Integrated Topology and Shape Optimization in Structural Design of a Multiple Tuned Mass Damper

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Abstract

Multiple Tuned Mass Dampers (MTMD) are passive solutions efficient to reduce vibrations for many engineering applications: theoretical studies show the ability of such devices to control one target mode of a main structure. In such studies, MTMD often consist in a set of spring, mass and dashpot system, with associated mechanical properties in terms of stiffness, mass and damping, arbitrary added to the structure. Only few works deal with the technological realization of the MTMD as the effective design is not an obvious work. The proposed paper focuses on the topological design of a MTMD integrated in a structure to control. Firstly, an optimal distribution of natural frequencies for the resonators composing the MTMD is defined using an optimization strategy based on the vibratory energy on a frequency band around the mode to control. The key point of the work is then to define an architected and integrated solution satisfying multiple criteria: respect the identified repartition of frequencies, respect a given mass criteria to limit the eventual added charge, respect stress constraints to ensure the mechanical behaviour of the solution to known severe solicitations. Two strategies are developed and applied to a designed architecture composed of a weight and two blades. The first one is a parametric optimization based on the parameters of the CAD design, the second one is a shape optimization using an adjoint solver as a gradient-based optimization algorithm. The approaches are illustrated in the case of a main structure consisting in a wing of an airplane model for which the MTMD is embedded in the matter to control the first bending mode.

Keywords: Multiple Tuned Mass Damper, Vibration Control, Parametric Optimization, Shape Optimization, Modal Effective Mass

1 Introduction

Multiple Tuned Mass Dampers (MTMD) are passive mechanical devices designed to absorb energy from a main structure on a frequency bandwidth. Despite all the research realized on the characteristics of such systems, there are not so many MTMD systems deployed in the industry except in civil engineering. Recently, in mechanical engineering, Carcaterra [1] developed a MTMD using cantilever beams as resonators for aerospace structures. Sangiuliano [2] has also developed a MTMD network to reduce vibrations on a rear shock tower in a car. The main purpose of this extended abstract is to develop topology and shape optimization tools in the context of MTMDs in order to design components adapted to industrial applications and integrated into the structures to control. In this context two strategies are considered : the first one is a parametric topological optimization for which the parameters of a given geometry for the TMD are optimized, and the second one is a shape optimization for which the shape of the TMD is optimized by controlling its boundary. Only results

obtained with the parametric optimization are presented here for sake of brevety.
The first step of the methodology is to determine the dynamic characteristics for each TMD in the network. Let consider a MTMD with n tuned mass dampers characterized by a mass m_j, damping $'\zeta_j$ and stiffness k_j ($1 \leq j \leq n$, Figure 1). For weight constraints, the added mass is limited to 1% of the mass M of the main structure, and this mass is equireparted between all the TMDs such that $m_j = \frac{0.01M}{n}$. The damping is fixed, only the stiffness properties k_j have to be determined. This is done solving an optimization problem based on the minimization of the strain energy of the main structure on a frequency bandwidth around the mode to control. It has been widely done in former papers [3,4,5,6] but still can be improved [7,8] for a better robustness. Following this optimization process, the optimal eigenfrequency repartition ($f_j = \frac{1}{2\pi}\sqrt{\frac{k_j}{m_j}}$) for the MTMD is determined, and the question is now to design the devices.

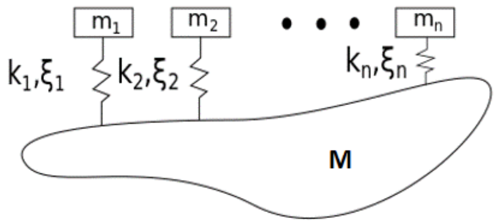

Figure 1: Primary structure mounted with discretized tuned mass dampers

Optimizations methods were applied on academic structures for confidentiality reasons.

2 Formulation of the optimization problem

The parametric topology optimization is done with the objective of maximizing the effectiveness of the TMD : this effectiveness can be linked to the effective modal mass of the TMD, the higher the mass, the more energy the TMD absorbs, the higher the vibration reduction is. The largest effective modal mass being the physical mass of the TMD, the objective is to find geometrical parameters to reach this value. The developed procedure thus consists in minimizing for each TMD the relative gap between its effective modal mass $m_{eff,j}$ and its physical mass m_j with the constraint on the TMD eigenfrequency equal to the one identified in the MTMD optimization process , and with a stress constraint to ensure the mechanical strength of the TMD,

Given	f_j $(1 \leq j \leq n)$
Find	parameters
Minimizing	$\frac{\lvert m_{eff,j} - m_j \rvert}{m_j}$
Subject to	$f = f_j$ where f is the eigenfrequency of the TMD
Subject to	$\sigma_j \leq \sigma_M$ where σ_M a fixed limit stress and σ_j the Von Mises stress in the TMD

$m_{eff,j}$ is the effective modal mass for the active mode ϕ (the first one in general) of the $j-th$ TMD such that

$$m_{eff,j} = \frac{(\phi^T \mathbf{M} U_d)^2}{\phi^T \mathbf{M} \phi} \tag{1}$$

where $\mathbf{M}$ is the global mass matrix of the TMD, U_d a unidirectionnel vector.

