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Modelling of the acoustic wave scattering on the aircraft surface using the boundary element method

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Abstract Sound localization tools are important in the environmental protection and the human searches. The article is one of the stages of the implementation of the concept of using aircraft to localize sound sources. The use of a fixed-wing aircraft instead of a multirotor would increase the total flight time, and expand the surveyed area. It is important to determine the most favourable positions of the receivers on the surface of the aircraft. The scattering effects of the sound waves coming from the ground source and aircraft engine on the acoustic field on the aircraft surface are not homogeneous. In the article the authors present the modelling of the scattering of the sound waves over the airplane surface with the usage of boundary element methods. After determining the effects from the sound source on earth and from the aircraft engine the conclusion was made, that the influence from the engine noise is greater than that from the ground source, and in order to localize the low amplitude signals, the aircraft need to glide. Considering only the effects of the ground source, the optimal areas for the microphones placement were determined.

Keywords: sound localization, boundary element method, sound scattering, noise, aircraft, Smart Acoustics.

1. Introduction

Acoustic measurements are the new research topics in a field of remote sensing [1]. Due to the miniaturization and a new technology of lightweight energy sources the unmanned aerial vehicles (UAV) are the new tool for scientific and commercial applications. Sound source localization with the help of UAV applies not only in acoustic measurements for environmental protection, but also in the human searching in a low visibility environment (due to smoke, fog, in the wooded areas or at night) [2,3]. Actual studies has focused the attention on multirotor UAVs as a carriers of research apparatus [2, 4-6]. This involves the use of complex algorithms to compensate for the noise associated with the propulsion of such UAVs [2, 3, 6, 7]. The complexity of such filtering is caused by a non-stationary noise signal [4]. As a result, with the use of such platforms it is difficult to locate sources with the low acoustic power [2]. The use of fixed-wing UAVs as a test platform would not only eliminate the non-stationary nature of the propulsion-induced noise, but also increases the area surveyed in one flight.

In order to create an effective tool for localizing the low acoustic power signal sources, it is necessary to determine the favorable localization of the sound measurement sensors in the vehicle structure [4]. In the article, the authors present one of the steps necessary to determine a favorable localizations of the microphones.

The distribution of the sound pressure caused by the scattering of an acoustic wave is not homogeneous. The first step of finding a favorable localizations of the microphones is a determinig of the acoustic pressure distribution on the surface of a vehicle. In this article, the authors focus on the issue of acoustic wave scattering on the vehicle surface, caused by two sound sources: the first source located at a distance from the aircraft and the second source – the noise source related to the propulsion system.

The authors used the boundary element method [8, 9, 10] to determine the acoustic pressure distributions on the aircraft surface. The advantage of this method is that only the edge of the computational domain is discretized. This results in a significant reduction of the computational complexity, in the comparison to methods where the entire volume of the computational domain needs to be discretized [11].

2. Methodology end research object

2.1. Acoustic wave equation

Acoustic wave equation is derived from fluid mechanics Navier-Stokes equation after assuming that: there is no heat flow (process is adiabatic), the fluid is non-viscous, there is no constant velocity and the pressure is a linear function of density. Acoustic field could be expressed by linear wave equation

$$\nabla^2\Psi(\mathbf{p},t) = \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\Psi(\mathbf{p},t), \tag{1}$$

where: $\Psi(p,t)$ – scalar time dependent velocity potential, $\mathbf{p}$ - spatial variable, t – time variable, c – speed of sound, ∇^2 – Laplace operator.
Considering the steady state with harmonic signals, the Helmholtz equation is obtained:

$$\nabla^2\varphi(\mathbf{p}) + k^2\varphi(\mathbf{p}) = 0, \tag{2}$$

where: k – wave number ($k = \frac{\omega}{c}$), ω – angular frequency, $\varphi(\mathbf{p})$ – time-independent velocity potential. If the q is the forced function (sound source), so instead of equation (2), the non-homogeneous wave equation is obtained:

