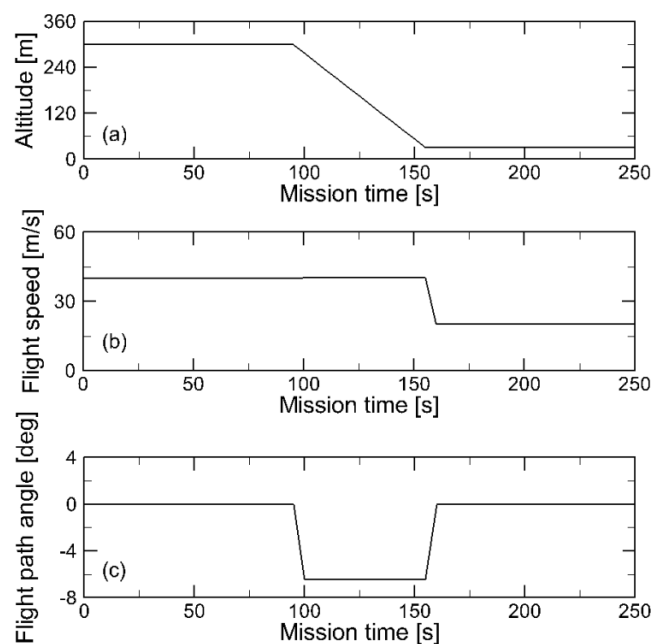


Fig. 6. Trajectory profile as function of time: (a) altitude; (b) flight speed; (c) flight path angle.

The multi-disciplinary optimization process described in Section 2.5 is applied at each waypoint of the derived trajectory to obtain optimized VRS and ABT settings targeting the concurrent reduction of $EAOASPL$ and NO_x^{rate} . Having established a methodology for the generation of Pareto optimal fronts for $\Delta EAOASPL$ and $\Delta NO_x^{rate} [\%]$, one or more specific points from the Pareto fronts can be selected based on design intent.

The minimum distance selection method [62] is utilized to determine the knee point of the Pareto front which will serve as trade-off point for the multi-disciplinary optimization. Specifically, a

Utopia-optimal point is determined as the combination of minimum noise and minimum NO_x points. This is a fictitious optimal point which would achieve idealized minimization of both objectives, concurrently. The Pareto trade-off point is then determined as the point which has the minimum Euclidean distance from the Utopia-optimal point. It is noted that for the calculation of Euclidean distance of each Pareto point from the Utopia-optimal point, the front is previously normalized (%) in both dimensions.

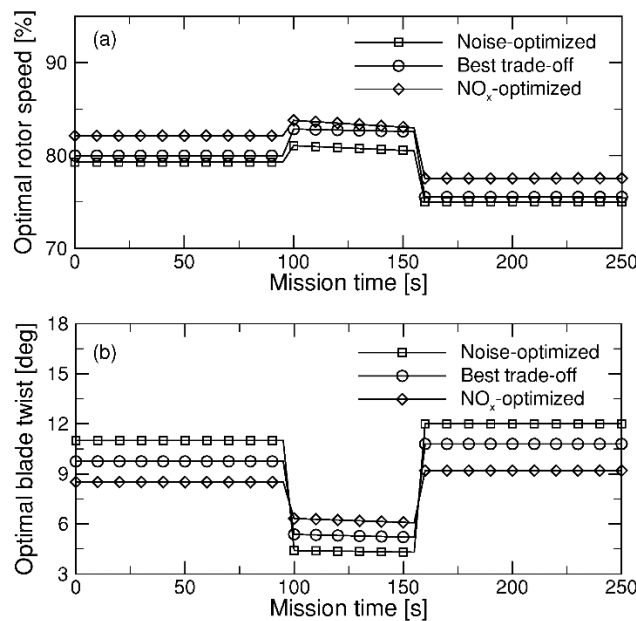


Fig. 7. Noise-optimized, NO_x -optimized and best trade-off rotor control schedules at $AUM = 1600 \text{ kg}$: (a) rotor speed; (b) blade twist.

Fig. 7 (a) presents the distribution of rotor speed, optimized for minimum noise, minimum NO_x and the best trade-off between the two objectives. The optimum Ω during descent is higher compared to the rest segments. The freestream upwash exerted in descent, yields the formation of a stalled region, a driving region and a driven region (moving radially outwards across the rotor disc). Increase in Ω leads to re-adjustment of radial variation of dynamic pressure and a (favourable) reduction of near-tip incidence. The reduction of the extent of stalled and driven regions in this case is beneficial for both NO_x and noise. Overall, the optimum Ω for NO_x minimization is higher compared with the noise minimization case, in accordance with the discussion of Fig. 2.

Fig. 7 (b) discusses the trade-off between noise and NO_x minimization in terms of optimal blade twist allocation along the trajectory. High θ_{tw}^{Opt} is required in level flight, primarily to off-load the blade tips and reduce the impact of tip-vortex circulation on airloads, which affect both power requirement and noise. It is also observed that noise optimization requires higher θ_{tw} compared to the NO_x optimization case in level flight. In descent, the considerable increase in upwash is compromised through reduced θ_{tw}^{Opt} , towards obtaining the best trade-off between $EAOSPL$ and NO_x^{rate} . The effect of altitude variation in descent is reflected on the gradual reduction of θ_{tw}^{Opt} as h decreases. This is primarily due to the reduced blade loading at low h which affects both $EAOSPL$ and NO_x^{rate} .

The Ω and θ_{tw} settings which achieve the best trade-off between $EAOSPL$ and NO_x^{rate} reduction effectively lie between the two aforementioned distributions. In this work, the best trade-off settings will be used to provide an analysis which resolves both the environmental and acoustic impact of optimized VRS and ABT helicopter concepts.

Fig. 8 (a) illustrates the optimized rotor speed settings along the trajectory for different AUM options corresponding to the best trade-off case. Generally higher Ω^{Opt} is required at higher AUM to compensate for the increased rotor blade loading through increasing rotor dynamic pressure. Fig. 8 (b) presents the corresponding θ_{tw}^{Opt} settings across the trajectory to achieve the best trade-off between $\Delta EAOSPL$ and $\Delta \text{NO}_x^{rate} [\%]$. At higher AUM , θ_{tw} lower than the nominal is required in level-flight, to satisfy the generally lower θ_{tw} requirements in terms of NO_x^{rate} reduction. In low-speed level flight, considerably high θ_{tw}^{Opt} is required to mitigate the impact of strong tip-vortex roll-up on vortex-induced velocity, airloads and eventually, noise.

