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METHODOLOGIES FOR HELICOPTER NOISE FOOTPRINT PREDICTION IN MANEUVERING FLIGHTS

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This paper investigates different techniques for the evaluation of the acoustic disturbance emitted by helicopters in unsteady maneuvers. Nowadays, the simulation of noise emitted by helicopters is of great interest to designers, both for assessing the acoustic impact of helicopter flight on communities and for identifying optimal-noise trajectories. Typically, these simulations consists in the atmospheric propagation of a near-field noise model, extracted from an appropriate database determined through steady-state flight simulations/measurements. In this work, two steady-flight/unsteady-flight noise equivalence criteria are examined, in order to assess their suitability by comparison with noise predictions directly evaluated through a fully-unsteady aeroacoustic solver. They differ in the flight parameters used to select the near-field noise model within the database to be associated to a given unsteady-flight condition.

1. Introduction

Nowadays, the prediction of noise generated aerodynamically by helicopters represents a crucial issue for modern rotorcraft researchers and designers. Indeed, the capability to accurately evaluate the radiated sound in terms of magnitude and directivity pattern has a fundamental role in estimating acoustic impact and detectability of the noise source, as well as in reducing noise disturbances emitted during helicopter operations.

In this context, computational solvers devoted to the analysis and reduction of helicopters acoustic impact on communities usually combine flight mechanics trajectory simulations followed by the selection of associated near-field noise models (*i.e.* noise radiated in proximity of the rotorcraft where atmospheric and reflection effects may be neglected), and by a noise propagation model accounting for orography and population density distribution of the interested area (see, for instance, [1, 2]).

Considering arbitrary unsteady flight conditions (including turns, changing descent angles, accelerations and decelerations), the noise source model must be updated in accordance with the instantaneous flight condition experienced by the helicopter during the maneuver. In order to avoid numerically expensive predictions, this is usually accomplished by selecting the near-field model

(provided in terms of a hemispheric acoustic map rigidly connected to the helicopter) from an appropriate database related to rectilinear, steady-state flights, defined in a domain of parameters suitably characterizing the noise source state (quasi-steady acoustic approach) [1, 2, 3]. It is worth observing that, these acoustic data could be useful also for developing helicopter in-flight noise monitoring systems, such as the Pilot Acoustic Indicator (PAI), object of the European project MANOEUVRES activities [4], aimed at making the pilot able to react adequately in case of excessive produced acoustic disturbance. Indeed, the PAI relies on a noise estimation real-time algorithm, which evaluates the acoustic impact by interpolating a database of noise hemispheres, as a function of helicopter flight parameters.

Throughout helicopter maneuvers, noise emitted may be strongly affected by unsteady effects that produce inertial and aerodynamic loads variations, as well as by pitch, roll and yaw motions causing shifts in noise directivity [5]. Therefore, the selection of steady-state flight acoustic sources suitable for approximating maneuvering helicopter noise is not a trivial issue. In the work presented here, two different criteria to select steady-flight noise models equivalent to noise radiated throughout unsteady flights are proposed and investigated. The aim is the assessment of the accuracy of such approaches in estimating the acoustic disturbance generated by maneuvering helicopters through correlation with predictions provided by a fully unsteady solver. The attention is focussed on main rotor noise emissions.

The evaluation of unsteady flight noise requires the extension of the commonly-used steady flight solvers to non-periodic blade motion and loading, larger time scales of analysis, as well as the generalization of the numerical scheme applied to evaluate signal propagation [5, 6]. Here, the near-field aeroacoustic simulation is carried out by application of the retarded-time formulation 1A developed by Farassat [7], as solution of the Ffowcs Williams and Hawkings equation [8]. Then, noise is propagated through atmosphere using a ray tracing model, which takes into account ground reflection and atmospheric effects (such as temperature gradient, relative humidity, wind speed and direction) [2].

Observing that blade-vortex interaction (BVI) phenomena often represent an important source of noise in maneuvering flights (especially in ground approaches), rotor blade pressure distribution is computed by a free-wake, aerodynamic/aeroelastic main rotor solver capable of capturing, with appropriate accuracy, wake vorticity and wake-blade miss distance. In particular, main rotor loads and aeroelastic response are evaluated through a modal formulation applied to a nonlinear beam-like rotor blade model [9, 10], coupled with a three-dimensional, boundary element method (BEM) for the solution of free-wake, potential flows [11]. Steady aeroelastic solutions are obtained by using a harmonic-balance approach [12, 13], whereas fully unsteady solutions are evaluated through a time-marching procedure based on a Newmark- β integration scheme [14].

