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2023

Preprint:

This is an accepted article published in AIAA SciTech Forum. The final authenticated version is available online at: https://doi.org/10.2514/6.2023-0974

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A modularized level set topology optimization methodology is used to solve vibro-acoustic topology optimization problems. The main objective is to minimize the sound pressure generated by vibrating structures at predefined locations within specified frequency ranges in an interior domain. The plug-and-play style architecture provides freedom to choose from a variety of software for the solution of the governing equations. Taking advantage of this, the opensource finite element package FEniCS is used in combintation with dolfin adjoint which can automatically compute sensitivities through the use of semi-symbolic differentiation. The examples presented in this extended abstract are 2D and more general 3D examples will be presented in the final manuscript. The results indicate the capability of the proposed methodology to minimize the acoustic pressure response within specified operating frequency ranges. Additionally, structural compliance can also be used as a constraint to control the capacity of the optimized structures to carry mechanical loads.

The article has been accepted for publication in 2023 AIAA Science and Technology Forum and Exposition (SciTech). The extended full paper has the following DOI: 10.2514/6.2023-0974.

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Structural-acoustic optimization for sound reduction is important in aerospace designs. Many research studies have focused on vibro-acoustic problems considering objective functions such as maximization of the fundamental and higher frequencies [1], dynamic compliance minimization [2] and radiated sound power and sound pressure [3].

When sound related objectives are considered, typically the interaction between the vibrating structure and the acoustic domain needs to be considered. For example, Yoon et al. [4] proposed a density-based approach with a mixed displacement-pressure finite element (FEM) formulation for acoustic-structure coupling without explicit boundaries. Du et al. [3] considered the interaction of vibrating plates analyzed with 3D solid elements in contact with an exterior acoustic domain using density-based topology optimization. In this work weak coupling is assumed thus ignoring the acoustic pressure in the structural equation. Using the level set topology optimization method, Shu et al. [5] focused on interior noise reduction within a frequency range of interest. The shape sensitivity was computed based on the continuous adjoint approach, whereas FEM with remeshing was used to solve the coupled system of equations. Zhang et al. [6] presented an efficient approach for minimizing the radiated sound power from a vibrating structure in which the radiated sound power is predicted using the mapped acoustic radiation modes, corresponding to the velocity patterns mapped from the acoustic radiation modes of an interior spherical source onto a convex surface of the vibrating structure.

The challenging nature of this multiphysics problem makes it difficult to consider more realistic, 3D problems. Some of the challenges include the computational cost and complexity associated with the solution of the equations and the computation of sensitivities, especially when considering different frequency ranges. This work aims to address these challenges by employing a modularized level set topology optimization framework for minimizing the sound radiated from vibrating structures in an interior acoustic domain. Specifically, the objective is to minimize sound pressure at predefined points in the acoustic domain for a specified range of frequencies. The key advantages of the proposed approach include decoupling of the optimization part from the sensitivity computation algorithm. This is possible in the context of LSTO through a discrete adjoint approach based on a boundary perturbation scheme [7]. Any software of choice can be used for solving the governing equations whereas automatic differentiation can be used to compute element-based sensitivities. These can then be transformed into discrete adjoint shape sensitivities through perturbations of the boundary points that map the sensitivities with respect to element area fractions to sensitivities with respect to boundary movements. This plug-and-play capability ensures interoperability of the methodology since it is not limited to a specific software implementation. In this work, the opensource FEM software FEniCS [8] is employed in combination with the automatic differentiation tool dolfin adjoint [9] which has been shown to achieve very high efficiency through the use of symbolic representation using the high level abstraction of the UFL language. The preliminary results are presented in this abstract.