$$\nabla^2\varphi(\mathbf{p}) + k^2\varphi(\mathbf{p}) = q. \tag{3}$$

Integral-solution of equation (3) has a form:

$$\int_S \left(G(\mathbf{p},\mathbf{q})\frac{\partial\varphi(\mathbf{q})}{\partial n} - \varphi(\mathbf{q})\frac{\partial G(\mathbf{p},\mathbf{q})}{\partial n}\right) dS + \int_V \left(G(\mathbf{p},\mathbf{q})\, Q\right) dV = \begin{cases} \varphi(\mathbf{p}) & \text{for } \mathbf{p} \text{ inside domain} \\ \frac{1}{2}\varphi(\mathbf{p}) & \text{for } \mathbf{p} \text{ on boundary} \\ 0 & \text{for } \mathbf{p} \text{ outside domain} \end{cases}, \tag{4}$$

where: $\mathbf{q}$ – spatial variable, $\frac{\partial}{\partial n}$ – derivative along the direction of the surface normal, Q – any function of sound source, $G(\mathbf{p},\mathbf{q})$ – fundamental solution of equation (3) if q is the Dirac delta function:

$$G(\mathbf{p},\mathbf{q}) = \frac{-e^{-ikr}}{4\pi r} = G_0 e^{-ikr}, \tag{5}$$

where: $r=|\mathbf{r}|$, $\mathbf{r}=\mathbf{p}-\mathbf{q}$, $G_0 = \frac{-1}{4\pi r}$. For discretization with N element, matrix of boundary element method get form:

$$\frac{1}{2}\boldsymbol{\varphi} = \boldsymbol{\alpha}\frac{\partial\varphi}{\partial n} - \boldsymbol{\beta\varphi} + \boldsymbol{\eta}, \tag{6}$$

where: $\boldsymbol{\varphi}$ -column vector of size [1 × N] with values of velocity potential, $\boldsymbol{\alpha}, \boldsymbol{\beta}$ – matrixes of size[N × N] with values of coefficients, $\boldsymbol{\eta}$ - column vector of size [1 × N] with values of velocity potential induced by source.

For discretization with zero-order elements, coefficients in matrixes $\boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\eta}$ have form:

$$\boldsymbol{\alpha}_{\mathrm{nm}} = G(\mathbf{p}_{\mathrm{m}}, \mathbf{p}_{\mathrm{n}})\, A_m \qquad \text{for} \qquad \mathrm{n,m} = 1,\ldots,\mathrm{N}, \tag{7}$$

$$\boldsymbol{\beta}_{\mathrm{nm}} = \frac{\partial G(\mathbf{p}_{\mathrm{m}}, \mathbf{p}_{\mathrm{n}})}{\partial n_{\mathrm{n}}} A_m \qquad \text{for} \qquad \mathrm{n,m} = 1,\ldots,\mathrm{N}, \tag{8}$$

$$\boldsymbol{\eta}_{\mathrm{n}} = G(\mathbf{p}_{\mathrm{n}}, \mathbf{q})\, Q \qquad \text{for} \qquad \mathrm{n} = 1,\ldots,\mathrm{N}, \tag{9}$$

where: $\mathbf{p}_{\mathrm{m}}$ – position of the center of m-th element, $\mathbf{p}_{\mathrm{n}}$ – position of the center of n-th element, A_{m} – area of m-th element, r_{nm} – vector between centers of n-th and m-th element, $\mathbf{q}$ -position of sound source. For acoustic impermeable, rigid surface, the derivative of velocity potential with the respect to surface normal is known, and equal to zero. It means that equation (6) can be expressed as:

$$\frac{1}{2}\boldsymbol{\varphi} = -\boldsymbol{\beta\varphi} + \boldsymbol{\eta}. \tag{10}$$

Solution for velocity potential for scattering sound wave over rigid acoustically impermeable surface by a monopole sound source is as follows:

$$\boldsymbol{\varphi} = \boldsymbol{Y}^{-1}\boldsymbol{\eta}, \tag{11}$$

where: $\boldsymbol{Y} = \left(\frac{1}{2}\mathrm{I} + \boldsymbol{\beta}\right)$.