2. Noise prediction in maneuvering flight

Noise emitted by helicopters during unsteady maneuvers is strongly affected by variations of speed, flight-path slope angle and radius of turns. Typically, computational tools aimed at this kind of analyses consider noise hemispheres derived from databases of steady, straight-flight acoustic simulations as equivalent acoustic sources. Such approach is based on the assumption of simulating the near-field acoustic disturbance through a sequence of steady-flight predictions corresponding to the evolving operating conditions.

In this work, the noise equivalence between steady and unsteady flight conditions is defined following two different approaches. In the first approach (approach A), similarity of advance ratio, μ , and flight-path angle, γ , is assumed to guarantee the similarity of the emitted noise, whereas in the second approach (approach B), μ , rotor thrust coefficient, C_T , and rotor disk orientation with respect to relative wind, α_{TPP} are considered as the noise equivalence parameters between different flight maneuvers. This means that, for a given unsteady flight condition, in approach A the corresponding noise source is determined by extracting from the steady-flight database the noise hemisphere cor-

responding to the same values of μ and γ , whereas in approach B the corresponding noise source is determined as the one associated to the same values of μ , C_T and α_{TPP} (see also [14]).

In order to assess the quality of the acoustic predictions obtained by these two approaches, their simulations are compared with those determined by the fully-unsteady solution (approach C) based on the general aeroacoustic formulation described in Section 2.1. More specifically, the method of analysis consists in the following steps:

- i. for a given unsteady maneuver, time histories of the corresponding pilot commands and flight conditions are identified by a comprehensive helicopter model aeromechanics solver (which includes a low-fidelity main rotor model, suited for this kind of problems) [15];
- ii. for selected points along the trajectory, trim pilot commands and flight conditions corresponding to steady, rectilinear flights characterized by the flight parameters considered both in approach A and in approach B are determined through the same aeromechanics solver;
- iii. a high-fidelity aerodynamic/aeroelastic solver (capable of capturing effects due to complex phenomena like BVIs) provides the pressure loads arising over the rotor blades throughout the unsteady maneuver (approach C), as well as during the steady-state flights of approaches A and B;
- iv. near-field acoustic disturbances corresponding to the three approaches are evaluated over a hemisphere rigidly connected to the helicopter in terms of Sound Pressure Level (SPL) distribution;
- v. noise footprints on the ground from approaches A, B and C are predicted, and the corresponding results are compared.

Next sections provides a brief outline of the prediction tools applied for the evaluation of the near-field noise and the propagation of the acoustic disturbance to the ground (steps iii.-v. of the method of analysis).

2.1 Near-field noise prediction

Noise radiated by rotor blades is evaluated through the widely-used boundary integral formulation developed by Farassat [7] for the solution of the well-known Ffowcs Williams and Hawkings equation [8], which governs propagation of acoustic disturbances aerodynamically generated by moving bodies. When the velocity of the rotor blades is far from the transonic/supersonic range, it yields the aeroacoustic field as a superposition of two terms: the loading noise, related to the distribution of pressure over blade surfaces, and the thickness noise, depending on blade geometry and kinematics.

The contributions of these two terms are evaluated by a zero-th order boundary element method: the blade surface is divided into quadrilateral panels, and the integrand functions multiplying kernel terms are assumed to be uniformly distributed within each panel, with values equal to those at the centroids. In problems dealing with weakly loaded rotors, thickness and loading noise are comparable. However, when strongly loaded rotors are examined (as in the case of BVI occurrence), the thickness noise contribution tends to be negligible and the acoustic disturbance is dominated by the loading noise.

Commonly, aeroacoustic formulations for helicopter rotor analysis consider steady, rectilinear, trimmed flights. In these operative conditions both kinematics and aerodynamics events are time-periodic thus yielding, correspondingly, time-periodic contributions to the aeroacoustic formulation. Differently, during unsteady helicopter maneuvers kinematic and aerodynamic terms are non-periodic, thus increasing the complexity of the algorithm. In this case, the instantaneous evaluation of thickness and loading noise contributions requires the knowledge of the past time histories of blade pressure loads, along with time histories of center of mass trajectory and velocity, vehicle attitude and angular velocity, for a lapse of time depending on observers location.