I. Modularized LSTO

The formulation of the level set topology optimization method used in this work is summarized in this section. The boundary is implicitly defined by the zero level set of an implicit function as

$$\begin{cases} \phi(\mathbf{x}) \geq 0 & \mathbf{x} \in \Omega \\ \phi(\mathbf{x}) = 0 & \mathbf{x} \in \Gamma \\ \phi(\mathbf{x}) < 0 & \mathbf{x} \notin \Omega \end{cases} \tag{1}$$

where ϕ is the level set function, Ω is the structural domain and Γ is the structural boundary. Conventionally, the implicit function is initialized as a signed distance function.

The structural boundary is optimized by iteratively solving the following Hamilton-Jacobi equation

$$\frac{\partial \phi(\mathbf{x}, t)}{\partial t} + |\nabla \phi(\mathbf{x})| \, V_n(\mathbf{x}) = 0 \tag{2}$$

where t is a fictitious time for the level set evolution and V_n is the normal velocity.

The velocities needed to update the level set function are provided by the solution of the following linearized optimization problem,

$$\begin{aligned} &\underset{V_{n,j}}{\textbf{minimize}} && \Delta F = \sum_j (s_{f,j} A_j \Delta t V_{n,j}) \\ &\textbf{subject to} && \Delta G_m = \sum j (s_{m,j} A_j \Delta t V_{n,j}) \leq g_m \quad m = 1, 2, ..., N_g \end{aligned} \tag{3}$$

where F and G_m are the objective function and mth constraint function, respectively, g_m is the target constraint value for the mth constraint, N_g is the total number of constraints. The index j refers to the jth discrete boundary point, $V_{n,j}$ is the normal velocity, $s_{f,j}$ and $s_{gm,j}$ are the boundary point sensitivities at point j for the objective and mth constraint function, respectively and A_j is the area of the local boundary around the boundary point j. The key element of the modularized LSTO used in this work is the computation of boundary point sensitivities using the discrete adjoint method. In this scheme, a given boundary point is perturbed implicitly by locally modifying the level-set functions around the boundary point to compute local perturbation sensitivities. Here, the local perturbation sensitivities can be understood as the amount of the changes in element densities with respect to a small movement of boundary points in the outward normal direction. Further details can be found in [10].

II. Acoustic-Structure Interaction

For the solution of the governing equations the FEM is used through the opensource software FEniCS. The acoustic domain is governed by the Helmholtz equation

$$p_{ii} + \frac{\omega^2}{c_a^2} p = 0 \quad in \quad \Omega_{acoustic} \tag{4}$$

whereas the dynamic equation for the solid domain can be expressed as

$$\sigma_{ij,j}(\mathbf{u}) + \omega^2 \rho_s u_i = 0 \quad in \quad \Omega_{solid} \tag{5}$$

where p is the acoustic pressure, ω is the the frequency, c_a is the wave propagation velocity, σ_{ij} is the stress tensor and ρ_s is the solid density. In the examples studied in this work the acoustic domain is predefined and remains unchanged throughout optimization, thus the acoustic-structure interface is explicitly defined. Furthermore, weak coupling is assumed, thus the acoustic pressure acting on the structure is ignored. Consequently, the equations can be solved sequentially with the solid displacement imposed on the acoustic domain through the interface once the structural equation is solved.

