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CFD-CAA Method for Prediction of Pseudosound and Emitted Noise in Quadcopter Propeller

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***Abstract*—Subsonic flow air blade machines like UAV propellers generate intensive noise thus the prediction of acoustic impact, optimization of these machines in order to reduce the level of emitted noise is an urgent engineering task. Currently, the development of calculation methods for determining the amplitudes of pressure pulsations and noise characteristics by CFD-CAA methods is a necessary requirement for the development of computer-aided design methods for blade machines, where the determining factors are the accuracy and speed of calculations. The main objective is to provide industrial computer-aided design systems with a highly efficient domestic software to create optimal designs of UAV blade machines that provide a given level of pressure pulsations in the flow part and radiated noise. It comprises: 1) creation of a method for the numerical simulation of sound generation using the correct decomposition of the initial equations of hydrodynamics of a compressible medium and the selection of the source of sound waves in a three-dimensional definition, taking into account the rotation of blades and their interaction with the stator part of the UAV; 2) decomposition of the boundary conditions accounting pseudo-sound disturbances and the complex acoustic impedance at the boundaries of the computational domain 3) development of an effective SLAE solver for solving the acoustic-vortex equation in complex arithmetic (taking into account the boundary conditions in the form of complex acoustic impedance); 4) testing of a new method at all stages of development using experimental data on the generation of pressure pulsations and aerodynamic noise, including a propeller noise measurements.**

***Index Terms*—UAV propeller, pressure pulsations, emitted noise, CFD-CAA method.**

I. INTRODUCTION

Small unmanned aerial systems (SUAS), also known as drones are becoming increasingly useful for commercial, private activities. Despite their usefulness, drones create noise that is annoying to the public [1]-[4]. Surprisingly, there are a lack of adequate safety and noise regulations for drones [5]. Given the need to reduce noise and develop appropriate standards, new research is required to understand the nature of drone noise production and develop novel methods of control [6]. Drone noise is dominated by the small propellers used as part of their propulsion systems. Acoustic signatures consist of strong harmonics occurring at multiples of the blade pass frequency as well as a broad-band component [7], [8]. The dramatic increase of the UAV market for civil purposes shows that the quietness and the efficiency of the propulsive system are key aspects in the design of advanced aerial vehicles and very often can lead to the success or failure of the mission [9]. From other hand, the acoustic signature of commercial propeller aircraft is becoming a key design parameter as airlines shift from turbofan to turboprop engines for short-duration flights [10, 11] and restrictions on the noise pollution surrounding airports become more stringent. The new International Civil Aviation Organization noise standard in Annex 16, Vol. 1, Chapter 14 constitutes a 7 dB increase in stringency of the effective perceived noise level and will apply to propeller aircraft under 55 ton in 2020 [12]. Propeller aircraft noise also has a direct impact on the health of those living or working near airports [13], [14].

Propeller noise can be classified into three categories: harmonic noise, broadband noise, and narrow-band random noise [15], [16]. Harmonic noise is the periodic component, that is, its time signature can be represented by a pulse which repeats at a constant rate. If an ideal propeller with B blades is operating at constant rotational speed N, then the resulting noise appears as a signal with fundamental frequency BN. The blade-passage period is 1/BN. Typically the generated pulse is not a pure sinusoid, so that many harmonics exist. These occur at integer multiples of the fundamental frequency. The first harmonic is the fundamental, the second harmonic occurs at twice the fundamental frequency, and so on. Broadband noise is random in nature and contains components at all frequencies. The frequency spectrum is continuous, although there may be a “shape” to it because not all frequencies have the same amplitude. Narrow-band random noise is almost periodic. However, examination of the harmonics reveals that the energy is not concentrated at isolated frequencies, but rather it is spread out. The frequency spectrum shows discrete components, but these spread out, particularly at the higher frequencies. Steady sources are those which would appear constant in time to an observer on the rotating blade. They produce periodic noise because of their rotation. Unsteady sources are time dependent in the rotating-blade frame of reference. They include periodic and random variation of loading on the blades. A typical example of periodic blade loading in propellers is the effect of shaft angle of attack. When the propeller axis is tilted relative to the inflow, each blade sees a cyclic change in local angle of attack. Therefore, the loading on the blade varies during a revolution. The loading change may be once per revolution or several times per revolution, depending on the source of inflow distortion. All inflow distortion which is invariant with time results in blade-loading changes which repeat exactly for every propeller revolution. The resulting periodic unsteady-loading noise occurs at harmonics of blade-passage frequency. Unsteady loading is an important source in the counterrotating propeller. Although the counterrotating