The time history of the blade surface pressure distribution is provided by the rotor aeroelastic/aerodynamic high-fidelity model. Aeroelastic and aerodynamic responses are obtained by com-

bining a nonlinear, bending-torsion, beam-like blade structural dynamics model [10] with a three-dimensional, free-wake, aerodynamic formulation based on a boundary integral equation approach, suited for the analysis of potential flows around helicopter rotors in arbitrary flight condition [11]. The resulting aeroelastic integro-partial differential system of equations is spatially integrated through the Galerkin approach. The harmonic balance approach is applied to determine the periodic aeroelastic response during steady flight [12, 13]. On the other hand, non-periodic aeroelastic responses during unsteady helicopter maneuvers are evaluated through a time-marching solution algorithm based on a Newmark- β integration scheme [14].

2.2 Atmosphere noise propagation algorithm

The propagation losses between source and receiver, and the resulting noise exposure on the ground are determined through a three-step process [16]. Firstly, the path of the sound ray between the helicopter and a ground-based receiver is determined. Rather than using an integration over time of the ray path, a geometrical approach is used where the atmosphere is represented as a number of layers with constant speed of sound gradients. Refraction is then accounted for within the layers rather than between the integration steps as in classical ray tracing approaches. This approach greatly reduces the number of integration steps due to the limited number of layers required, and as such allows the numerical determination of the ray paths between the source and a discrete number of receiver positions.

In the second step, the bearing between the source and the receiver and the launch angle of the sound ray at the source determines the azimuth and elevation angles where the ray passes through the hemisphere, hence providing the Sound Pressure level (SPL) emitted at the source. Since the ray tracing method described above is independent on the frequency, the source noise levels for all available frequencies can be determined concurrently.

With the source noise level and the ray path known, the propagation losses can be determined. The algorithm takes into account three attenuation effects. Firstly, atmospheric attenuation (or absorption) is accounted for using the method defined by ICAO [17] and depends on the ray path and sound frequency. Secondly, spreading loss is accounted for, which includes the effects of focusing in a refracting atmosphere [18]. Finally, to account for secondary rays reflecting off different ground surface types, the ground effect is included using the approach defined by Delaney and Bazley [19]. In addition to the three attenuation effects mentioned above, also the sound level in the shadow zone is determined. Based on the approach developed by Arntzen [20, 21], the strong decrease of the sound level at the transition between the illuminated and the shadow zone is determined, as well as the noise levels penetrating the shadow zones due to ground waves, diffraction and scattering due to turbulence.

For each of the time steps available in the hemisphere samples, the total sound energy reaching the ground is determined based on the source noise levels and the propagation losses. This A-weighted sound level in each of the grid points can then be integrated over the execution time of the trajectory to obtain the Sound Exposure Level (SEL) of the full trajectory.

3. Numerical results

The numerical investigation on noise prediction capability of the approaches described in Section 2 considers the unsteady flight of a lightweight helicopter model inspired by the BO105. The BO105 is a relatively small, multi-purpose helicopter with an empty mass of about 1200 kg and a maximum gross mass of 2300 kg. It has a four-bladed, hingeless, counterclockwise rotating main rotor of 4.91 m radius, with blade pre-cone angle of 2.5° and rotor shaft tilted 3° forward. Inertial and elastic characteristics of the helicopter model used here may be found in [22].

The unsteady maneuver considered consists in an initial level, steady rectilinear flight, followed by a straight, decelerated descent, and a final pull up that precedes a steady level turn [15]. The time histories of the main flight parameters determined by the aeromechanics solver for the flown trajectory

are shown in Fig. 1. In this figure, moreover, some noteworthy maneuver points are marked: these identify the flight conditions where the quasi-steady aeroacoustics approaches A and B are compared with the fully-unsteady solution, C, in the following.