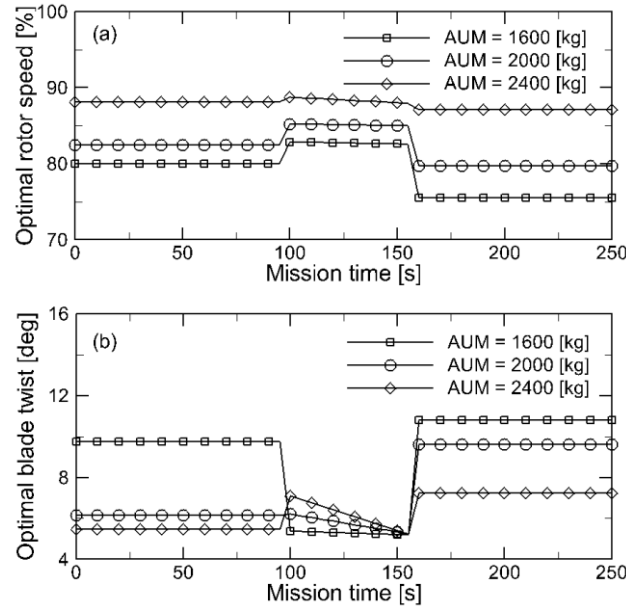


Fig. 8. Optimized rotor control schedules as function of time for different AUM options: (a) rotor speed; (b) blade twist.

3.4. Aerodynamic analysis

A thorough analysis of the aerodynamic effects in the vicinity of the main rotor along the derived trajectory can shed light on the complex inter-coupled phenomena associated with VRS and ABT optimization. The $AUM = 1600 \text{ kg}$ case will be analyzed, where higher combined environmental and acoustic benefits are anticipated, to showcase the best potential of the investigated rotor morphing technology. Fig. 9 (a) and (b) illustrate the tip-vortex geometries for nominal and optimized Ω and θ_{tw} , respectively, at the selected time-instant $t = 50 \text{ s}$. As discussed by Leishman [63], the advancing-side BVIs can be nearly parallel at specific flight conditions, which is a potential source of intensive noise. It can be seen that due to reduced Ω , the spacing between wake tip vortices is increased in the optimized case compared to the nominal. Therefore, fewer tip-vortex filaments are rolled up in the vicinity of the rotor disc, which in combination with inboard loading shift due to increased blade twist, yield temporarily reduced rolled-up vortex strength on the advancing side. However, the remaining filaments roll-up downstream which appears to make the roll-up stronger, but the circulation shed per unit time is less for the reduced rotor speed case.

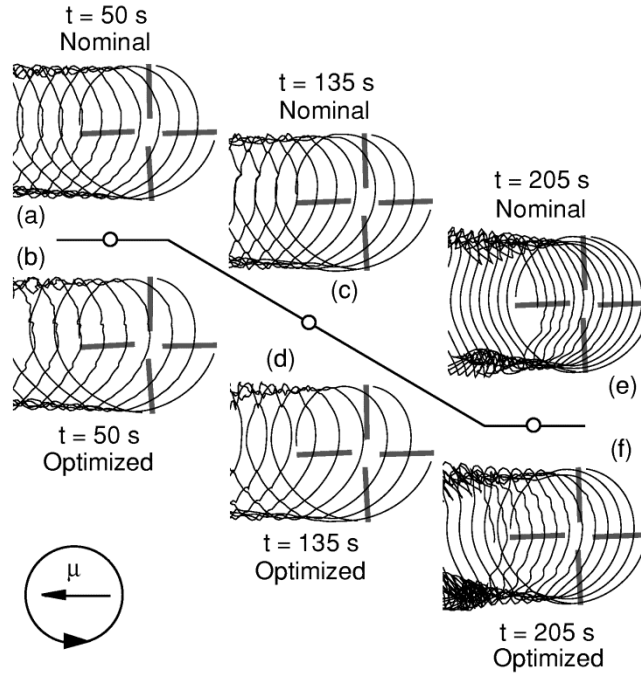


Fig. 9. Evolution of main rotor wake along the descent trajectory for $AUM = 1600 \text{ kg}$: (a) nominal control at $t = 50 \text{ s}$; (b) optimized control at $t = 50 \text{ s}$; (c) nominal control at $t = 135 \text{ s}$; (d) optimized control at $t = 135 \text{ s}$; (e) nominal control at $t = 205 \text{ s}$; (f) optimized control at $t = 205 \text{ s}$.

Similar response is observed in Fig. 9 (c) and (d), where the descending flight conditions at $t = 135 \text{ s}$ promote BVI phenomena. It is noted that the temporal shift resulting from reduced Ω leads to reduced frequencies of the BVI events. Low frequency noise is generally less annoying for the human hearing; however it is less easily attenuated with distance.

Fig. 9 (e) and (f) present the corresponding tip-vortex topologies at low-speed level-flight at $t = 205 \text{ s}$ with nominal and optimized Ω and θ_{tw} , respectively. Tip-vortex roll-up is considerably more pronounced compared to the previous flight states due to low advance ratio. It can be seen that increased θ_{tw} leads to reduced-strength roll up at the retreating side, primarily due to tip off-loading arising from the radial inboard shift of bound circulation. At the advancing side, reduced strength of the roll-up in the close vicinity of the rotor is observed, although increased concentration of vortex structures is observed in the downstream direction.