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propeller does not contain any additional or unique sources of noise, the aerodynamic interference between the two rotors gives rise to significant levels of unsteady-loading noise which are particularly significant at low flight speeds, such as during take-off and landing. Aerodynamic interaction is a significant source of noise for low-speed operation. Under certain conditions blade loading which is nearly periodic can occur. An example of this is the ingestion of a vortex, which could be induced by the propeller and attached to the fuselage or to the ground ahead of the propeller. As such, propeller noise testing and prediction are active fields of research.

The first successful acoustic theory was developed by Gutin in 1936, when he represented the steady aerodynamic forces on the propeller as a ring of acoustic dipole sources acting at a certain effective radius [17]. Gutin’s theory, however, was limited to loading noise for propellers with axial flow, simple geometry, low tip speed, and no forward speed. Since then, there have been significant advances in acoustic theory due to the work of many researchers who have removed these limitations [18]-[20]. A thorough review of propeller noise prediction methodology, detailing these advances, has been published by multiple authors [21]-[23].

Noise prediction methods are typically grouped into two categories: frequency-domain methods and time-domain methods. Time-domain methods retain the pressure time history and allow the propeller geometry to be treated with superior precision. However, they require the computation of retarded blade locations and, due to their sensitivity to aerodynamic error, need high-quality aerodynamic data to obtain accurate results.

The physical mechanisms of aerodynamic noise generation in bladed machines are well studied, with the example of fans [24], where it was noted that the noise spectrum of fans consists of broadband noise and tonal components at frequencies that are multiples of the Blade Passing Frequency of the rotor blades (BPF). With the development of computational fluid dynamics, methods have been developed for calculating pressure pulsations in blade machines based on solving RANS equations [25], [26]. Another approach using the Reynolds equations was proposed by S. Chu *et al.* [27]. A similar approach is developed in the work of M.S. Thompson *et al*. [28], who also use laser anemometry data, but pressure pulsations are calculated by solving equations of the Blokhintsev-Howe type [29] with respect to the stagnation enthalpy. Currently existing approaches for modeling the noise of blade machines are based mainly on the application of the Lighthill equation [30]. Later, the works of Curle [31], Flowcs-Williams and Hawkings [32] formulated the theoretical basis for the development of methods for calculating the aerodynamic noise of blade machines based on the so-called aero-acoustic analogy, as well as the application of Kirgoff's theorem [33], [34].

As is known, in blade machines, where the Mach number at the periphery of the rotor is lower than 0.5, the noise is emitted mainly by the type of a dipole source. Aeroacoustics’ analogy introduces a certain simplification of the physical processes of noise generation for the purpose of their analytical description. The dipole nature of the radiation is due to pressure forces acting on the rotor and stator blades from the flow. These forces, steady or unsteady, are the cause of the tonal noise of the BPF and its higher harmonics, which is generated by the rotor blades, and also, as a result of the interaction of the rotor - stator, with guide stator blades. The analytical formulation of these processes is based on the formalization proposed by Sears [35], and represents the emitted sound in the form of the so-called spiral modes [36]-[38].

In connection with the development of the possibilities of using methods of computational fluid dynamics and acoustics, approaches based on the numerical simulation of unsteady flow in blade machines using modern methods of computational fluid dynamics, for example, LES with subsequent determination of acoustic radiation, are gaining wider development [39]-[41]. In combination with the aeroacoustic analogy, other methods are also being developed, such as, for example, RANS + LEE + SNGR [42], as well as DDES [43] in conjunction with the Lighthill or Ribner equation [44].