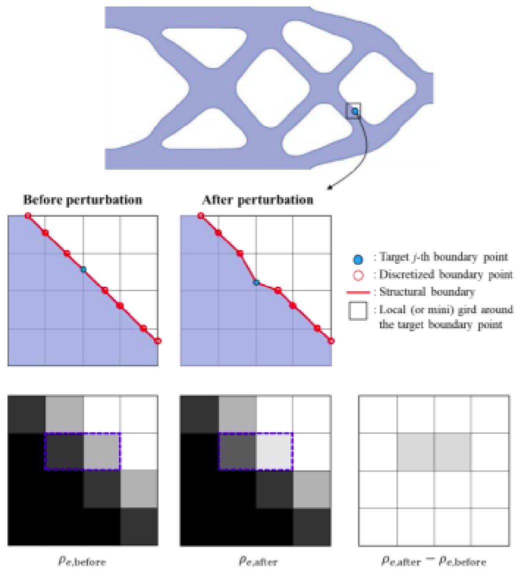
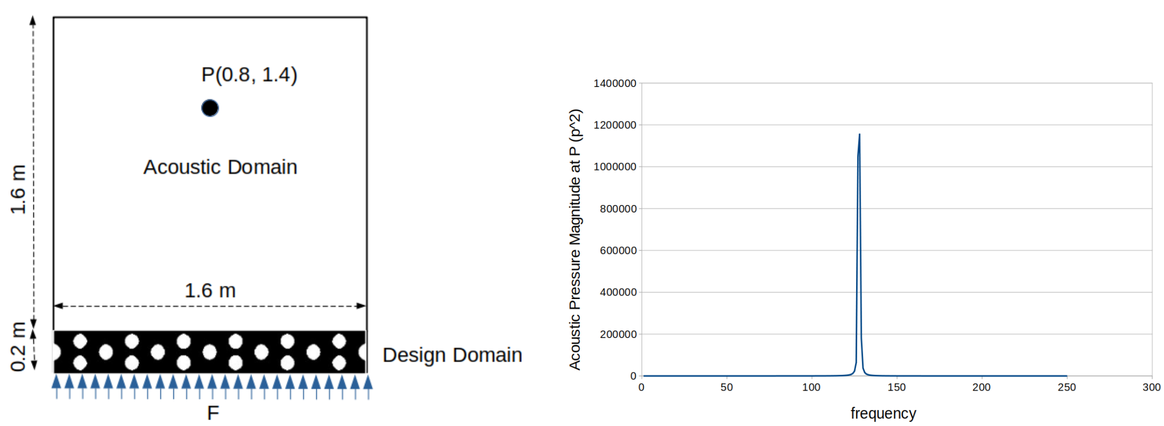


Fig. 1 Computation of boundary sensitivities through the local perturbation scheme and the discrete adjoint method. [10]

III. Examples

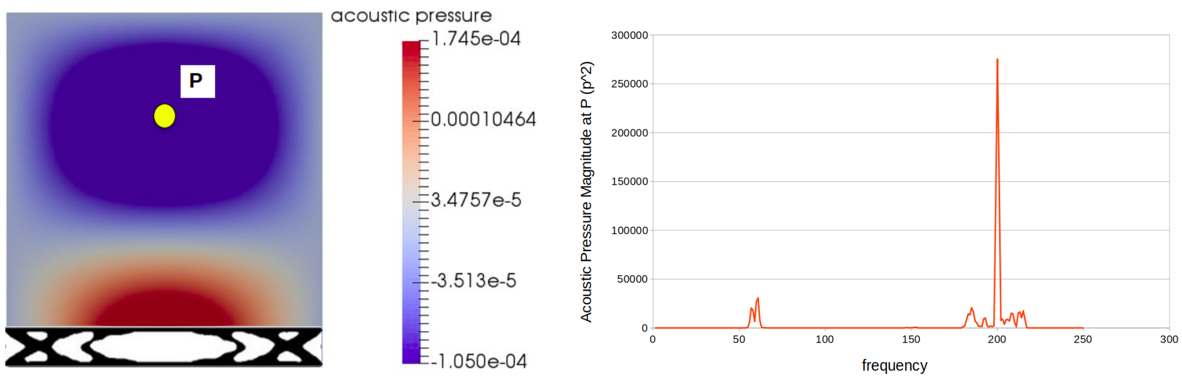
The example presented here consists of a vibrating beam in contact with an enclosed acoustic domain as shown in Fig. 2 (a) [5]. The beam is subjected to a harmonic load at the bottom edge. For the beam, the Young's modulus is 6.9 $\times 10^{10}$, Poisson's ration is 0.3 and density is equal to $7730 kg/m^3$. The acoustic medium is assumed to be air with density equal to $1.21 kg/m^3$ and wave propagation velocity $344 m/s$. Based on the initial beam topology shown in Fig. 2 (a), the frequency response at the point of interest, P, is illustrated in Fig. 2 (b). It can be seen that a resonance frequency appears in the range between 100 Hz and 150 Hz. The aim is to minimize the acoustic pressure at P within that frequency range considering a volume constraint of 50%. The trapezoidal rule is used for the integration of the acoustic pressure within the specified range and the computation of the total sensitivity. The optimum solution along with the pressure distribution in the acoustic region are shown in Fig. 3 (a) whereas the resulting frequency response is provided in Fig. 3 (b). As can be seen, the optimizer has pushed the response frequencies outside the specified range.