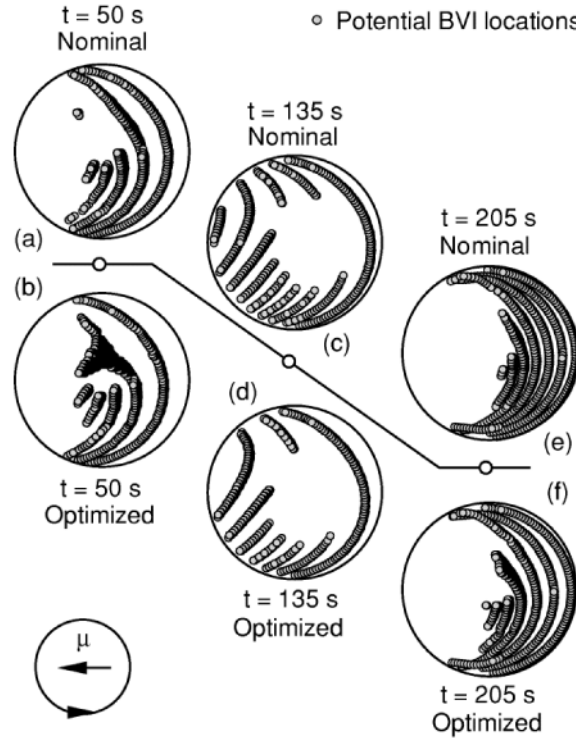


Fig. 10. Potential BVI locations along the descent trajectory for $AUM = 1600 \text{ kg}$: (a) nominal control at $t = 50 \text{ s}$; (b) optimized control at $t = 50 \text{ s}$; (c) nominal control at $t = 135 \text{ s}$; (d) optimized control at $t = 135 \text{ s}$; (e) nominal control at $t = 205 \text{ s}$; (f) optimized control at $t = 205 \text{ s}$.

The locations of tip-vortices relative to the elastic rotor blades affect the possibility of BVI events across the rotor tip-path-plane. Fig. 10 depicts the locus of potential BVI events, calculated using the spherical detection method [64]. The illustrated trajectory waypoints correspond to the selected time-instances analyzed above. It can be seen that the combined VRS and ABT optimization leads to reduced number of potential BVI locations at all investigated flight states. It needs to be noted that due to the multi-disciplinary nature of the optimization, Ω^{Opt} and θ_{tw}^{Opt} are not determined solely by noise minimization, but by the best trade-off between noise and NO_x minimization. Therefore, the combination of simultaneous acoustic and environmental benefits comes at a cost in the maximum improvements that could potentially be obtained through isolated treatment of each objective.

In Fig. 10 (b) it is shown that the mitigation of potential BVI locations in the blade tip region comes at a cost of increased-concentration potential BVI events close to the rotor hub at the retreating

side. This is attributed to the impact of high θ_{tw}^{Opt} which results in an excessive increase in induced velocity and inboard incidence angle at this *AUM* option. However, it needs to be noted that the inboard regions of the rotor disc feature lower magnitudes of radiation Mach number which reduces the impact of Doppler amplification on noise generation.

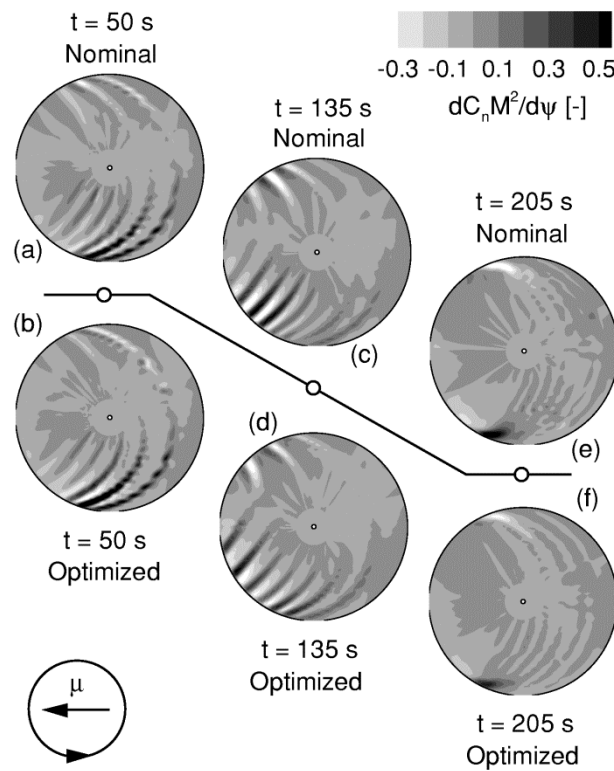


Fig. 11. Azimuthal derivative of normal force coefficient along the descent trajectory for $AUM = 1600 \text{ kg}$: (a) nominal control at $t = 50 \text{ s}$; (b) optimized control at $t = 50 \text{ s}$; (c) nominal control at $t = 135 \text{ s}$; (d) optimized control at $t = 135 \text{ s}$; (e) nominal control at $t = 205 \text{ s}$; (f) optimized control at $t = 205 \text{ s}$.

Even though the number of interactions may decrease, it is their intensity that determines the magnitude and directivity of the associated BVI noise [63]. The intensity of BVI aerodynamic events is quantified via the azimuthal derivative of normal force coefficient $dC_n M^2 / d\psi$ across the rotor disc. This metric represents the intensity of unsteady blade airloads; hence serves as a surrogate for BVI noise. Fig. 11 presents the impact of VRS and ABT optimization on $dC_n M^2 / d\psi$. In Fig. 11 (b) it can

be seen that the high value of θ_{tw}^{Opt} does not allow any significant reductions in $dC_n M^2 / d\psi$. At low weight, the rotor has a low collective pitch angle. The blades operate at relatively low incidence hence at low loading and profile drag. There is benefit to increase twist and recover some induced losses as the inboard incidence will not increase prohibitively. This margin for twist increase progressively reduces as the weight increases. However, it is evident that the frequency of BVI events is reduced after the optimization, and considerable noise mitigation is expected from reduced Doppler amplification, as well. Similar benefits are observed in Fig. 11 (d): the most significant reductions of the magnitude of $C_n M^2$ azimuthal derivative can be achieved at the advancing side, although complete alleviation of loading peaks seems not attainable.

Fig 11 (e) shows the impact of strong vortex roll-up on the formation of high-loading cells in the tip region at both port and starboard directions. These are attributed to the concentration of high-circulation vortical structures in the close vicinity of the blade tips near the aforementioned locations. Fig. 11 (f) depicts the effectiveness of increased θ_{tw}^{Opt} in off-loading the blade tips and reducing the impact of vortex roll-up on unsteady airloads and consequently, noise.

3.5. Aeroacoustic analysis

The distribution of unsteady airloads across the rotor disc is effectively reflected on the corresponding noise hemispheres at the investigated trajectory waypoints. The employed radius for the generation of noise hemispheres is 150m. Fig 12 (b) illustrates the impact of reduced Ω on thickness noise, which has its maximum directivity in the upstream direction in the plane of the rotor. Additionally, it is shown that even without significant reduction in the magnitude of unsteady airloads, considerable loading noise mitigation can be achieved through the reduction of the impact of Doppler amplification on acoustic source terms.

