

Optimal Acoustic Metamaterial Property Determination for the Reduction of Propeller Noise

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Introduction

Many aircraft configurations rely on propellers as the primary propulsion type. Especially for novel aircraft types for the transportation of cargo and persons in urban areas, propeller noise emissions are an issue since they limit the societal acceptance of this technology [1]. The integration of Acoustic Metamaterials (AMMs) in novel aircraft designs is a potential means for the reduction of tonal propeller noise.

Noise Reductions Through the Use of AMMs

Acoustic Metamaterials (AMM) are designed to control, direct, and manipulate sound waves through dissipation, local resonance, and phase shift [2]. AMMs can, for example, be used to mitigate noise to improve acoustic comfort in cars [3] [4], passenger aircraft [5], or buildings [6].

The homogenous acoustic wave equation can be expressed as

$$\nabla^2 p(\mathbf{x}) - \frac{\rho}{B} \frac{\partial^2 p(\mathbf{x})}{\partial t^2} = 0 \quad (1)$$

with density ρ and bulk modulus B . In natural media, density, and bulk modulus are positive. However, in AMM, those parameters can take on arbitrary values allowing AMMs to achieve acoustic properties beyond what is possible with natural materials [2]. AMMs are mostly used to achieve noise reductions. In typical applications, transmission losses are increased, or absorption and phase shifts are controlled such that noise reductions are achieved.

Aircraft Exterior Noise Reduction and AMMs

Turbofans are the dominant noise sources of contemporary airliners. It is state of the art to reduce the fan noise component of turbofan engines through acoustic liners inside the nacelle that basically act as Helmholtz or quarter chord length resonators. However, the effectiveness of those acoustic liners is limited for high wavelengths as those would require a liner thickness in roughly the same order of magnitude as the resonance wavelength. To overcome those limitations, it is attempted to include AMMs in acoustic liner design [5] since the thickness of AMMs can be orders of magnitudes lower than the affected acoustic wavelengths [7]. Inside the nacelle, noise propagates mainly in the shaft direction of the turbofan. This effect tends to reduce the sound field complexity and can even lead to a one-dimensional sound field for low-frequency noise inside the nacelle. Therefore, the application of acoustic liners or AMM inside the nacelle is straightforward.

However, the situation is different in the case of open/unducted propellers. As no rotationally symmetric structures encase the propeller as the main noise-generating region, suitable locations on the airframe for the placement of noise-absorbing materials or, potentially, AMMs are not a priori clear. Secondly, the propeller sound field has a pronounced three-dimensional character as it is not encased by a duct-like structure. Due to this fact, the sound field of an open propeller is harder to control through passive acoustic materials (like resonators or AMMs) than the rather one-dimensional sound field inside a nacelle. The main reason for this is that destructive interference of different sound components is harder to achieve in a three-dimensional than in a one-dimensional sound field, given a fixed number of sound sources.

Besides the passive noise reduction measures mentioned in this section, aircraft propulsion noise can also be reduced through active measures like active noise canceling (ANC). Schmidt developed an ANC system for single-engine light propeller aircraft [8] and reports noise reductions of up to 5 dB close to the propeller plane. However, his research shows that an effective ANC system is complex and relatively large, see Figure 1. Consequently, using such systems would increase the drag and reduce the usable payload mass. The work of Schmidts demonstrates that an active system can overcome the difficulties of controlling a three-dimensional sound field stated in the paragraph above. However, this is only possible at the cost of high system complexity and weight. Thus, ANC systems are nowadays not considered for



Figure 1: flyable ANC system for a Bölkow Monsun Bo 209 using a linear arrangement of four anti-sound actuators in a tube-like structure [8]

the reduction of aircraft exterior noise from open propellers anymore.

In contrast to traditional tractor propeller aircraft like the Bo 209 in Figure 1, novel aircraft types for the transportation of cargo and passengers in urban areas often show multiple propellers that are installed close to the airframe. E.g., see the electric vertical take-off and landing (eVTOL) unmanned aerial vehicle (UAV) configuration in Figure 2. This leads to airframe scattered noise being a significant contributor to the overall noise emissions [9]. Due to the fact that airframe surfaces are significant noise contributors, installing AMM layers at those noise-emitting surfaces might have the potential to reduce noise.



Figure 2: cargo eVTOL UAV 'PW.Orca'

Noise Reduction Attempt with AMMs

In the recently finished research project Promedras, noise reduction measures for cargo drones were studied. One of those measures is the development and integration of AMM into the airframe.

Characterization of the Reference Aircraft

The reference aircraft in this research endeavor is the eVTOL UAV configuration 'PW.Orca'. This aircraft has separated power trains for the generation of lift in the hover phase and for the generation of forward thrust in the horizontal cruising flight phase. As can be seen in Figure 2, the two cruising propellers operate in close vicinity to the fuselage (inboard) and the hover booms (outboard). Numerical simulations have revealed that the contribution of the airframe scattered noise to the overall far-field noise of the aircraft is as big as the direct propeller noise [10]. Therefore, the placement of sound-absorbing AMM on airframe outer skin vicinities close to the propellers has the potential for significant cruise flight noise reductions.