2.2. Research object

The object of research is the moto glider with a wingspan of 5 m. In Figure 1 the geometric model of the analysed unmanned aerial vehicle is shown.

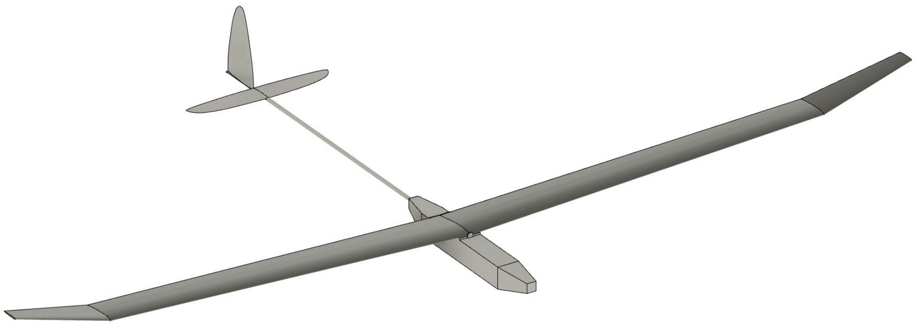

Figure 1. Geometric model of analysed UAV moto glider.

In the simulation of scattering sound waves over aircraft body two scenarios of the sound source was taken into consideration. In the first scenario the sound emitted from the aircraft engine was considered. The engine's sound was modelled as a monopole source placed in the front of the aircraft fuselage (Fig. 2).

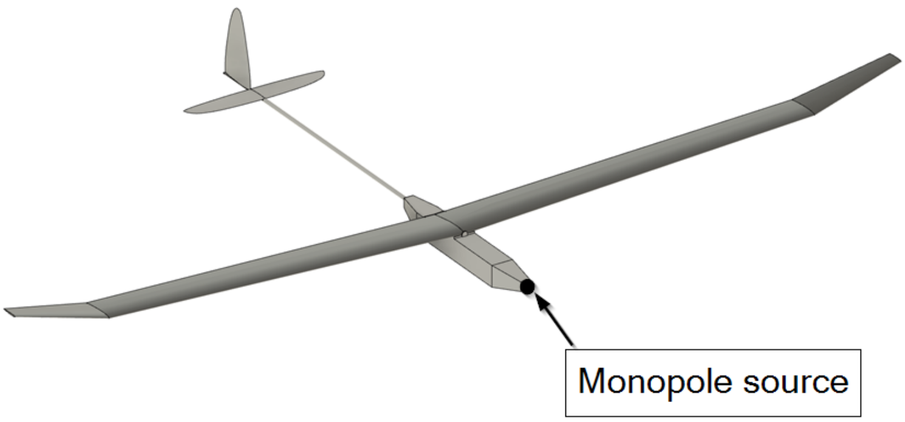

Figure 2. First scenario - engine sound source.

In the second scenario the sound source localized on the ground was examined. The distance from the aircraft to the ground was set to 100 m, and the source was placed directly beneath the aircraft (Fig. 3). This sound source is also treated as a monopole sound source.

The influence of the aircraft speed was not considered. In both scenarios scattering effects was examined for frequencies from 50 Hz to 1000 Hz with the increment of 50 Hz. In Fig. 4 computational mesh was shown. The mesh is composed of 32 thousands of hexahedral elements in order to reproduce the geometry of wings profile.