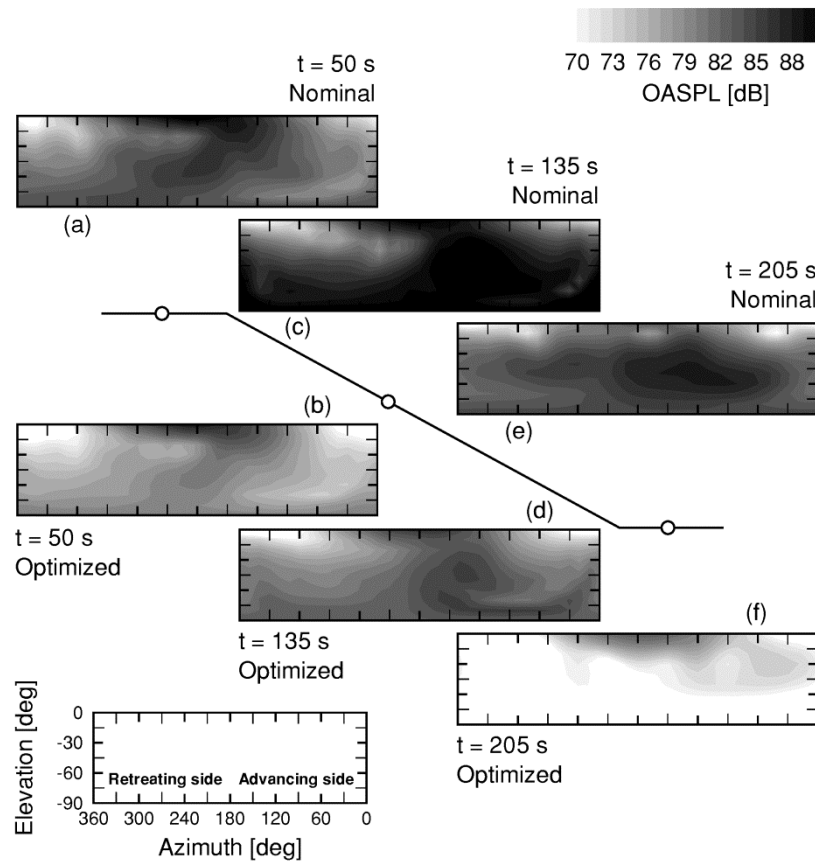


Fig. 12. Main rotor source noise hemispheres along the descent trajectory for $AUM = 1600 \text{ kg}$: (a) nominal control at $t = 50 \text{ s}$; (b) optimized control at $t = 50 \text{ s}$; (c) nominal control at $t = 135 \text{ s}$; (d) optimized control at $t = 135 \text{ s}$; (e) nominal control at $t = 205 \text{ s}$; (f) optimized control at $t = 205 \text{ s}$.

Similarly, in strong BVI conditions as in Fig. 12 (c) and (d), the combination of reduced magnitude of radiation Mach number with reduced frequency of intense loading peaks, can lead to considerable reductions of source noise, even at the BVI-dominated regions of the noise hemisphere at $\psi = 90 \text{ deg.}$ and $\beta = -45 \text{ deg.}$ Finally, the intensive loading noise generated by the high-loading cells at the sides of the rotor in low-speed cruise is efficiently ameliorated by the combined VRS and ABT optimization, as shown in Fig. 12 (e) and (f).

Fig. 13 presents a detailed analysis on the impact of combined VRS and ABT optimization on mitigating low-harmonic and mid-frequency BVI noise. The analysis refers to the time instant $t = 135 \text{ s}$ when the helicopter is located directly above Microphone B at altitude $h = 120 \text{ m}$. It is

noted that due to the fact that the nominal and optimized rotors run at different rotor-speeds, the Blade Passage Frequency (BPF) is different between the two pulses. This requires to establish a consistent and unbiased basis of interpretation, aligned with how an external observer would perceive the impinging acoustic signal. This process is in line with the interpretation of the acoustic signal from the observer's time-dependent perspective. As a result, BVI related peaks appear at different relative normalized time values.

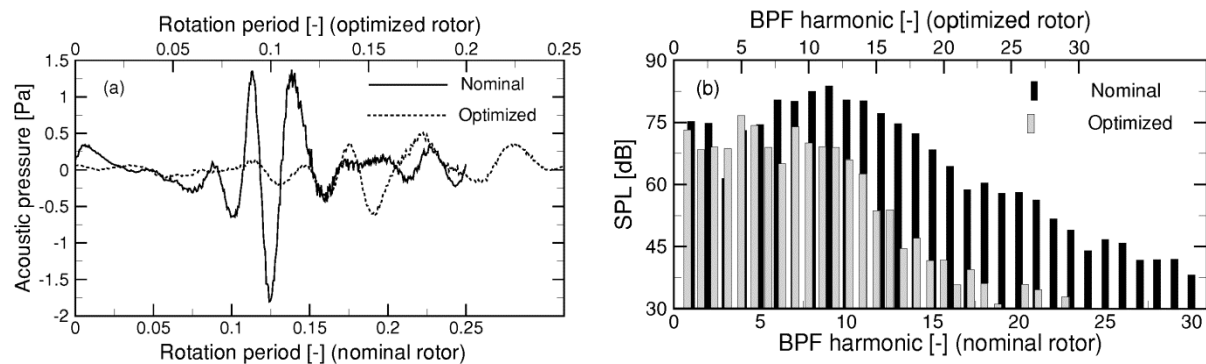


Fig. 13. Impact of optimized VRS and ABT control on ground noise spectrum at microphone C around $t = 135$ s : (a) acoustic pressure pulse; (b) spectral analysis.

Fig. 13 (a) illustrates the acoustic pressure signal at Microphone C, dominated by advancing-side BVI noise, for nominal and optimized rotor VRS and ABT control settings. Since the acoustic signal is periodic with four identical pulses, it is decided to isolate the signal of one pulse only for better clarity. Time axes are both normalized with the duration of a full rotor rotation of each case. The bottom horizontal axis corresponds to the nominal acoustic signal and the top to the optimized one. Axes scaling corresponds to the relative duration of nominal and optimized pulses. It can be seen that the optimized VRS and ABT control efficiently mitigates the amplitude of BVI-related peaks in the acoustic signal. The corresponding spectral analysis of both signals is represented in a similar manner in Fig. 13 (b). A clear reduction in the order of 8 dB is calculated for the 6th-30th BPF harmonics, whilst the associated low-frequency noise penalty, expressed as LFSPL for the first 5 BPF harmonics, is limited in the order of 1 dB within the first five BPF harmonics.

