Mechanical Systems and Signal Processing 70-71 (2016) 699–713

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Shaping frequency response of a vibrating plate for passive and active control applications by simultaneous optimization of arrangement of additional masses and ribs. Part II: Optimization

Stanislaw Wrona, Marek Pawelczyk *

Institute of Automatic Control, Silesian University of Technology, Akademicka 16, 44-100 Gliwice, Poland

ARTICLE INFO

Article history:
Received 12 March 2015
Received in revised form
20 June 2015
Accepted 3 August 2015
Available online 8 September 2015

Keywords:
Structural control
Frequency response shaping
Active noise control
Vibrating plate
Optimization

ABSTRACT

It was shown in Part I that an ability to shape frequency response of a vibrating plate according to precisely defined demands has a very high practical potential. It can be used to improve acoustic radiation of the plate for required frequencies or enhance acoustic isolation of noise barriers and device casings. It can be used for both passive and active control. The proposed method is based on mounting several additional ribs and masses (passive and/or active) to the plate surface at locations followed from an optimisation process. In Part I a relevant model of such structure, as a function of arrangement of the additional elements was derived and validated. The model allows calculating natural frequencies and mode-shapes of the whole structure. The aim of this companion paper, Part II, is to present the second stage of the method. This is an optimization process that results in arrangement of the elements guaranteeing desired plate frequency response, and enhancement of controllability and observability measures. For that purpose appropriate cost functions, and constraints followed from technological feasibility are defined. Then, a memetic algorithm is employed to obtain a numerical solution with parameters of the arrangement. The optimization results are initially presented for simple cases to validate the method. Then, more complex scenarios are analysed with very special demands concerning the frequency response to present the full potential of the method. Subsequently, a laboratory experiment is presented and discussed. Finally, other areas of applications of the proposed method are shown and conclusions for future research are drawn.

1. Introduction

Vibrating plates have met considerable interest of researchers and practitioners because of their high potential for two kinds of applications. They can be used as structural sound sources highly resistant to unfavourable environmental conditions, or as efficient noise barriers. If it were possible to appropriately locate resonances and anti-resonances, sound power radiated could be significantly increased [1–5], energy harvesting efficiency could be enhanced [6], a higher passive attenuation of noise passing through could be obtained or active structural control ability could be improved [7–9], dependent on the given application.

* Corresponding author.
E-mail addresses: Stanislaw.Wrona@polsl.pl (S. Wrona), Marek.Pawelczyk@polsl.pl (M. Pawelczyk).

http://dx.doi.org/10.1016/j.ymssp.2015.08.017
0888-3270/

Nomenclature

Roman Symbols

a	Length of the plate
$A_{r,i}$	Cross-sectional area of the i-th rib
b	Width of the plate
E	Young modulus of the plate
$e_{r,i}$	Width of the i-th rib
h	Plate thickness
$h_{r,i}$	Thickness of the i-th rib
$I_{ax,i}$, $I_{sx,i}$, $I_{mx,i}$, $I_{ay,i}$, $I_{sy,i}$, $I_{my,i}$	Moments of inertia of the i-th actuator, sensor and additional
$I_{r,i}$	Second moment of inertia about the plate mid-plane of the i-th rib
$J_{r,i}$	Torsional constant of the i-th rib
J	Cost function
J_{opt}	Value of a cost function for particular solution
$k_{r,i}$	Radius of gyration of the i-th rib
$m_{a,i}$, $m_{s,i}$, $m_{m,i}$	Mass of the i-th actuator, sensor and additional mass, respectively
N	Number of eigenmodes considered
N_a, N_s, N_m, N_r	Number of actuators, sensors, additional masses and ribs
i, j, k	Positive integers
(x, y)	Global coordinates
$\lambda_{c,i}$, $\lambda_{o,i}$	i-th elements on the diagonal of the controllability and observability Gramian matrices, respectively
ν_x, ν_y	Poisson's ratios of the plate
ρ_p	Mass density of the plate material
$\rho_{r,i}$	Mass density of the i-th rib
ω_i	i-th eigenfrequency

This is the second of two companion papers offering a complete method for shaping frequency response of a plate in strict accordance with the requirements, which has been submitted by the authors as a patent application [10]. In the literature there are no reported methods of similar capabilities. In the proposed method the frequency shaping is obtained by simultaneous optimisation of arrangement of additional masses and ribs on the plate surface. For active control purposes, arrangement of actuators and sensors is included in the optimisation process to improve controllability and observability of the structure. The benefit of this approach is that they can be mounted on the inner side of the plate, and do not change appearance of the outer side. Therefore, the method is especially attractive for designing device casings.

The modelling of vibrating plates together with all those elements was discussed in detail in Part I. The model was validated by means of numerical simulations and laboratory experiments, and it was compared with other models. In this paper, Part II, an optimization problem is formulated to find proper arrangement for the elements. It is shown by several representative examples how the cost function can be built to reflect frequency response demands. Constraints for the optimisation are related mainly to the maximum dimensions and mass of the created structure, as well as types of actuators and sensors if active control is concerned.

Due to complexity of the search space, a memetic algorithm is proposed to be used for solving the optimisation problem. Numerical algorithms have been used in the literature for simpler problems. For instance, a genetic algorithm has been used to optimize locations of piezoelectric actuators based on the cost function utilizing the modified H_∞ norm [11]. Performance of a linear quadratic regulator (LQR) was considered as an objective in piezoelectric sensor/actuator pairs optimization [12]. The spatial H_2 norm of the closed-loop system has been utilized as the performance index [13]. However, usually it was assumed that mounted elements did not affect the plate frequency response itself. That assumption is justified in case of piezoelectric actuators or sensors. However, in case of, e.g. inertial actuators used to control thin light-weight plates, it is crucial to take into account the impact of their mass. Such problem has been analysed and discussed by the authors in [14]. A memetic algorithm has proven its efficiency. That research inspired the method applied for the present work. However, this optimization problem is substantially more complex. Firstly, because of ribs, which are included additionally in these considerations. Secondly, because of higher number of elements considered and due to simultaneous optimization of their shape along with location and orientation. Moreover, the optimization problem becomes multi-objective when the frequency response is shaped along with ensuring sufficient controllability and observability for the active control system.

This paper is divided into four main sections. Section 2 is devoted to proper formulation of the optimization problem. The representation of the search space and an individual for the memetic algorithm are described. Then, the cost functions are discussed. Section 3 presents the optimization results for several examples. The calculations are initially performed for simple cases to validate the method. Subsequently, more complex scenarios are analysed to present the full potential of the method. Section 4 presents an exemplary application, where the idea of shaping frequency response is very useful. It also describes and discusses a related laboratory experiment. The advantages and limits of the method are discussed and conclusions for future research are drawn.

2. Optimization process

In this section, the optimization process of arrangement of additional elements mounted on a vibrating plate surface in order to obtain shaped frequency response according to precisely defined demands, and enhance controllability and observability measures is described. The memetic algorithm is proposed to solve this problem. It is briefly introduced, with emphasis on proper definition of an *individual*. Finally, the set of possible cost function types are discussed.