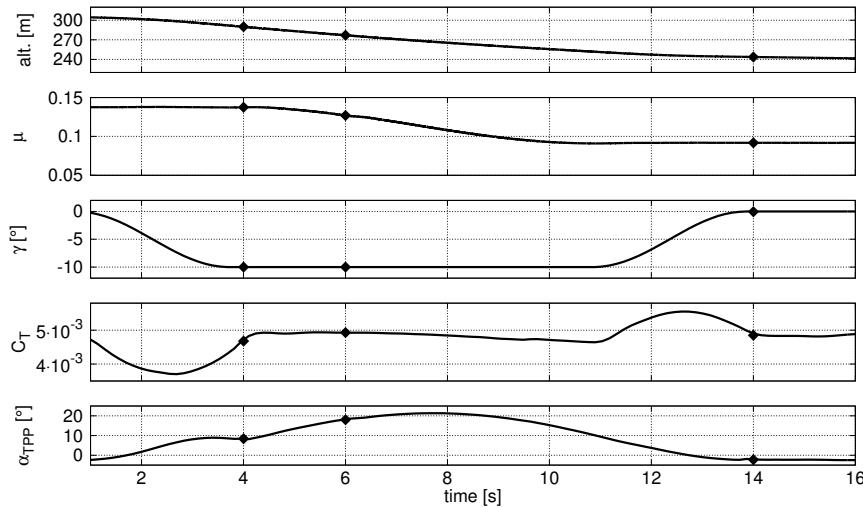


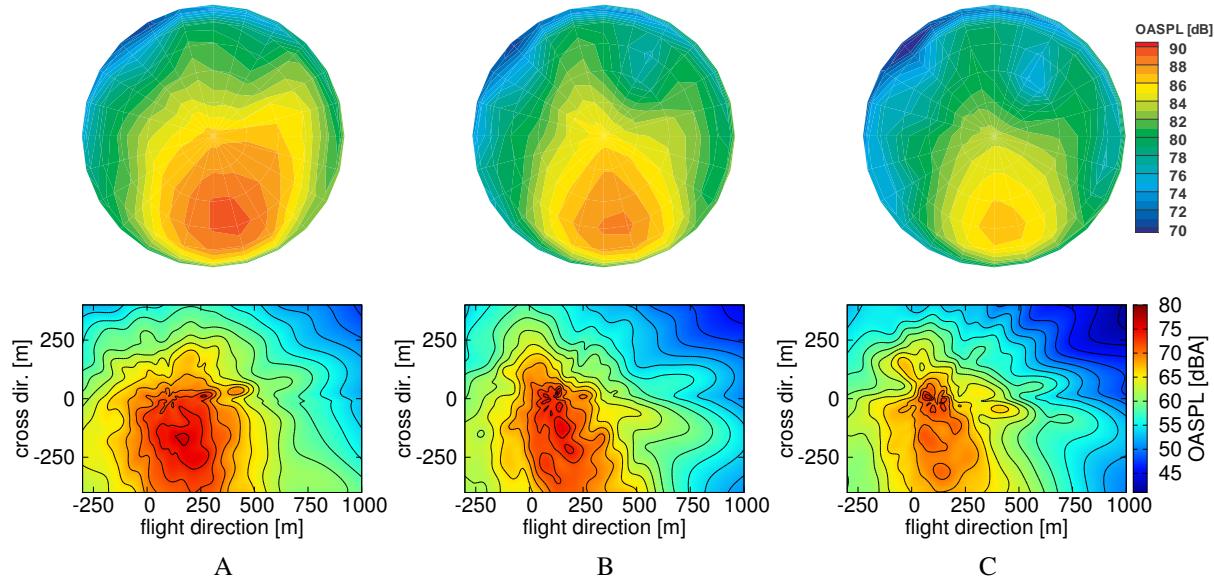
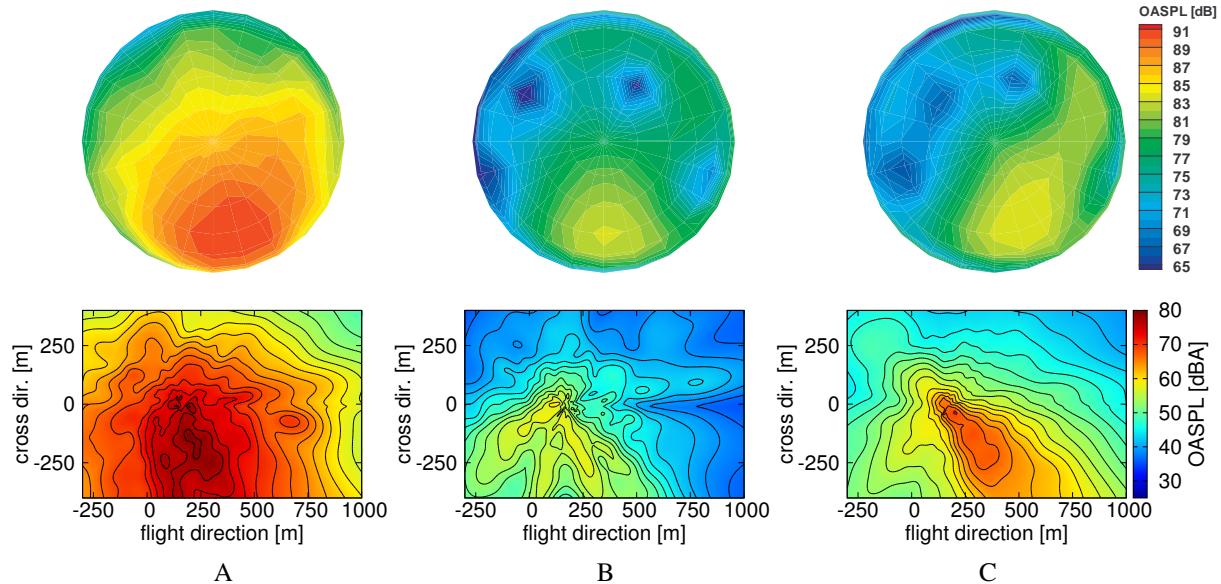
Figure 1: Helicopter rotor state during the manoeuvring flight.