3 Application

The primary structure is a model of a plane used in Femto laboratory for both students and research activities. Plane dynamics is perfectly known and the first bending mode of the plane will be the one that needs to be controlled (Figure 2)

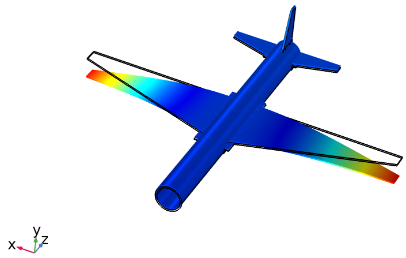

Figure 2: Bending eigenmode to control for the plane application

The MTMD system consists in a network of tuned mass dampers presenting a cross section (Figure 3). They are set at the free end of the wing (Figure 4). Firstly, a sensitivity analysis is run to reduce the number of

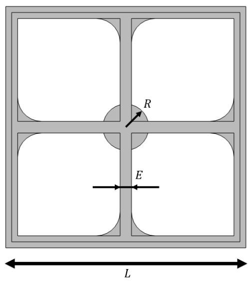

Figure 3: Cross Section Tuned Mass Damper

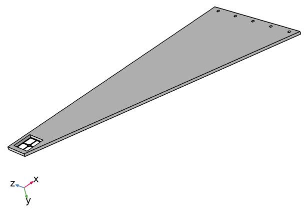

Figure 4: TMD integrated in the plane's wing

geometrical parameters in the optimization process : the more influent parameters are precised on figure 3. It allows to find that the radius R, thickness t, the beam width support E and the framework length L are the most sensitive parameters, and they are chosen as parameters for the TMD optimization. The optimization problem is solved using the fmincon function available in the optimization toolbox of the mathematical software MatLab®. Optimization criteria are such that the process ends when change in the objective function and in the variables is less than 10^{-6}. The starting point is arbitrary chosen with no impact checked on the result. Figure 5 presents the values of the optimization variables at each iteration as well as the effective modal mass. It globally leads to an increase of the effective modal mass that reaches 50% of the physical mass. The analysis of the vibratory response of the main structure with the optimized TMDs is in progress.

4 Conclusion and perspective

The paper is dedicated to topology optimization of Tuned Mass Dampers constituting a MTMD for a practical realization of the devices in an industrial application. The optimal eigenfrequency repartition of the TMDs is firstly determined using an approach based on energy minimization, and the purpose is to design the adequate TMDs to obtained these frequencies. To improve the effectiveness of the devices, the proposed methodology is based on the maximization of the effective modal mass for each TMD, or in the same way the minimization between this mass and the physical mass. Results presented in the abstract focus on a parametric optimization for which geometrical parameters are used as optimization variables. Optimal parameters can be identified and effectively lead to an increase of the effective modal mass. Work remains to do to analyze the performance of the MTMD. As parametric optimization costs a lot of time and as a certain amount of parameters is needed to reach unexpected geometry, the next idea is to used shape optimization. Hence, the principle of this method is to declare nodes locations as variables in an optimization problem. Then an adjoint solver is used as a gradient-based optimization algorithm in order to reduce computation time. This approach will be applied to compare the optimal design to the one given by a parametric study.

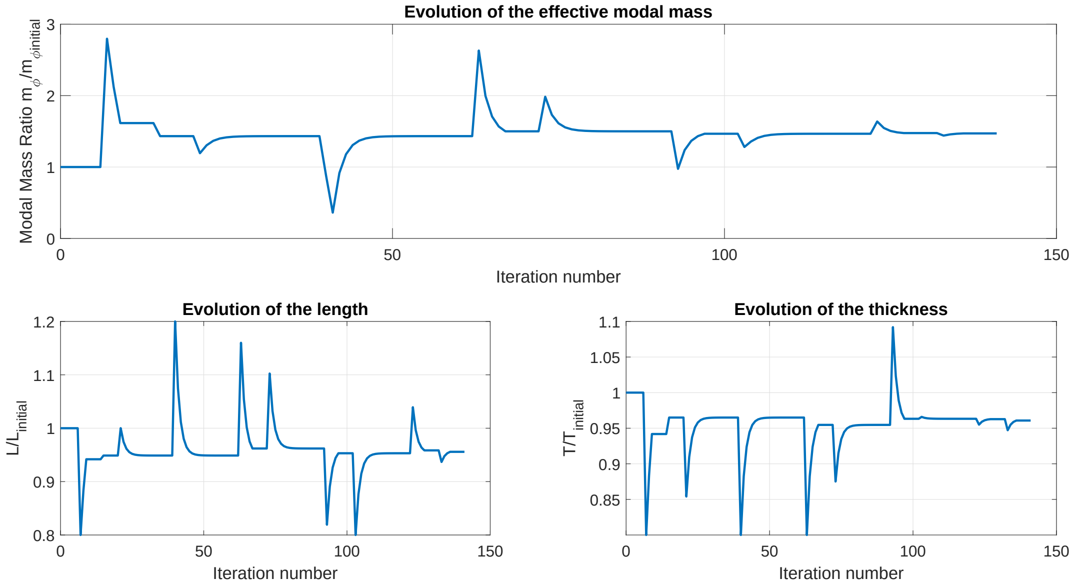

Figure 5: Evolution of the optimization variables and of the effective modal mass of one TMD during the optimization process

5 Acknowledgements and references

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