(a) (b)

Fig. 2 Example setup: (a) Acoustic domain with point of interest P and initial beam topology and (b) Frequency response at point P.

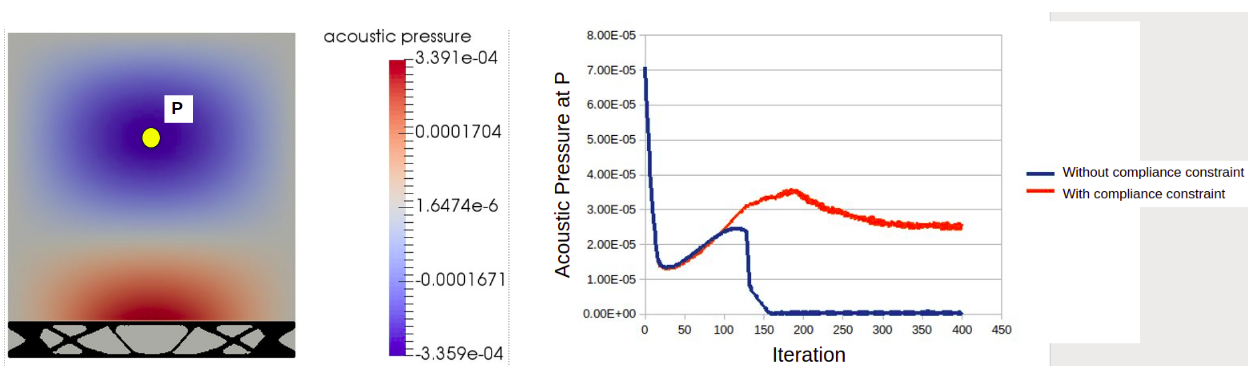
Figure 4 (a) illustrates the optimum solution when a compliance constraint is considered along with the volume



(a) (b)

Fig. 3 (a) Optimum solution for acoustic pressure minimization at point *P* under volume constraint along with the resulting pressure field. (b) Freqency response at *P* for the optimum topology.

constraint which adds to the structure an additional functionality of load-carrying as well as the acoustics functionality. As can be seen in the convergence plots in Figure 4 (b), the compliance constraint increases the final objective value as expected. It is also apparent that the reduction compared to the initial value remains significant.



(a) (b)

Fig. 4 (a) Optimum solution for acoustic pressure minimization at *P* under volume and structural compliance constraints along with the resulting pressure field. (b) Convergence plot with and without the compliance constraint.

IV. Conclusion

In this work we minimize the acoustic pressure at predefined points inside an acoustic domain in contact with vibrating structures for specified frenquency ranges. A modularized LSTO software is used which allows for automatic computation of the sensitivities and provides a well defined structural design. The obtained optimum solutions push acoustic pressure peaks outside the specified frequency range in order to minimize the acoustic pressure response. To ensure the structure is still capable of carrying mechanical loads, we included a compliance constraint in our examples. The effect is that the optimizer tends to increase the objective in order to satisfy the constraint. Nevertheless the acoustic pressure reduction is still significant compared to the initial value. The 2D examples presented in this abstract will be extended into 3D and different shapes of interior domain in the full manuscript.

Aknowledgements

Andreas Neofytou, Jaeyub Hyun and H. Alicia Kim, gratefully acknowledge the financial support from Honda Research Institute Europe (HRI-EU).

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