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ScienceDirect

Procedia Engineering 199 (2017) 330–335

Procedia Engineering

www.elsevier.com/locate/procedia

X International Conference on Structural Dynamics, EURODYN 2017

Development of a non-destructive bell-tuning technique through optimized structural modifications

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Abstract

Carillons are musical instruments constituted by a set of bells that forms a musical scale encompassing several octaves. For carillons to work in a musically satisfying manner, bell tuners pre-define commonly accepted harmonic relationships between the first five modal frequencies of all bells, typically 0.5:1:1.2:1.5:2 (internal tuning), and a specific target pitch for each bell (external tuning) in order to suit a given musical scale. Currently, bell-tuning is performed by removing metal on the inside of the bell wall. In most cases this process is made empirically, through trial and error, frequently leading to ineffective results. Moreover, this approach can weaken the bell structure and is irreversible, a far from ideal situation in the case of historical carillons. Following our recent work on bar tuning, this paper addresses a non-destructive multimodal tuning method, which consists of attaching suitably designed masses to the bells, in order to comply with the pre-defined set of target frequencies. This is achieved through the combination of dynamical modelling and structural modification techniques with optimization methods, in order to compute the optimal location and magnitude of the tuning masses. First, a full-sized finite element model of a real-life bell is used to compute the modal properties of the original, imperfectly tuned, system. A physical model based on the modal formulation is then built from the modes of the original system, allowing the reduction of the number of equations by several orders of magnitude, compared to the finite element model. This modal formulation is particularly effective for the subsequent iterative optimization process, leading to significant improvements in convergence, as well as computational efficiency. Outcomes from this work attest the effectiveness and robustness of the proposed tuning method and provide encouraging results towards the development of feasible non-destructive methods for bell-tuning.

Keywords: Physical modeling; Structural modifications; Multi-modal optimization; Axisymmetric structures; Bell tuning.

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1877-7058 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the organizing committee of EURODYN 2017.
10.1016/j.proeng.2017.09.019

1. Introduction

Musical bells are three-dimensional shell-like structures designed toward a specific dynamic behavior, in which the frequencies of a few low-order modes must fall into a sequence of musical intervals. This tuning is actually crucial for musical purposes, since a well-sounded note must convey a strong sense of pitch with a specific overtone structure [1]. In practice, the tuning of a bell is achieved after the process of casting, by removing some of the bell material using a tool-shop lathe. According to the amount and location of the removed metal, the bell modal frequencies increase or decrease. In practice, this is a very challenging issue because every structural change affects many vibrational modes at different degrees. From the knowledge of empirical design rules discovered in the 17th century, bellfounders look for a suitable compromise between accurate tuning, aesthetic design and geometrical constraints, and in these terms address an optimization problem. Even if numerical tools are sometimes used for the design of modern bells, it is worth noting that the tuning process is still necessary for final tuning adjustments.

The original motivation of this work comes from the search for innovative solutions for bell tuning, toward the development of a non-destructive approach which could be especially adequate for improving the tuning deficiencies of historical bells. Cultural objects indeed require careful preservation methods, and the traditional approach, which irreversibly damages the bell structure, seems today unacceptable for reasons of preservation. Interestingly, new ways can be sought for bell tuning, especially by noting that the problem is very close to other structural modification problems found in engineering applications, where the most common objective is to relocate a natural frequency of the system, usually in order to avoid resonance phenomena.

Inspired by such concepts, we propose in this work an innovative non-destructive and reversible strategy for the multi-modal tuning of bells, where the use of auxiliary attached masses is considered to change the bell vibrational properties. We reckon that this is the first time that such a solution is implemented for the problem at hand. Nevertheless, the proposed approach is rooted on well-established formulations [2–4], and also benefits from encouraging results recently obtained by the authors for tuning bar musical instruments, by coupling physical modeling and optimization techniques [5]. In this paper, we start by presenting the dynamical equations for structural modifications of a bell-like structure, by considering mass changes, and adopting a modal representation for the system dynamics. The bell tuning problem is then stated and formulated as a minimization problem, where the optimization algorithm inputs are the modal parameters of the unconstrained bell. The optimization strategy is presented on a case study, consisting on improving the tuning of a laboratory bell. The preliminary results obtained are quite encouraging and demonstrate the effectiveness of the proposed non-destructive technique.

2. Dynamical formulations

Bells are essentially axisymmetric shells which, as any structure of this type, vibrate in a complex way. Bell motions involve a combination of longitudinal, torsional and flexural motions, even if from the acoustical point of view, only the flexural modes associated to motions normal to the bell surface are particularly relevant as they radiate effectively [1]. Due to the axisymmetry of the system, these modes occur in degenerate pairs, with the same natural frequency but different orientations. In real bells however, this degeneracy usually disappears, due to slight deviations from the perfect symmetry in the bell profile. This results in some audible beats in the sound radiated, which are said to influence the musical quality of bells [6].

2.1. Structural modification formulation for physical mass change

In terms of physical coordinates, a general description for the vibratory response $\boldsymbol{\xi}(\mathbf{r}, t)$ of a flexible structure is given by the standard equation of motion:

$$\mathbf{M}_u \ddot{\boldsymbol{\xi}}(\mathbf{r}, t) + \mathbf{C}_u \dot{\boldsymbol{\xi}}(\mathbf{r}, t) + \mathbf{K}_u \boldsymbol{\xi}(\mathbf{r}, t) = \mathbf{F}(\mathbf{r}_0, t) \tag{1}$$

where $\mathbf{M}_u$, $\mathbf{C}_u$ and $\mathbf{K}_u$ are matrices associated to the physical properties, i.e. mass, damping and stiffness, of the original unconstrained structure, and $\mathbf{F}$ is a vector representing an external force field applied at location $\mathbf{r}_0$. When adding mass modifications to the structure, the dynamical equations simply become:

$$\mathbf{M}_c \ddot{\boldsymbol{\xi}}(\mathbf{r}, t) + \mathbf{C}_u \dot{\boldsymbol{\xi}}(\mathbf{r}, t) + \mathbf{K}_u \boldsymbol{\xi}(\mathbf{r}, t) = \mathbf{F}(\mathbf{r}_0, t) \tag{2}$$