3.6. Environmental and ground noise impact

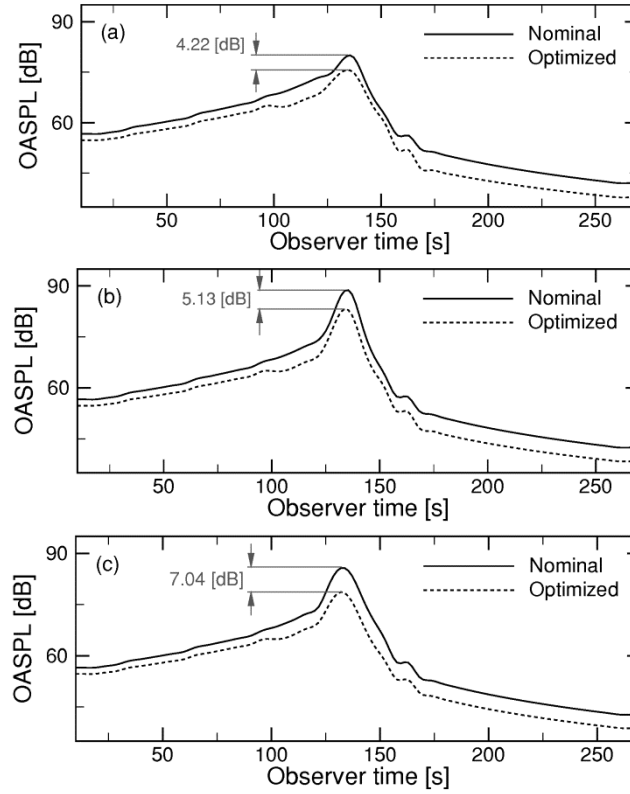


Fig. 14. Comparison of nominal and optimized rotor control in terms of ground noise at three selected microphones: (a) microphone A; (b) microphone B; (c) microphone C.

Fig. 14 (a)-(c) present the full time-history of noise signals at Microphones A-C, respectively. Specifically for Microphone C, it can be seen that the overall noise is 7.04 dB lower when VRS and ABT optimization is employed compared to the nominal Ω and θ_{tw} settings. Similar improvements are observed in Microphones A and B, albeit with slightly smaller magnitude, which can be attributed to the behavior of $dC_n M^2 / d\psi$, presented in Fig. 11 (d).

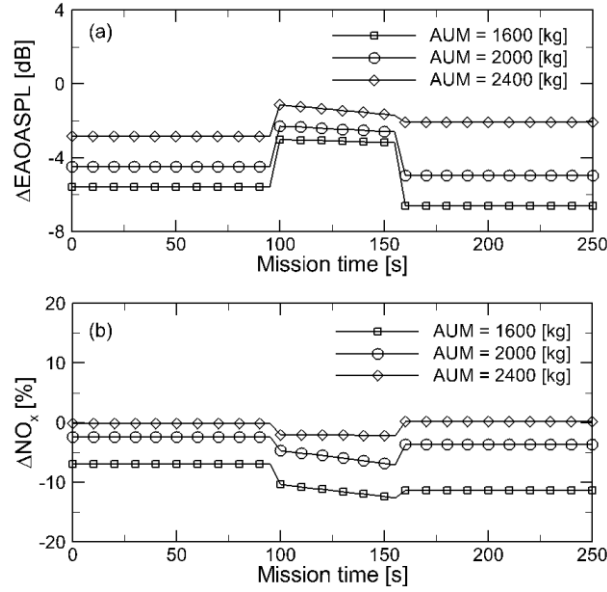


Fig. 15. Acoustic and environmental benefits for three different AUM arising from optimized VRS and ABT rotor control: (a) Source noise benefits; (b) NO_x benefits.

Fig. 15 (a) and (b) illustrate the accrued benefits in terms of $\Delta EAOASPL$ and ΔNO_x^{rate} [%] which are the objectives of the multi-disciplinary optimization carried out in this work. Generally lower concurrent $EAOASPL$ and NO_x^{rate} benefits arise from the optimization at high AUM . As shown in Fig. 4, higher noise benefits can be accrued at high AUM at a cost of excessively increased NO_x emissions. As regards NO_x^{rate} , it has been shown that the combined VRS and ABT concept is less efficient in high disc loading conditions as discussed in [24]. Due to the multi-disciplinary nature of the undertaken optimization, the determination of best trade-off point at high AUM conditions is unavoidably favoring NO_x^{rate} reductions to achieve a sufficient compromise with $\Delta EAOASPL$. Hence, in the realistic part of the design space where both NO_x and noise need to be reduced, the overall benefits are more substantial for the low AUM case.

At $AUM = 1600$ kg, source noise improvements of 6.60 dB are attained during the third segment of the trajectory where ABT effectively mitigates the impact of strong vortex roll-up at the sides of the rotor by off-loading the blade tip-region. Concurrently, VRS results in a reduced number of vortex filaments being entangled in the roll-up initially for the optimized case. The lowest

$\Delta EAOASPL$ is achieved in the descent segment, due to the strong impact of BVI phenomena which cannot be entirely diminished by VRS and ABT. NO_x^{rate} improvements of up to 11.4% are observed during descent and low speed cruise at $AUM = 1600 \text{ kg}$, which represent the flight states with the minimum disc loading along the derived trajectory. The slight slope observed in the distribution of $\Delta EAOASPL$ and $\Delta NO_x^{rate}[\%]$ during descent reflects the impact of altitude variation on both parameters.

