Towards Dynamic Copies of Guitars – Shape Optimization vs. Material Variability

Alexander Brauchler, Pierfrancesco Cillo, Pascal Ziegler and Peter Eberhard

May 29, 2024

Towards Dynamic Copies of Guitars – Shape Optimization vs. Material Variability

Alexander Brauchler, Pierfrancesco Cillo, Pascal Ziegler, Peter Eberhard

Institute of Engineering and Computational Mechanics
University of Stuttgart
Pfaffenwaldring 9, 70569 Stuttgart, Germany
pascal.ziegler@itm.uni-stuttgart.de

Abstract

Although many good luthiers exist and build excellent instruments some instruments even stick out of these high quality instruments and some luthiers, like Antonio Torres or Antonio Stradivari for example, have received almost irrefutable iconic status. To many musicians their instruments are unrivaled and real myths have grown around them. Naturally many attempts were made to copy those instruments as closely as possible just to find out that these copies hardly sound like the original. These audible differences can be attributed largely to the natural variability of the woods used in instruments of identical manufacture, and it is known that professional musicians can distinguish even seemingly identical instruments only by their sound, [1].

We present a methodology that allows the replication of reference instruments based on their vibrational characteristics rather than solely on their geometry. It allows building instruments that sound alike rather than merely look the same as geometric copies do. This is achieved by compensating unavoidable differences in vibrational properties between reference and replica caused by the natural variability of the wood through specific geometric adaptions. The challenge of such an approach is to reliably and non-destructively identify material parameters of the reference in order to be able to predict the necessary geometry modifications before the replica is built. One novel contribution is that we experimentally validated computer models to quantitatively predict the effects of material and design variations. This is a powerful new tool to systematically improve instruments, or to minimize scattering in series production of instruments.

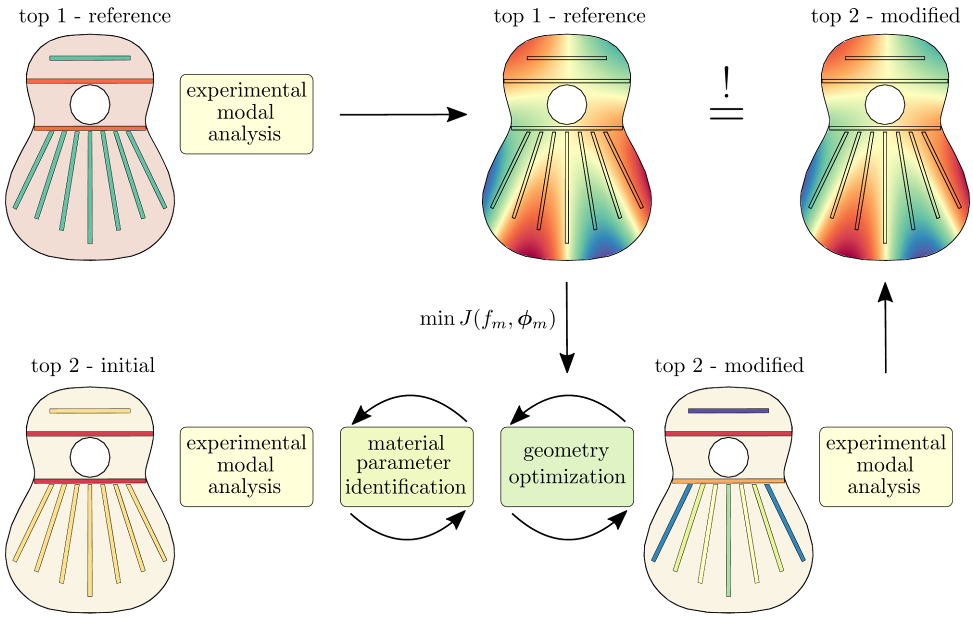

Figure 1: Workflow of shape optimization to produce a dynamical copy of a guitar.

As summarized in Figure 1, in this contribution we first focus on matching the vibrational response of individual elements of a guitar, namely the soundboard, [2]. Two soundboards made from spruce with initially equal geometry and Torres bracing were manufactured. One is defined as reference soundboard while the other represents the copy to which eventually geometric modifications are applied. The eigenfrequencies and eigenmodes, identified with experimental modal analysis, are used to compare the soundboards. Although the same tonewood from the same batch was used the relative difference of the first few eigenfrequencies is about 5% initially due to the natural variability of the tonewood.

A detailed and experimentally validated numerical finite element model of the soundboards is developed to predict suitable geometry modifications that can reduce the difference of eigenfrequencies between the soundboards. The individual heights of the different braces are chosen as the geometric parameters to influence the modal behavior of the soundboards. This numerical model is used as a virtual prototype that allows to find suitable modifications to significantly reduce the differences between the two soundboards' lowest eigenfrequencies. In order to efficiently solve the optimization problem, model order reduction is utilized. Finally, the mean difference in eigenfrequencies of the first couple of modes decreased to 2.5%, solely by changing the height of four braces by about 1mm.

The extension of this approach to full guitars requires adaptions in several areas. First, mode shapes need to be considered in the cost function of the shape optimization. In order to do so it is very advantageous to have finite element meshes whose nodes remain consistent across geometric variations of the domain, instead of re-meshed discretizations, because it allows to directly compare mode shapes. This is achieved by using mesh morphing approaches which will be presented. An advantageous feature of the presented morphing strategies is that they allow to increase the manifold of geometric variations, since high-level parameters like arcs, polynomials, etc. are used to define the geometry, i.e. the contour of the instrument. One problem arising from the increased possibilities to alter geometry is the increasing dimensionality of the optimization domain, making it increasingly difficult to extract a reasonably accurate and efficient parameterized reduced order numerical model by affine approaches. We will present an approach in which the dependency of the high-level parameters (which determine the overall geometic changes) are mapped to the element level, such that each finite element depends on all design parameters. The advantage of this approach is that all element-specific dependencies can be formulated symbolically and this symbolic relationship carries over to the assembled finite element matrices, [3]. This in turn allows a very efficient model order reduction, hence a very efficient and precise symbolically parameter-dependent model order reduced numerical model. The approach will be presented for hexahedral elements.

References

[1] Merchel, S.; Altinsoy, M.; Olson D.: Perceptual Evaluation of Bracewood and Soundboard Wood Variations on the Preference of a Steel-string Acoustic Guitar. The Journal of the Acoustical Society of America. Vol. 146, No. 4, pp. 2608-2618, 2019.

[2] Brauchler, A; Hose, D.; Ziegler, P.; Hanss, M.; Eberhard, P.: Distinguishing Geometrically Identical Instruments: Possibilistic Identification of Material Parameters in a Parametrically Model Order Reduced Finite Element Model of a Classical Guitar. Journal of Sound and Vibration. Vol. 535, paper 117071, 2022.

[3] Fröhlich, B.; Gade, J.; Geiger, F.; Bischoff, M.; Eberhard, P.: Geometric Element Parameterization and Parametric Model Order Reduction in Finite Element Based Shape Optimization. Computational Mechanics. Vol. 63, No. 5, pp. 853-868, 2019.