The key issue in computational aeroacoustics studies is an adequate source definition. It should also be noted that the Lighthill equation obtained under the assumption of small oscillations in the turbulent flow of a compressible medium, while in the bladed machines pressure pulsations and the generation of emitted sound occur in a wide range of wave numbers when large-scale vortex disturbances decay in a cascade process into a small-scale turbulence [45], and the generation of acoustic waves occurs in this process.

II. ACOUSTIC-VORTEX METHOD

A. Main Equations

The acoustic model describing the isentropic inviscid flow is constructed based on the decomposition proposed by Crow S. [46] and K. Artamonov. [47]. Currently, the acoustic-vortex decomposition method and the acoustic radiation source are analyzed. The equations of aeroacoustics are derived in terms of the parameters of the hydrodynamic flow and, as indicated in the works of Doak P. [48] and Goldstein M. [38] cannot be considered as purely sound. The right-hand sides, or source terms, in these equations describe the generation of perturbations of the flow parameters without distinguishing the acoustic component proper, and the left-hand sides describe the spatiotemporal propagation of wave-type acoustic-vortex perturbations, taking into account convective transport and spatial inhomogeneity of sound speed. The initial equations of aeroacoustics are linearized with respect to their perturbed values.

One can represent the compressible fluid velocity as the sum of the main flow velocity and the velocity of acoustic motion that leads to the wave equation. The use of decomposition with the representation of enthalpy in the form (angle brackets means that the time average value of the expression enclosed in them is taken, and a stroke indicates its component pulsating relative to the average value), we obtain the following equation

$$\frac{1}{c^2}\frac{d^2h'}{dt^2}-\Delta h' = f \quad , \tag{1}$$

with a source term

$$f=\nabla(\mathbf{u}\nabla)\mathbf{u}-(\mathbf{u}\nabla)\nabla\mathbf{u}-\frac{1}{c^2}\frac{d^2\langle h\rangle}{dt^2}+\Delta\langle h\rangle \quad . \tag{2}$$

Such linearization allows one to carry out the Fourier transform of the obtained equations and impedance boundary conditions and formulation of the boundary value problem.

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$$\frac{1}{c^2}\left(i\omega+\langle \mathrm{v}_i\rangle\frac{\partial}{\partial x_i}\right)\left(i\omega+\langle \mathrm{v}_j\rangle\frac{\partial}{\partial x_j}\right)h'-\frac{\partial^2 h'}{\partial x_i^2}=\Phi(\omega)(f) \tag{3}$$

$$\Phi(\omega)(f)=\Phi(\omega)\left(\frac{\partial \mathrm{v}_i}{\partial x_k}\frac{\partial \mathrm{v}_k}{\partial x_i}\right) \tag{4}$$

The momentum equation and continuity equation for modeling the vortex mode motion are [49]

$$\frac{\partial\rho\cdot V}{\partial t}+\nabla(\rho\cdot V\times V)=-\nabla P+\nabla(\mu\cdot(\nabla V+(\nabla V)^{\tau}) \tag{5}$$

$$\partial\rho/\partial t+\nabla(\rho V)=0$$

B. Boundary Conditions

The boundary conditions of the impedance type are written in terms of perturbations of the flow parameters relative to their average value.

Assuming the flow perturbations in the vicinity of impedance boundary are isentropic then boundary conditions and non-reflecting condition on the outer boundary of the computational domain can be represented in the frequency domain as follow

$$\frac{\partial h'}{\partial n}+\left(i\omega+\langle \mathrm{v}_i\rangle\frac{\partial}{\partial x_i}-\frac{\partial\langle \mathrm{v}_i\rangle}{\partial x_k}n_i n_k\right)\left(\frac{\partial p}{\partial h}\right)_s\frac{h'}{\rho c Z}=0 \tag{6}$$

$$\frac{\partial h'}{\partial n}+\left(i\omega+\langle \mathrm{v}_i\rangle\frac{\partial}{\partial x_i}-\frac{\partial\langle \mathrm{v}_i\rangle}{\partial x_k}n_i n_k+\frac{ic^2}{2\omega}\Delta_n\right)\left(\frac{\partial p}{\partial h}\right)_s\frac{1}{\rho c}h'=0 \tag{7}$$