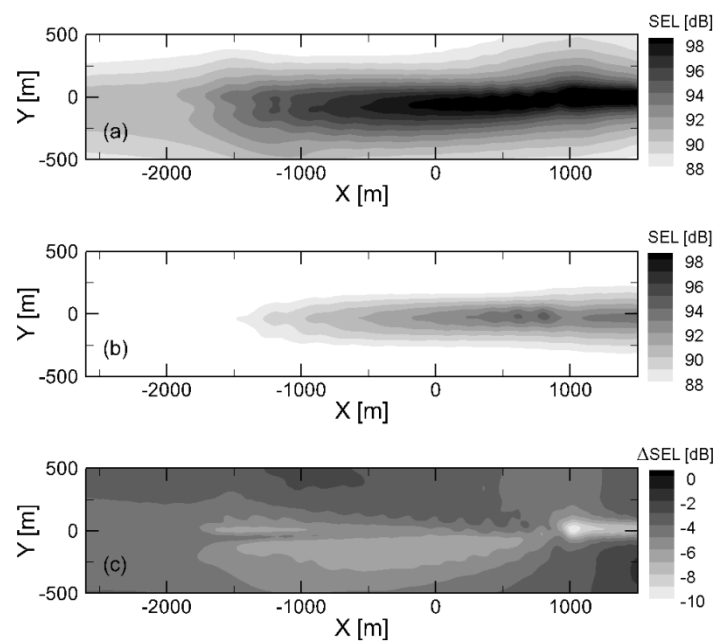


Fig. 16. Sound exposure levels of the descent trajectory for $AUM = 1600 \text{ kg}$: (a) nominal; (b) optimized; (c) difference (b)-(a).

The overall impact of optimized VRS and ABT rotor control on ground noise footprint is quantified using the Sound Exposure Level (SEL) metric introduced in [40]. Fig. 16 (a) and (b) illustrate the resulting SEL of the nominal and the optimized VRS and ABT control schedule derived from the multi-disciplinary optimization. SEL is generally higher towards the end of the trajectory due to the accumulated time exposure of this region in noise emitted by the rotor during the entire trajectory duration. It is evident that SEL is considerably reduced in the optimized case. Fig. 16 (c) quantifies the

spatial distribution of noise deltas across the investigated ground region. SEL deltas of up to -10.74 dB are calculated at $AUM = 1600 \text{ kg}$.

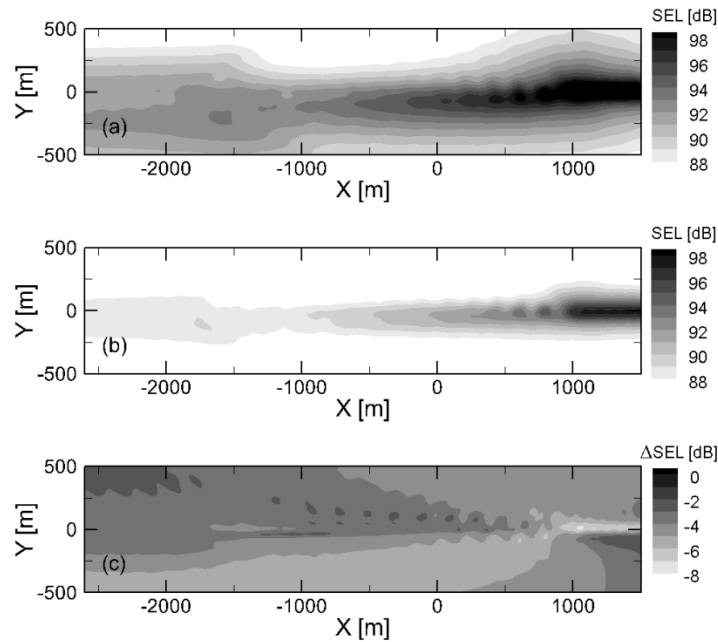


Fig. 17. Sound exposure levels of the descent trajectory for $AUM = 2000 \text{ kg}$: (a) nominal; (b) optimized; (c) difference (b)-(a).

Fig. 17 (a)-(c) depict the corresponding SEL and accrued noise benefits for $AUM = 2000 \text{ kg}$. Similar trends are observed, although with noise reductions reaching up to 8.06 dB. Finally, as shown in Fig. 18 (c), noise benefits range between 1.14 to 6.70 dB for $AUM = 2400 \text{ kg}$. This is attributed to the reduced effectiveness of ABT towards mitigating the adverse aerodynamic effects of strong vortex roll-up encompassed by the highly loaded rotor disc during the third section of the derived trajectory. It is suggested that future works consider different helicopter configurations and different rotor designs, to explore the impact of technology levels and rotor geometry on the potential benefits of combined VRS/ABT concepts.

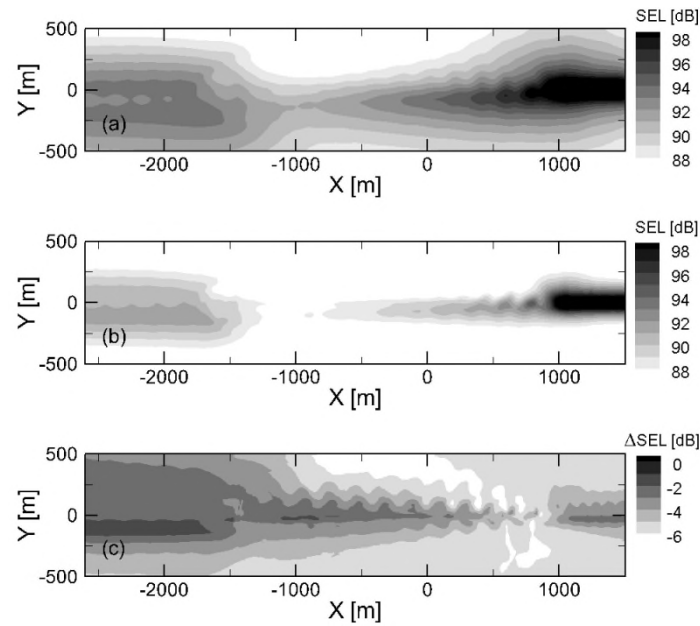


Fig. 18. Sound exposure levels of the descent trajectory for $AUM = 2400 \text{ kg}$: (a) nominal; (b) optimized; (c) difference (b)-(a).

3.7. Uncertainty in aeroacoustic simulation

This study investigates aeroacoustic effects of VRS and ABT rotors across a BVI-dominated descent trajectory. Prediction of BVI noise is a major challenge for the aeroacoustics community, primarily due to the lack of extensive experimental data for the growth of the viscous core of tip vortices. These data are essential for the calibration of free-wake aerodynamic models, therefore the uncertainty related to noise prediction is an inherent function of the uncertainty in aerodynamic inputs. BVIs are prominent when the miss-distance between trailed tip vortices and rotor blades is small. The free-wake aerodynamic model described in Section 2.2 is consistently utilized throughout the trajectory, therefore resolving the potential aerodynamic interactions both during level-flight and descending conditions. As shown in Section 3.4, these interactions are stronger during descent and weaker in level flight. Consequently, the impact of uncertainty related to tip-vortex core growth is expected to be higher during descent, where BVIs dominate the aeromechanical environment of the main rotor.

