REDUCTION OF THE NOISE RADIATED BY
SUBMERGED STRUCTURES: OPTIMISATION OF
LAYERED COATINGS
B. Nicolas-Vullierme, D. Osmont

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We propose an optimization process in order to design optimal viscoelastic (isotropic or transverse-isotropic) layered coatings for submerged structures. These coatings are optimized in order to reduce the far-field pressure radiated by the structure when subjected to time-harmonic prescribed forces or displacements. These coatings have to satisfy three inequality constraints: maximum thickness, maximum and minimum mean value mass density, maximum mean value compressibility. In order to define a fast and efficient optimization process, we have considered the structure to be an infinite plate radiating in a semi-infinite fluid and the coating to be an infinite layered medium. The optimization has to provide coatings feasible with respect to the constraints and inducing the maximum far-field radiated noise attenuation in the largest frequency range. We present the software named OPTIMASQ we have developed for this purpose and some of the results we have obtained which prove the efficiency of the optimization process even for severe constraints.

1. INTRODUCTION

We propose an optimization process in order to design optimal viscoelastic (isotropic or transverse-isotropic) layered coatings for submerged structures. These coatings are optimized in order to reduce the far-field pressure radiated by the structure when subjected to time-harmonic prescribed forces or displacements. These coatings have to satisfy three inequality constraints: maximum thickness, maximum and minimum mean value mass density, maximum mean value compressibility. Optimisation processes have been developed for particular applications [ref. 1 to 5] but not, to our knowledge, for the application we present here.

In order to define an efficient optimization process we propose to design optimal layered coatings for an infinite plate. This plate, subjected to prescribed time harmonic forces or displacement radiates far-field pressure in a semi infinite fluid (Figure 1). In the following we will only refer to prescribed forces. The prescribed forces may be:

- sinusoidal forces reading \( S_0 \exp(ik_2x_2+ik_3x_3-i\omega t) \)
- forces reading \( S_0s(x_2,x_3)\exp(-i\omega t) \) where \( s(x_2,x_3) \) is a scalar function having Fourier type decomposition:
  \[
  s(x_2,x_3) = \frac{L_0}{2\pi} \int_{-\infty}^{\infty} \hat{s}(k_2,k_3) \exp(ik_2x_2+ik_3x_3) \, dk_2 \, dk_3,
  \]

where \( L_0 \) is a reference length. For example, for a point force \( \hat{s}(k_2,k_3) = 1 \) for every \( (k_2,k_3) \).

Let \( p \) be the far-field pressure radiated in the fluid. In order to define the reduction of this pressure we introduce measures of this pressure. Let \( \Sigma \) be a control surface related to the prescribed force, the measures of the far field pressure read \( M_m(p) = \frac{1}{\Sigma} |\int \rho(x,\omega) \omega^m \, d\Sigma|^{1/m} \) for \( 1 < m < \infty \). For example, for a sinusoidal force, the control surface is part of a plane parallel to the plate; for a point force, the control surface is a half-sphere of great radius.
Let \( p_X \) and \( p_0 \) be the far field pressures when the plate is covered or not covered with the layered coating \( X \). The control surface must satisfy the condition that the ratio \( M_m(p_X)/M_m(p_0) \) is independent of the distance of the control surface to the plate. Then it is possible to define the attenuation \( A_m \) of the radiated noise using the following formula:

\[
A_m = -20 \log_{10}(M_m(p_X)/M_m(p_0)).
\]

It is to be noticed that for \( m=1, m=2, m \) large, \( M_m(p) \) respectively the mean-value of the pressure, the quadratic mean-value of the pressure, close to the maximum pressure relative to the control surface. The corresponding attenuations will be named "mean-value" attenuation, "quadratic mean-value" attenuation and "minimum value" attenuation.

As it is desired to design an optimal layered coating having the best radiated noise attenuation capabilities for prescribed time harmonic forces \( S_0 \exp(ik_2 x_2 + ik_3 x_3 - i \omega t) \) in the range of circular frequencies \( \Omega = [\omega_1, \omega_2] \), it is natural to introduce the constraint optimization problem which reads:

Find a feasible layered coating \( X \) so that the objective function:

\[
F_m(x, \omega_1, \omega_2) = \frac{\int_\Omega [\int_{\Sigma} |p_X| \rho d\Sigma] d\omega}{\int_\Omega [\int_{\Sigma} |p_0| \rho d\Sigma] d\omega}
\]

be minimum.