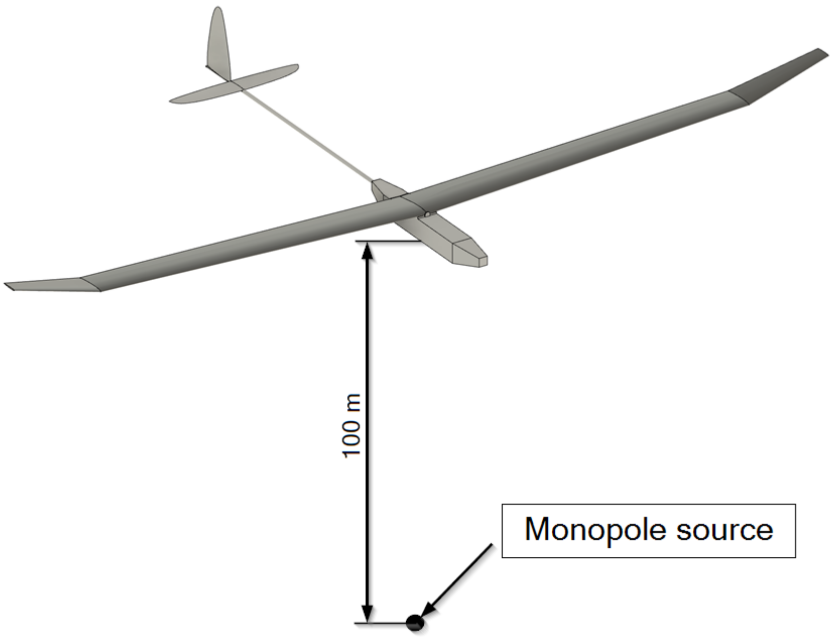

Figure 3. Second scenario - ground source.

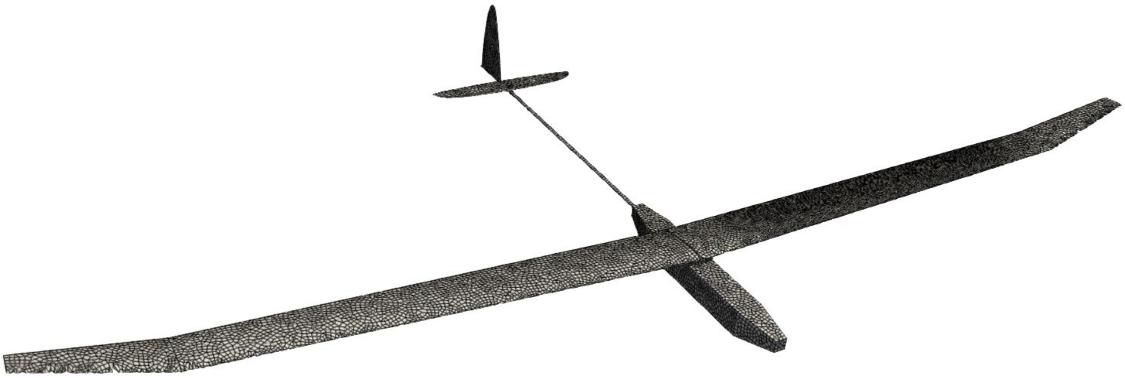

Figure 4. Computational surface mesh.

Numerical analysis were prepared in AcouSTO – open source simulation software [12]. All surfaces of the aircraft geometry were considered as a non-flexible.

3. Results

Pressure distribution of scattered field was calculated using following equation:

$$p(\mathbf{p}) = i\ \rho\ \omega\ \varphi(\mathbf{p}), \tag{12}$$

where: ρ – medium density.

The amplitudes from pressure fields for different frequencies was added. As the results the three scenarios was assessed (Fig. 5-6). The analyzes were qualitative, not quantitative. The goal was to determine the distribution of the acoustic field, exact values were not taken for evaluation. The pressure scale in the presented results was adjusted for each scenario to highlight the non-homogeneous nature of the field.