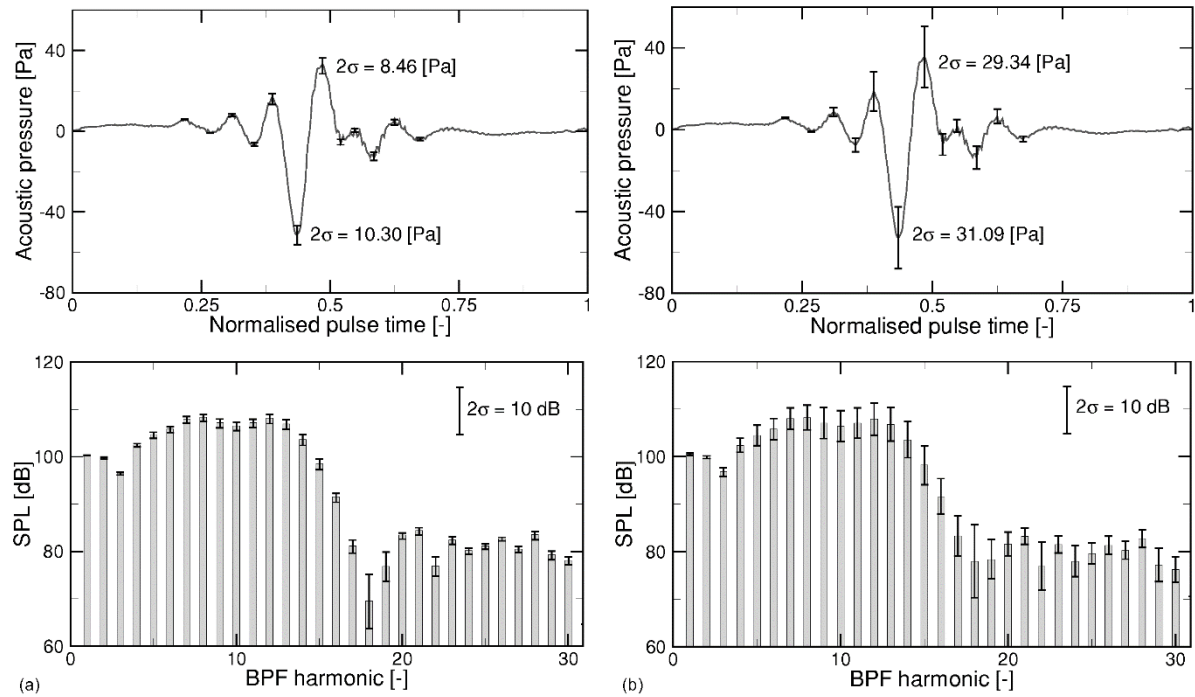


Fig. 19. Uncertainty quantification in the prediction of acoustic pressure and corresponding spectral content: (a) experimental data for tip-vortex core growth model are available; (b) experimental data for tip-vortex core growth model are not available.

The impact of tip-vortex core growth modelling uncertainty on the prediction of BVI noise has been investigated by the authors [65], [66] through a method for non-intrusive Polynomial Chaos expansion [67]. Figure 19 (a) presents the quantification of uncertainty in acoustic pressure and corresponding spectral content for the case of available experimental data for tip-vortex core growth modelling. This case refers to the baseline HART-II rotor experiment, for which detailed tip-vortex core growth data were available at the nominal rotational speed and blade twist angle. The aeroacoustic predictions refer to the advancing-side observer which perceives the highest levels of BVI noise in this experiment [42]. The associated error bars represent the $\pm\sigma$ margins based on the calculated uncertainty. When experimental data for the calibration of tip-vortex core growth parameters are available, the uncertainty in acoustic pressure prediction is $\sigma = 4.23Pa$ and $\sigma = 5.15Pa$ for the positive and negative peak of the BVI pulse, respectively. The associated sound pressure levels (SPL) present individual frequency σ of less than 1 dB in the range between the 1st and the 15th harmonic of

BPF, which governs the OASPL levels. The corresponding OASPL levels, calculated as a frequency-domain integration of the SPL signal, present uncertainty of $\sigma = 1.17\text{dB}$ [66]. Further to the uncertainty related to tip-vortex modelling, an experimental scatter of 2dB was reported in the measured ground noise levels of the baseline HART-II experiment [42]. The aforementioned uncertainty levels should only be considered for the quantifications which refer to the nominal rotor speed and blade twist in this work.

The optimized VRS and ABT schedules derived in the present work, suggest rotor speeds of down to 75% of the nominal and blade twist variations in the range of ± 3 deg. No explicit correlation between tip vortex core properties and combined rotor speed and blade twist variation was found in the open literature. Therefore, the uncertainty levels for absent experimental input data will be considered for the cases with VRS and ABT settings far from the nominal. Figure 19 (b) depicts these uncertainty levels which represent the case of absence of tip-vortex core growth data for model calibration. Wider levels of input uncertainty are considered, which yield noise uncertainties of $\sigma = 15.55\text{Pa}$ in acoustic pressure and individual frequency σ of more than 3 dB in SPL, respectively. This is reflected as a $\sigma = 3.71\text{dB}$ in the OASPL noise for this observer [66]. It needs to be noted that smaller uncertainty should be anticipated for states with VRS and ABT settings closer to the nominal values. Furthermore, the impact of tip-vortex modelling uncertainty should be less pronounced in level-flight conditions, as BVI dominates in descent conditions.

Overall, the SEL benefits reported in Section 3.6, in conjunction with the discussion on uncertainty, demonstrate that the low AUM case offers significant noise benefits, of up to 10.74dB, even at the regions governed by the highest uncertainty levels. On the other hand, the calculated noise reductions at high AUM conditions, up to 6.7 dB, suggest that uncertainty is an important factor to be considered in future implementations.