III. FEASIBILITY STUDY ON A QUADCOPTER PROPELLER

Feasibility computational study is undertaken of a quadcopter propeller with 70 mm diameter under rotation speed 12,000 RPM. In Fig. 1 there is shown the instantaneous velocity field in the rotor plane scaling from zero (blue) to 5 m/s (red). In Fig. 2 pressure isolines and the source function are presented. To represent the source spatial structure two iso-surfaces are introduced for the level +/- 50,000 s-2. The computation completed by the “sliding surface” method [49]. The positive level is marked by red, and negative – by blue color. In the rotor domain of blades, the source function zeroed.

Additional data obtained by the “moving body” method,

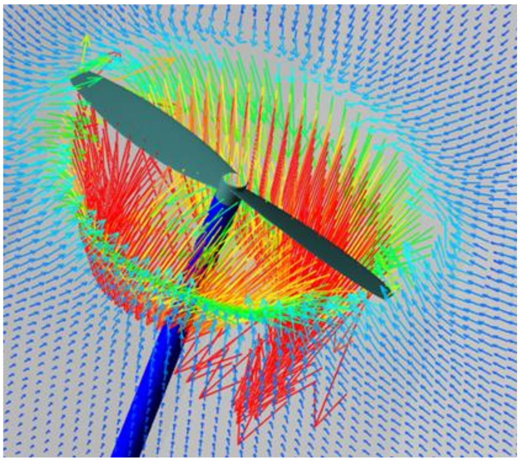

Fig. 1. Velocity by “sliding surface” method.

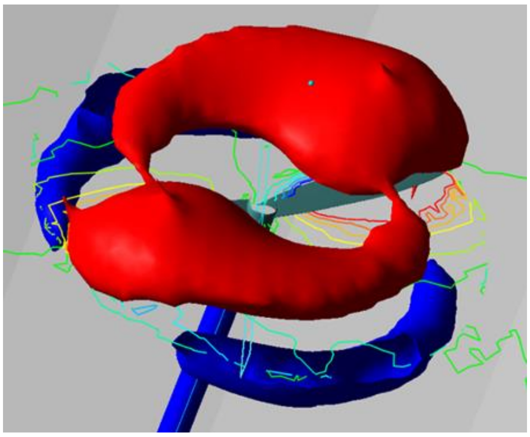

Fig. 2. Source function by “sliding surface” method.

where the rotating propeller installed in the motionless domain of semi-sphere of 5 m radius. The propeller locates in the center of semi-sphere under 1 m of the ground surface. Grid adaptation of 6th level [49] completed for resolving parameters’ gradients near the propeller and accurate computation of the source function.

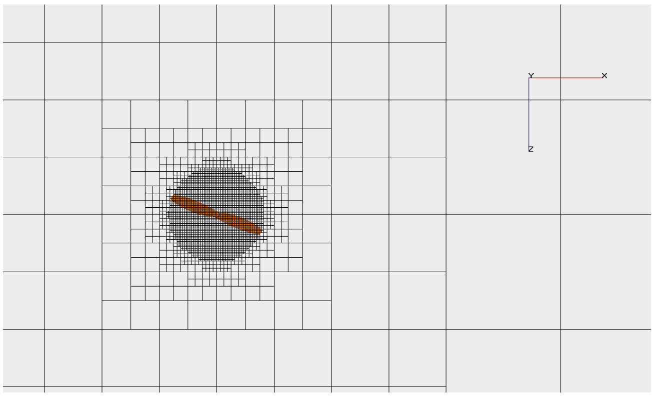

Fig. 3. The grid of 6th level plane view.

Grid adaption made by splitting each neighboring initial rectangular cell on eight smaller ones. Then, the so-called sub-grid adaptation implemented on the propeller surface, where the accurate discretization completed on arbitrary polyhedron cells.

The computational grid in the plane and meridional view are shown in Fig. 3 and 4.