The feasibility of the coating refers to the total thickness, mean-value mass density and compressibility constraints which will be named "functional" constraints but also to "physical constraints" making it possible to be sure that the thickness and mechanical constants of each layer have physical meaning.

\section*{2) THE OPTIMIZATION PROCESS}

We will not describe in details the optimization process but will only present the main points. These points are:

1) the optimization process is based on a conjugate gradient algorithm needing only the computation of the objective function \( F_m \) and of the first derivatives of this function with respect to the thicknesses and mechanical constants of the layers. These computations only require the computation of the transmission and first derivatives of the transmission of the layered coating for sinusoidal time-harmonic forces inducing radiated pressure, namely sinusoidal time-harmonic forces reading \( S_0 \exp(ik_2 x_2 + ik_3 x_3 - i \omega t) \) for which \((k_2)^2 + (k_3)^2)^{1/2} \leq \omega/c_f \) where \( c_f \) is the speed of sound in the fluid.

2) the constraints are taken into account by means of mixed penalty functions

3) the optimization parameters are:
   - the thickness of each layer
   - the mass density of each layer
   - the elastic constants of each layer, two constants for isotropic media, four constants for transverse-isotropic media
   - two viscoelastic constants \( a_i, i=1,2 \) which make it possible to define viscoelastic constants \( E^* \) related to the elastic constant \( E \) by means of the relation \( E^* = E(1 + a) \) where \( a \) stands for \( a_1 \) or \( a_2 \).

4) "physical constraints" may be set for each layer in order that:
   - the thickness, the mass density and the viscoelastic constants \( a_i \) lie between a minimum and a maximum value
   - the elastic constant have physical meaning

5) "functional constraints" may be set for the layered coating in order that the total thickness, the mean-value mass density and the mean-value compressibility lie between a minimum and a maximum value.

\section*{3) SOME RESULTS}

We present, figures 2 and 3, results obtained for:

- a plate subjected to time harmonic point-forces
- one to four viscoelastic and isotropic layers coatings
- a complete set of "functional" constraints including inequality constraints for the total thickness and mean-value compressibility and an equality constraint for the mean-value mass density.

The optimization has been done in order to obtain maximum "quadratic mean-value" attenuations in the widest
frequency range centered on the reference frequency $f_0$. We have done optimizations for one, two, three and four layers coatings. We present two results for optimized one layer coatings and one result for optimized two, three and four layers coatings. A reference coating is also presented which is the coating from which the one layer optimization starts.

Figure 2 shows the "quadratic mean-value" attenuation of the radiated far field noise versus the reduced frequency. This figure shows that multi-layered coatings are much better than one layer coatings. This is due to the equality constraint on the mean-value mass density. This figure also shows that for multi-layered coatings, the attenuations are of the same order of magnitude and that increasing the number of layers makes it possible to lower the frequency from which positive attenuations are obtained. It is to be remarked that the low level of the attenuations obtained is related to the severe "functional" constraints prescribed for this case.

![Figure 2](image1)

Figure 2 shows the "minimum value" attenuation of the radiated far field noise versus the reduced frequency. This figure shows that the improvements of the "minimum value" attenuation are less than the improvements of "quadratic mean-value" attenuation. This is due to the inequality constraint on the mean-value compressibility.

![Figure 3](image2)

Figure 3
The results presented prove the optimization process we use in the software OPTIMASQ we have developed is able to provide significant improvements of the attenuation of the noise radiated in the fluid even if severe "functional" constraints are prescribed which make it impossible to retain usual solutions obtained for such layers in acoustics.

4) CONCLUSION

The optimization process we present is a fast and efficient process to design layered coatings, especially when severe constraints on total thickness, mean value mass density and compressibility are prescribed. Notice that this process requires some physical insight to be used efficiently due to the difficulty to impose the whole set of constraints at the same time. Notice that a particular attention has to be paid to the forces and to the measure for which the optimization is done, their choice may have great influence on the results.

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