3.8. ABT system weight penalties

The analysis undertaken in the previous sections was focused on quantifying the maximum theoretical benefits of combined VRS and ABT with respect to noise and NO_x emissions without

including weight penalties imposed by the implementations of ABT. It is noted that VRS is achieved through the engine full authority control system by transient adjustment of fuel flow, instead of a variable ratio transmission. Therefore, no significant weight penalties shall be considered for VRS alone. With respect to twist actuation system weight, it is the actuation mechanism itself which yields more than 70% of the resulting weight penalties, whilst the rest is attributed to power supply and transmission, and control electronics [68]. The weight of a single actuator is proportional to the actuation force and stroke length. An actuator weighting 13.8 kg was developed for an IBC system retro-fitted on the full-scale rotor swashplate of the 10-ton class Sikorsky UH-60 helicopter [69]. The actuator was designed for ± 6 deg. blade pitch motion at the 2/rev frequency, diminishing to ± 6 deg at the 7/rev frequency. The weight of the complete actuation system depends on its unique mechanical design, materials used, and actuation technique implemented. The overall weight of a swashplateless IBC actuation system for a 19-ton class Sikorsky CH-53G helicopter was calculated at 790 kg [70].

Table 3: Impact of overall ABT system weight on accrued source noise and NO_x benefits for the three selected waypoints of the descent trajectory.

ABT system weight [kg]	t=50s		t=135s		t=205s	
	$\Delta\text{EAOASPL}[\text{dB}]$	$\Delta\text{NO}_x^{\text{rate}}[\%]$	$\Delta\text{EAOASPL}[\text{dB}]$	$\Delta\text{NO}_x^{\text{rate}}[\%]$	$\Delta\text{EAOASPL}[\text{dB}]$	$\Delta\text{NO}_x^{\text{rate}}[\%]$
0	-5.59	-6.89	-3.11	-11.23	-6.58	-11.39
30	-5.52	-6.41	-2.97	-10.63	-6.47	-10.35
60	-5.44	-5.93	-2.85	-10.06	-6.32	-9.45
90	-5.34	-5.52	-2.72	-9.56	-6.17	-8.64
120	-5.22	-5.15	-2.60	-9.09	-6.00	-7.93
150	-5.14	-4.74	-2.49	-8.65	-5.88	-7.24

The estimation of actuation system weight requires dedicated design of the complete mechanism which goes beyond the scope of this work. For the purposes of this study, the impact of ABT weight penalties on noise and NO_x benefits is quantified through the parametric analysis of Table

3. ABT system weight values ranging between 0 and 150 kg are examined for the 2.5-ton class Bo 105 helicopter, in analogy to the values reported for the heavier helicopters of the previous paragraph. The analysis was undertaken for the selected waypoints of the investigated descent trajectory. It is noted that a dedicated multi-disciplinary optimization was carried out at each operating point for all the ABT weight variants under examination. It is observed that a linear correlation between weight penalties and $\Delta EAOASPL$ and $\Delta NO_x^{rate}[\%]$ occurs. This allows for the derivation of practical exchange rates, useful for the design and evaluation of different ABT systems. Specifically, the exchange rate, or penalty, for $\Delta EAOASPL$ is between 0.003 and 0.004 dB per kg of added ABT weight, whilst the same penalty for $\Delta NO_x^{rate}[\%]$ ranges between 0.02 and 0.03 % per kg of added ABT weight. Considering the ± 3 deg. range of static twist variation, it is expected that a total weight penalty of less than 100 kg will occur for the helicopter under investigation, which would limit source noise benefits roughly by up to 0.5 dB and NO_x benefits by up to 1.5%, relative to the zero-ABT-weight quantifications.

The accrued potential benefits, as well as the abovementioned, first-order estimations of weight penalties, suggest that future works, focused on the structural aspects of the concept, should consider a state-of-the-art actuation weight estimation method to pave the way for further advancements.

4. Conclusions

This work investigated the potential concurrent improvements on helicopter environmental and acoustic impact, stemming from the multi-disciplinary optimization of a novel combined variable rotor speed and active blade twist rotor morphing technology. An integrated framework was deployed comprising models for helicopter flight dynamics, blade aeroelasticity and unsteady aerodynamics, rotor aeroacoustics, engine performance and gaseous emissions. A multi-disciplinary optimization approach was presented, based on surrogate modeling and genetic-algorithm global optimization. The overall methodology was utilized to derive optimized variable rotor speed and active blade twist schedules for simultaneous mitigation of rotor source noise and NO_x emissions for a representative twin-engine light helicopter along a benchmark descent trajectory.

The impact of VRS and ABT optimization on main rotor wake geometry was explored. Reduced rotor speed effectively leads to a temporal shift of wake vortex filaments, reducing the possibility of BVIs in moderate speed cruising or descending flight. Increased blade twist off-loads the blade tips by re-distributing the peak circulation towards the blade inboard region, consequently mitigating the adverse effects of strong tip-vortex roll-up in low-speed cruise. It has been shown that the first-order effects of the investigated concept are associated with the mitigation of the impact of Doppler amplification on source noise terms, whilst second-order effects are associated with reductions in the magnitude of unsteady airloads. Overall, the acoustic source terms are considerably affected: both low-frequency thickness noise in moderate-speed cruise and low-frequency loading noise in low-speed cruise are effectively reduced.

Specifically, it has been shown that source noise reductions of up to 6.6 dB can be achieved with concurrent NO_x benefits of up to 11%, without accounting for ABT system weight penalties. The deficit in source noise benefits due to ABT weight has been approximated to 0.003-0.004 dB per added kg, whilst NO_x benefits are lowered by 0.02-0.03% per added kg. Additionally, the time-domain analysis of the acoustic signal of a BVI-dominated ground microphone showed that BVI noise reductions of up to 8 dB can be achieved, with only 1 dB low-harmonic noise penalty. Overall, SEL ground noise reductions of more than 10 dB, 8 dB and 6 dB can be achieved for lightly, medium and highly loaded helicopters, respectively. The aforementioned benefits have been achieved through combined variation of rotor speed within 75% to 83% of the nominal and blade twist within 5.5 deg. and 11 deg. The uncertainty related to the above quantifications can reach up to 3.71 dB, which depicts that the potential of the proposed concept is higher at low all-up-mass conditions.

The accrued results shed light into the unexplored trade-off between NO_x and noise emissions for combined VRS and ABT configurations, therefore demonstrating a direction towards greener and more quiet future helicopters. Concluding, the developed computational strategy constitutes an enabling methodology for the holistic and multi-disciplinary assessment of conceptual rotorcraft technologies.

Conflict of interest statement

None declared.

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