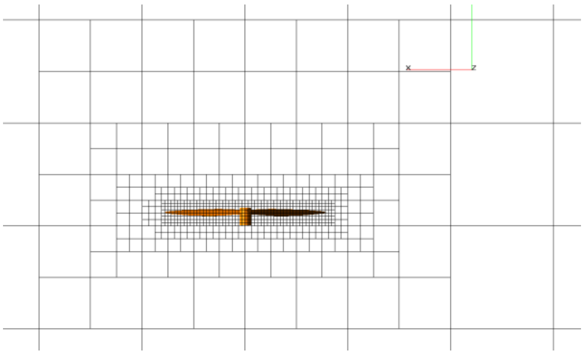

Fig. 4. The grid of 6th level meridional view.

In the current study the source function of BPF noise is obtained with the "moving body" method as well. Below (see Fig. 5) there are presented isolines of static pressure (scaled from the zero level) and the source function color map in the plane of blades. One can see that maximums of the source function correspond to the negative pressure peaks.

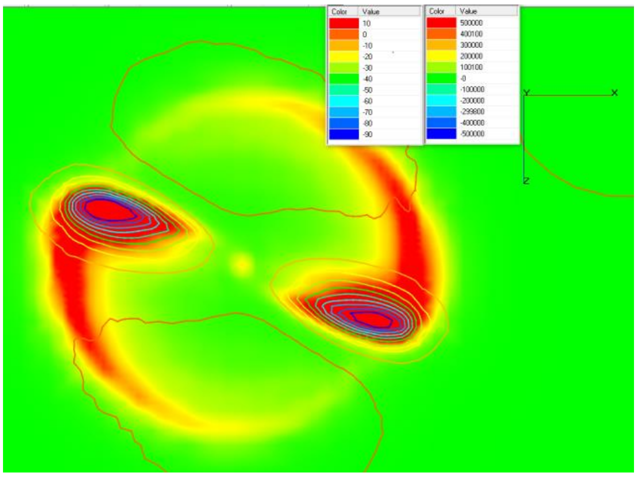

Fig. 5. Source function (+/- 5e05 s^{-2}) and isolines of static pressure (+10/-90 Pa).

It agrees with results obtained by the "sliding grid" method (see Fig. 2).

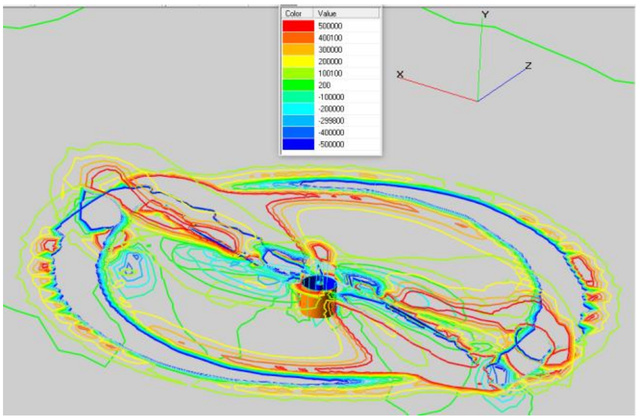

Fig. 6. Source function.

The source function isolines in 2 perpendicular planes present a spatial structure with two adjacent negative and two positive protuberances connected and rotated with blades. This result opens the way to investigate the effect of contrarotating propellers interaction on the emitted UAV BPF noise.

IV. CONCLUSION

CFD-CAA method based on acoustic-vortex decomposition is under development for prediction of UAV propeller acoustic field. It gives the explicit and infinite approaches for resolving emitted noise accounting boundary conditions with using the complex acoustic impedance. The source term of the acoustic-vortex equation computed by two methods. Both methods reveal the spatial source structure with two adjacent negative and two positive protuberances connected and rotated with propeller blades. This result opens the way to investigate the effect of contrarotating propellers interaction on the emitted UAV BPF noise.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

S. Timushev wrote the text, D. Klimenko and A. Yakovlev conducted the computations and analyzed the data.; all authors had approved the final version.

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In 2002-2005 he worked for EU scientific project NORMA on noise and vibration reduction in high speed ships and LaMoNoV EU project on noise reduction of lawn movers. The last decade he works on the problem of computational prediction of pressure pulsation in centrifugal pumps and ventilators and reduction of vibration and noise in such machines.

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