AMM Design and Integration

Since the development of system noise prediction tools and the design of the AMM ran in parallel, it was decided to base the AMM design and integration on engineering judgment. Hence, the AMM unit cells were designed for later integration into the fuselage due to installation space availability. The idea was to flush the openings of the AMM cells with the outer skin of the fuselage in this area. Space-coiling AMM unit cells absorbing sound at the blade passing frequency (BPF) of the cruise (100 Hz) and hover propellers (260 Hz) were designed utilizing a combination of numerical simulation models and a so-called conditional generative adversarial network (GAN). According to Kundt tube measurements, the sound absorption coefficient α of the BPFs are between 70 to 80 %. However, the effectiveness of

the installed AMM could not be confirmed during noise measurements with an acoustic mock-up, see Figure 4. [11]

Optimization Approach

The setback in the initial and straightforward AMM design and integration demonstrates the need for a numerically efficient system-level noise prediction method to numerically assess the effect of AMM integration. The toolchain implementing such a method for the reference aircraft is basically taken over from [10]. It consists of a blade element momentum theory (BEMT) code to predict the aerodynamic loads of the propeller blades, including unsteady loading due to installation effects. Consecutively, the propeller sound field is computed from the blade loads utilizing a Ffowcs Williams and Hawkings (FW-H) solver. Lastly, the sound scattering of the propeller sound at the airframe is predicted with a boundary element method (BEM) solver. The openBEM code is employed for this purpose [12]. Hence, the far-field noise prediction consists of the direct propeller noise and the scattered airframe noise component.



Figure 3: propeller/AMM mockup for acoustic measurements

According to [12], the following relationship between overall sound with scattered component \mathbf{p} , incident sound \mathbf{p}_I , and collocation matrix \mathbf{A} holds:

$$0 = \mathbf{A}\mathbf{p} + 4\pi\mathbf{p}_I \quad (2)$$

where

$$\mathbf{p} = \mathbf{p}_I + \mathbf{p}_s \quad (3)$$

with scattered sound \mathbf{p}_s . In solving the scattering problem, Equation (2) is rearranged for \mathbf{p} :

$$\mathbf{p} = \mathbf{A}^{-1}(-4\pi\mathbf{p}_I) \quad (4)$$

The basic idea proposed by this paper is to model the AMM's effect on the scattered sound by manipulating the collocation matrix \mathbf{A} and the scattered sound component \mathbf{p}_s . To accomplish that, Equation (4) needs to be reformulated for \mathbf{p}_s , which is accomplished through inserting Equation (3) into Equation (2). After a few manipulation steps, this leads to

$$0 = \mathbf{p}_s - \tilde{\mathbf{A}}\mathbf{p}_I \quad (5)$$

with

$$\tilde{\mathbf{A}} = -\mathbf{A}^{-1}(\mathbf{A} + 4\pi\mathbf{I}) \quad (6)$$

The damping property of AMM is considered by multiplying all complex entries of $\tilde{\mathbf{A}}$ corresponding to surface mesh

nodes located in an AMM region with factor $(1 - \alpha)$. Consideration of the phase shift ($\Delta\phi$) property is accomplished through manipulating the phase of the incident sound pressure p_I arriving at nodes being located in an AMM region. Effectively, this changes the phase of the corresponding scattered sound. Figure 5 depicts all regions of the airframe surface being considered for AMM placement in the following, where case 2 corresponds to the AMM placement originally planned in the Promedras project. The overall AMM modeling approach is justified by the assumption that surface-spread assemblies of AMM unit cells “exhibit collectively an on-demand property, which can [...] be described by effective media parameters” [2], which are absorption coefficient and phase shift in this case.

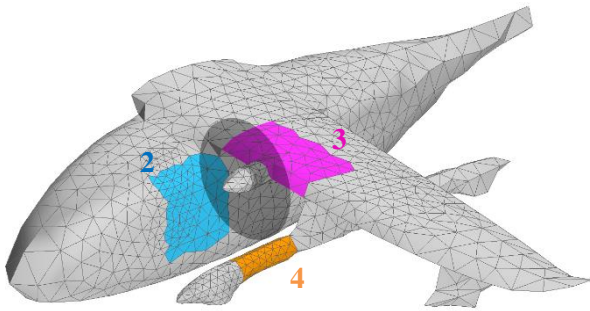


Figure 4: airframe surface mesh with AMM regions (all surfaces: 1; fuselage region close to propeller: 2 (blue); wing region close to propeller: 3 (magenta); boom region close to propeller: 4 (orange))

Additionally, the toolchain outlined in this section is integrated into an optimization framework that is able to minimize the sound power level ($L_{p,A}$) of the lower noise hemisphere. The absorption coefficients and phase shift properties of the considered AMM regions form the design variables (DVs) in this optimization problem.