The first point corresponds to the flight time $t = 4$ sec, and represents the beginning of the decelerated descent, subsequent to a vertical-plane, curved trajectory segment causing a remarkable variation of the thrust coefficient for $1 \text{ sec} < t < 4 \text{ sec}$ (see Fig. 1). At $t = 6\text{sec}$ (second mark) the helicopter is in the middle of the decelerated descent at a constant flight-path angle, with the tip-path plane tilted rearward, as observed in Fig. 1. The last point of analysis is at $t = 14$ sec, that corresponds to the end of the pull-up maneuver executed to achieve the final level flight.

The comparisons among the acoustic predictions provided by the three aeroacoustic approaches presented in Section 2 are shown in Figs. 2-4, for the three trajectory points selected for the analysis. These are presented both in terms of Overall Sound Pressure Level (OASPL) evaluated over hemispheres of radius $R = 150$ m, centered at the main rotor hub, rigidly connected with the helicopter, and in terms of A-weighted sound pressure levels (dB_A) determined on the ground surface underneath the flight trajectory (its extension is indicated in Figs. 2-4, whereas the helicopter altitude is depicted in Fig. 1). In these figures, noise hemispheres top views are illustrated, along with noise footprints corresponding to the helicopter travelling from the origin of the axes to ($t = 0$ sec) to the point with coordinates $x = 360$ m, $y = 0$ m (reached at $t = 15$ sec).

In Fig. 2 the aeroacoustic results at $t = 4$ sec are shown. At this point, the hemisphere noise is affected by the inertial effects due to trajectory curvature, strictly related to the remarkable variation of the thrust coefficient occurring for $1 \text{ sec} < t < 4 \text{ sec}$. BVI effects are also present because of the just started descent flight. The comparison of the results from approaches A and C, reveals that the former does not capture the noise effects of rotor disk loading alleviation due to the unsteady maneuver occurring for $1 \text{ sec} < t < 4$, whereas approach B provides lower levels of acoustic disturbance, in line with approach C results. Noise effects due to BVI events seem to be captured by the three approaches and hence comparable hemisphere and ground noise directivity are predicted.

The results for the flight condition occurring at $t = 6$ sec are shown in Fig. 3. At that time, the helicopter is experiencing a decelerated descent flight, with flight-path angle $\gamma = -10^\circ$: approach A seems to capture higher noise levels related to BVI events that might occur at that flight condition and that, evidently, do not appear in the fully-unsteady simulation. Akin to the first point correlations, approach B predicts hemisphere and ground noise levels that are in good agreement with those from approach C. Again, the correlation among BVI noise directivity simulated by the three approaches is satisfactory. In the third trajectory point considered, the helicopter is completing a pull-up maneuver, before entering a steady, level turn. Likewise the first point, it is located at the end of a trajectory

Figure 2: Noise hemispheres and noise footprints at $t = 4$ sec.Figure 3: Noise hemispheres and noise footprints at $t = 6$ sec.

segment where remarkable inertial effects due to the trajectory curvature characterize the helicopter flight. In this case, these produce an increase of the rotor disk loading that, as shown by Fig. 4, is similarly captured by approaches C and B. Flight parameters used to identify the noise source in approach A are such that this effect is not perceived, and hence the corresponding predicted acoustic disturbance is underestimated both on the hemisphere around the helicopter and on the ground. The spatial distribution of noise simulated by the three approaches is in good agreement, and proves that the influence of BVI events on noise is of negligible entity.

