Physics-based Sound Synthesis of String Instruments Including Geometric Nonlinearities

Abstract of the Ph.D. thesis of Balázs Bank

The present work is about the synthesis of string instruments based on physical principles. The general idea of physics-based sound synthesis is that it models the sound production mechanism of the instrument, instead of the generated sound itself. As an introduction, Chap. 1 compares physics-based modeling to the more common signal modeling technique. This is followed by the summary of the main physics-based modeling methods for the different parts of the instrument (string, excitation, body) in Chap. 2.

Chapter 3 is about the loss filter design for digital waveguide string models. Two loss filter design techniques are developed, both of them are minimizing the error in terms of decay times. The first technique is a polynomial-regression based design of the one-pole loss filter. The design applies the approximate formulas for the decay times of a digital waveguide with such a filter. Then a simple and robust technique is proposed for high-order loss filter design that applies a special weighting function. The weighting function is derived from the Taylor series approximation of the resulting decay times.

The multi-rate approach is utilized for increasing the efficiency of string instrument modeling in Chap. 4. A multi-rate excitation model is presented where the numerical stability of the model is maintained by running the excitation model at a higher sampling rate compared to the rest of the system. For modeling beating and two-stage decay, the multi-rate resonator bank approach is proposed, where a few second-order resonators are running parallel with the basic string model. In the proposed instrument body model the low frequency part of the body response is rendered by a high-order filter running at lower sampling rate, while in the high frequencies a lower-order filter approximates the transfer function of the body.

Chapter 5 provides the theory required for modeling the geometric nonlinearities of strings. First, a "nonlinearity map" is introduced which helps to separate the different cases of nonlinear behavior. For the case when the tension is space- and time-dependent, but only the transverse to longitudinal coupling is significant, a comprehensive modal model is developed that is able to analytically compute the longitudinal vibration for arbitrary transverse motion. The model provides the explanation for earlier measurement results, besides forming the basis of sound synthesis algorithms.

In Chap. 6 the theoretical results of Chap. 5 are applied for sound synthesis purposes. Various physics-based techniques are developed that are based on computing the longitudinal response by nonlinearly excited second-order resonators. The approaches differ mainly in the accuracy of modeling and in the required computational complexity. As the most efficient approaches, "physically-informed" modeling techniques are also provided, where the linear transverse vibration is modeled by a physical model, while a signal model is used for recreating the perceptual effect of the longitudinal components.

Chapter 7 summarizes the main results of this thesis in a concise form and proposes future research directions.