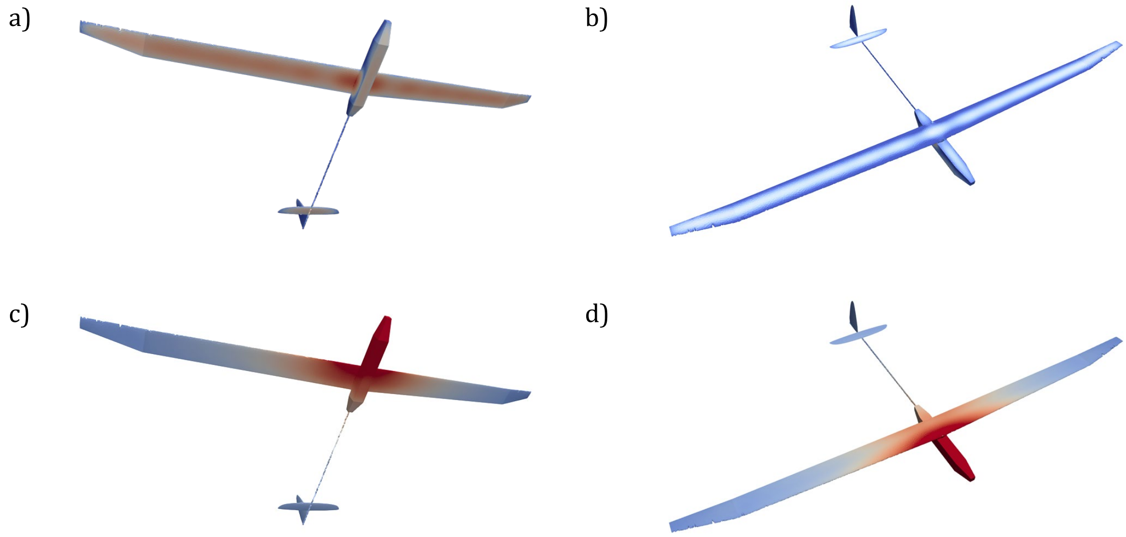

Figure 5. Results of sound pressure amplitude for scenarios:
a) sound source on the ground (view from the bottom),
b) sound source on the ground (view from the top),
c) engine as a sound source (view from the bottom),
d) engine as a sound source (view from the top).

Figure 6. Results of sound pressure amplitude for both analysed sources (view from the bottom).

4. Discussion and conclusions

In the results obtained for the sound source located on the ground (Fig. 5a-b) it can be seen that the high acoustic pressure values are located in bottom of the wing, in the middle of the wing chord. High intensity of the pressure is located near the fuselage of the aircraft. It is due to the reflection from the fuselage surface.

In the results obtained for the second scenario (engine as a sound source, Fig. 5c-d) it can be seen that the pressure is distributed radially from the source position.

The last analyzed case (Fig. 6) presents the superposition from the two analyzed sound sources. Because of the large difference in distances of the sound sources, the field caused by a source on the ground has a minor effect on the resulting field. The numerical results prove that in order to achieve the high signal to noise ratio for signal located on the ground, the aircraft need to have the engine turned off, and glide over the sound source. Based on the performed analysis, the favorable areas of localizing the microphones were determined (Fig. 7).

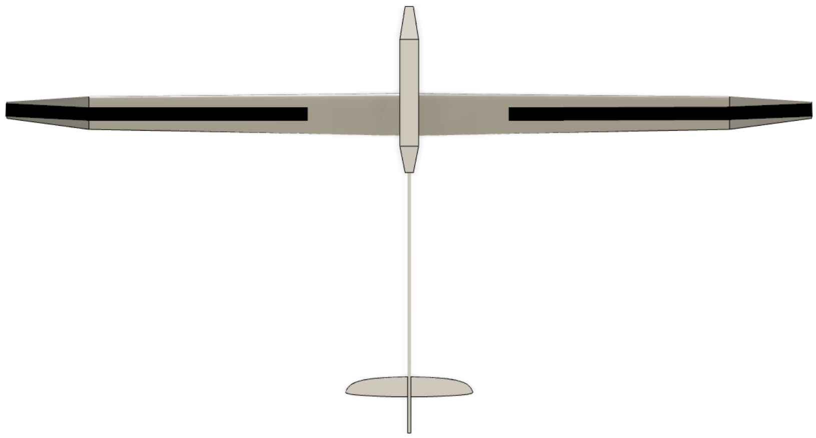

Figure 7. Favourable positions of acoustic measuring devices (view from the bottom).

In the next stage of the designing the structure of microphones arrays, the authors will conduct the aeroacoustic analysis in order to determine the distribution of the flow-induced sound on the aircraft surface.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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