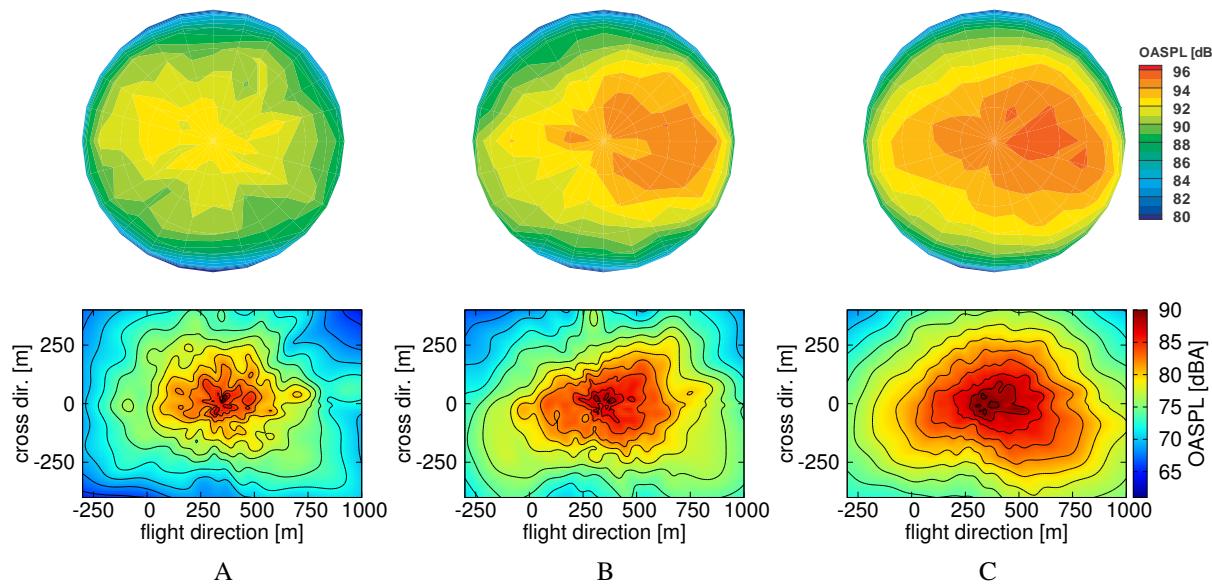


Figure 4: Noise hemispheres and noise footprints at $t = 14$ sec.

4. Concluding remarks

Considering an unsteady helicopter maneuver, noise predictions determined by a fully-unsteady aeroacoustic numerical tool have been compared with those given by two equivalent quasi-steady noise simulation methods that might conveniently be applied for low time-consuming predictions of the noise emitted by helicopters in unsteady flight (as required, for instance, by optimal-noise trajectory search tools). The aim is the assessment of accuracy of the predictions provided by the quasi-steady approaches. In the overall, the numerical investigation has demonstrated that the quasi-steady approach matching advance ratio, disk loading and rotor attitude occurring during an unsteady maneuver (approach B) provide noise predictions of higher accuracy than those given by the one matching only advance ratio and path-slope angle (approach A). This conclusion has been drawn both for unsteady maneuver segments dominated by inertial effects affecting rotor disk loading and for unsteady maneuver segments where rotor disc tilting effects produce remarkable variations of BVI events. For the flight conditions considered, the noise spatial distributions predicted by the three approaches examined have been observed to be in good agreement. Finally, it is worth noting that the noise hemisphere evaluated at a point along a trajectory of a helicopter in unsteady flight is affected by aeromechanics and aerodynamics occurring during a suitable past lapse of time, because of the time delay in noise radiation. The extent of this lapse of time depends on hemisphere radius that, in turn, is such that noise propagation outside of the hemisphere is of monopole type. Similar considerations should be made when defining the flight parameters through which quasi-steady noise hemispheres to be applied at a given unsteady flight point are determined from an available database.

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