Results

All studied and optimized AMM configurations are listed in Table 1. The cases range from the baseline case without AMM (case 0.1), the case with the Promedras project AMM design and integration (case 0.2), and six optimization cases (cases 1-6). The DVs are unconstrained, it is assumed that arbitrary combinations of absorption and phase shift properties are possible. In other words, this means that any “on-demand property” [2] can be delivered by the AMM.

Table 1: overview of study and optimization cases

No.	AMM regions	Description
0.1	No AMM considered	Reference case, no AMM considered
0.2	2	$\alpha=0.8, \Delta\phi=0$
1	2	DVs: only α
2	2	DVs: no restrictions
3	1	DVs: only α
4	1	DVs: no restrictions
5	2,3,4	DVs: only α
6	2,3,4	DVs: no restrictions

The study results are listed in Table 2 and allow for several conclusions:

1. The noise reduction of the Promedras AMM design and integration (case 0.2) is close to zero. This is consistent with the results from the AMM mock-up test.
2. The optimization algorithm only makes use of the absorption DV(s) if the phase shift DV is deactivated and locked at $\Delta\phi = 0$. In those cases, α is set to one (full absorption).
3. If no DV restrictions are imposed, the optimization algorithm only uses the phase shift DV(s) to minimize noise. The noise reduction is always higher compared to the cases where the phase shift DV is deactivated. The corresponding noise reduction mechanism is destructive interference between direct propeller noise and airframe scattered noise in the far-field (where the sound power level is computed).

Table 2: result overview, $\Delta L_{p,A}/\Delta L_{\max,A}$ refer to maximum level delta to reference case (without AMM)

No.	α [-]	$\Delta\phi$ [rad]	$\Delta L_{p,A}$ [dB(A)]	$\Delta L_{\max,A}$ [dB(A)]
0.1	-	-	0.0	0.0
0.2	0.8	0.0	0.1	0.6
1	1.0	0.0	0.4	0.8
2	0	2.4	0.9	1.5
3	1.0	0.0	2.1	2.9
4	0.0	-2.31	3.7	5.1
5	1.0, 1.0, 1.0	0.0, 0.0, 0.0	1.1	1.4
6	0.0, 0.0, 0.0	0.86, 1.08, -1.91	2.5	2.7

Discussion

Besides showing the noise reduction potential of AMM, the Table 2 results confirm the ineffectiveness of the initial AMM approach. Although the Kundt tube measurements confirmed the functionality of the unit cells, the straightforward integration approach did not lead to measurable system noise reductions.

Therefore, a key contribution of this work is the system-level noise prediction toolchain for the numerical assessment of AMM integration. This feature enables this work to identify realistic AMM configurations for which significant sound power reduction in the order of 3 dB(A) are predicted. The concurrent lack of efficient system-level noise prediction methods is identified as a major hindrance to the effective use of AMM in aircraft in the literature [5]. This work aims to overcome that problem and to leverage more effective AMM aircraft applications in the future.

AMMs for future aircraft integration projects should comply with the following requirements:

1. Thin layers with a maximum thickness in the order of $10^{-3}m$ that affect frequencies between 100-1000 Hz [7]

2. Ability to accomplish arbitrary phase shifts
3. AMMs have to be able to cope with near-field conditions (where pressure fluctuations at the airframe surface mainly stem from the rotating hydrodynamic pressure field of the propeller)
4. Aerodynamically smooth outer surface
5. Ideally AMMs should be effective for a broader frequency spectrum and not only distinct frequency peaks.

While AMMs satisfying some of the above-stated requirements are already known in the literature, it is unclear if state-of-the-art AMM methods allow for the design of new AMMs simultaneously satisfying all five requirements.

Both, ANC systems and envisioned future AMM applications (as suggested in this work) reduce the aircraft system noise through destructive interference of tonal propeller noise components. Therefore, it is meaningful to compare the two approaches in a bit more detail. While ANC systems lead to an increase in aircraft complexity, weight, and drag due to added components [8], the passive AMMs consume no energy and can directly be integrated into the airframe structure. Apart from their noise reduction function, they could potentially be designed such that they also contribute to carrying the structural loads of the aircraft cell. In combination with an aerodynamically smooth outer surface, future AMM integration into aircraft could be neutral in terms of weight and drag. However, there are also two advantageous aspects of active systems. E.g., they could be used for different propellers and flight speeds through active adjustment of the target frequency of the ANC system. Furthermore, they also work for aircraft configurations without significant airframe noise scattering (like the traditional one-engine tractor propeller aircraft).

Conclusion

Mitigating community noise from novel aircraft types will require a combination of different measures. The authors believe that passive AMM-based measures are an attractive alternative to traditional noise reduction measures since they reduce noise without adding much weight to the system and without affecting the propulsive efficiency [13] [14]. Future research should study the practical feasibility of such noise reduction systems.

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