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Musical instruments – Sound synthesis of virtual idiophones

Pascal Bestle, Peter Eberhard *, Michael Hanss

Institute of Engineering and Computational Mechanics, University of Stuttgart, Pfaffenwaldring 9, 70569 Stuttgart, Germany

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ABSTRACT

The design of tuned idiophones, such as bells, gongs, and metallophones, has undergone centuries of development, pushed forward by instrument makers. All these improvements have the purpose of optimizing the sound such that it is pleasing to the human ear, resulting in complex geometries of the instruments. This empirical process is rather similar to the work of structural engineers who also optimize physical structures. In general, an idiophone can be described by its elastic properties, where eigenmodes and corresponding eigenfrequencies correspond to the overtones of the sound. However, this alone is not sufficient to evaluate sound. In particular, it is most important to take into account the time behavior of striking instruments like the vibraphone.

It is the novel contribution of this paper to provide a systematic approach for synthesizing sound from vibrating structures with arbitrary geometries just from their surface vibrations. In case of musical instruments, the resulting sound can be evaluated and rated by psychoacoustic criteria to define a target function for their numerical optimization. The method is applied to a bar modeled according to the design of typical vibraphone bars. The sound resulting from the synthesis algorithm is validated against the boundary element approach and results from microphone measurements.

1. Introduction

The history of musical instruments dates back nearly as long as humanity itself. During the last centuries, the development of the quality as well as of the play of musical instruments were pushed empirically and experimentally by both instrument manufacturers and players, where the current stage of development is already on very high level. At first sight, the scientific study of instruments does not seem to be required for further significant improvement [1]. However, manufacturing musical instruments requires a high level of expertise by the manufacturer. Thus, a deepened understanding of these complex systems and their sound behavior is needed to get a change for systematic improvements by modern approaches like numerical optimization which are not just based on experience.

The sound of tuned idiophones originates from the whole vibrating instrument which exhibits a specific tone pitch and a harmonic 'overtone' series. The musical term overtone corresponds to the frequencies of the eigenmodes with a characteristic ratio to the first frequency, which is called the fundamental or pitch. In order to achieve a pleasant sound, the empirical design process of geometric forms and materials resulted in rather complex profiles [2].

This heuristic optimization process is very similar to the traditional work of structural engineers who also change physical structures to improve the efficiency of a design. From an engineer's point of view, a musical instrument is also a

* Corresponding author.
E-mail address: peter.eberhard@itm.uni-stuttgart.de (P. Eberhard).

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physical structure which may be described by numerical models such as the Finite Element Method (FEM) or an Elastic Multibody System (EMBS) [3–5]. In this particular case, the optimization goal is not to reduce costs or mechanical stresses, but to influence the eigenfrequencies in such a way that a more pleasing and agreeable sound is obtained.

Commonly, the perception of sound is regarded as purely subjective and strongly dependent on the musical experience of the audience. In fact, objective criteria for the evaluation of sound can be defined by use of psychoacoustics. These criteria can be used as performance criteria for the optimization of the sound, where the shape of the structure is optimized. For this purpose, the sound of the virtual idiophone needs to be synthesized from numerical results in order to make the sound evaluable and rateable. Furthermore, the sound of the optimized instrument can be made audible to be acknowledged by a specialist.

The novel contribution of this paper is the introduction of a method for synthesizing the radiated sound from the surface velocities of vibrating structures obtained from simulation. The idiophone is described as a reduced elastic body using methods of EMBS, where the elastic quantities are obtained from an FE discretization. In order to reduce computational time, an essential step is the reduction of the number of elastic degrees of freedom. For this model order reduction, a variety of projection methods exists, see [6–8]. The investigations of this paper focus on idiophones because the sound of musical instruments is very sensitive to small changes of the dynamics of the elastic The results of the numerical investigations are carefully compared to measurements, showing a high degree of accordance. Furthermore, the computational time is significantly lower compared to established methods like FEM and BEM. Nevertheless, the approach of synthesizing sound from arbitrary vibrating structures can also be applied to other mechanical problems, like the computation of break squeal or interior noise in the cabin of a vehicle, better known as NVH (Noise, Vibration, Harshness).

The underlying assumption behind the presented method is the weak coupling of the pressure of the surrounding air to the structural behavior of the idiophone. Therefore, a two-step approach can be applied. In the first step, the structural behavior of the solid body under applied forces and boundary conditions is computed, neglecting the coupling to the surrounding air. In the second step, the propagation of pressure waves in the air is evaluated. The presented sound synthesis algorithm is based on the analytical solution for the propagation of sound waves from point sources, whereby these point sources are spatially distributed on the surface of the vibrating structure.

Based on the design of vibraphone bars, the introduced methods are applied to a solid beam with rectangular cross section which is modified with different undercuts. These undercuts are created to influence the overtone series and the resulting sound is evaluated in a musical manner using psychoacoustic criteria. The three simulated models have then been manufactured to perform measurements. These measurements are divided into two parts. The first part is the experimental modal analysis (EMA) with Laser Doppler Vibrometers (LDVs) to determine the material and damping properties for the simulation. In the second part, microphone measurements are performed to validate the results of the synthesized sound from the simulation.

The following section gives a brief introduction on the modeling of reduced elastic bodies as the initial step for synthesizing the sound of virtual idiophones. In Section 3, the analytic solution of the emission and propagation of sound waves for point sources is derived and the applicability of this approach to arbitrary discretized geometries is shown. The results of the presented synthesis algorithm are compared to the well-known boundary element method (BEM). The setup for the experimental analysis of the manufactured bars is introduced in Section 4. The results of the microphone measurement are used to validate the accuracy of the presented synthesis algorithm. In Section 5, two different modifications of the bar are analyzed in the simulation and the resulting sound is evaluated by selected psychoacoustic criteria. Section 6 provides conclusions and an outlook.

2. Modeling of idiophones as reduced elastic bodies

The synthesis of sound from surface velocities of vibrating structures requires a time integration of the equations of motion of the elastic body. The numerical simulation of the vibration can be performed without taking into account the coupling to the surrounding air. A vibraphone bar is described as a reduced elastic body based on the modal modeling of undamped systems. For the consideration of dissipative effects, arising from structural damping as well as damping due to the surrounding air, an additional proportional damping term is introduced. The time integration is performed using the EMBS tool Neweul-M^2, which has been developed at the Institute of Engineering and Computational Mechanics of the University of Stuttgart [9]. The elastic quantities of the FE model are obtained from the FEM tool Ansys [10]. For adequate computational efficiency, the number of degrees of freedom of the elastic body needs to be reduced, e.g., by performing model order reduction using modal truncation.

2.1. Description of elastic quantities

In structural mechanics, the motion of a continuum may be described by partial differential equations, where an analytical solution is only available for simple geometries. The FEM is a well-suited method for solving problems with complex geometries and boundary conditions [11]. For the approximation of small displacements and linear-elastic material properties, the equation of motion