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A landmark article on nonlinear time-domain modeling in musical acoustics FREE

Gary Scavone; Julius O. Smith

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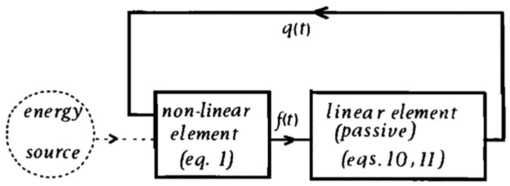
JASA REFLECTIONS

The *Reflections* series takes a look back on historical articles from *The Journal of the Acoustical Society of America* that have had a significant impact on the science and practice of acoustics.

A landmark article on nonlinear time-domain modeling in musical acoustics

Article: On the oscillations of musical instruments
Author: Michael E. McIntyre, Robert T. Schumacher, James Woodhouse
Publication Date: November 1983 (JASA **74**, 1325); https://doi.org/10.1121/1.390157

ARTICLE OVERVIEW



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The influential invited review article of McIntyre *et al.*[1] summarized and extended an efficient approach to the time-domain modeling of musical instruments that has spawned extensive applications and further research ever since. Motivated in part by difficulties in the application of frequency-domain methods to systems exhibiting strong nonlinearities, the authors advanced a generalized model for self-sustained musical oscillators in terms of coupled linear and nonlinear elements. The passive, linear responses of the clarinet, flute, and bowed-string were characterized in terms of simplified reflection functions, extending Cremer's "method of the rounded corner" for bowed-string modeling. The use of reflection functions led to significant computational savings, by comparison with complete impulse responses, or Green's functions, because of the relatively short durations of the reflection functions. The nonlinear mechanisms of each instrument, generalizing the Friedlander-Keller graphical formulation for bow-string interaction, were represented with approximate functions relating reed flow to differential pressure (clarinet), friction force to differential bow velocity (violin), and jet flow to acoustic air displacement (flute). The coupling between linear and nonlinear elements was shown to follow a common procedure involving the iterative solution of three equations at each step in time. Throughout, they presented examples demonstrating how time-domain simulations could be used to analyze and understand fundamental behaviors of musical instruments that were hard to explain using the then-predominant frequency-domain methods, such as pitch flattening and "wolf notes" in bowed strings, and oscillation onset characteristics in clarinets.

HISTORICAL BACKGROUND OF THE ARTICLE

This JASA "review/tutorial" article can be seen as the culmination and grand unification of a sequence of earlier publications focused more specifically on either bowed strings or clarinets.[2–6] According to Woodhouse,[7] the key year was 1977, during which Schumacher spent a six-month sabbatical in Cambridge. In the course of analyzing bowed-string dynamics and the propagation of the Helmholtz corner as described by Cremer,[8] the idea of a time-marching algorithm was born and "coded up within a day" in FORTRAN 2 on a Computer Automation LSI-2. The applications to the clarinet and flute were primarily conducted by Schumacher and McIntyre, the former having already conducted a sequence of simulations of wind instruments using an integral-equation formulation and the latter having a particular interest in fluid dynamics.

IMPACT OF THE ARTICLE

Nearly 40 years since its publication, this article continues to be cited on a regular basis. As of early 2021, Google Scholar reports 519 citations in fields such as acoustics, mechanics, differential equations, and computer music. By highlighting the efficiency of the computational approach, back in the early 1980s when computers were relatively slow, the authors helped create the field of efficient computational modeling in musical acoustics. In particular, the authors noted that "There is now no mathematical nor computational impediment to running extremely realistic and detailed simulations of musical oscillators, which could lead to quantitative comparisons with experiment, and ultimately to simulations sophisticated enough to be useful as practical design tools in musical instrument manufacture." This statement has proven true even for real-time audio synthesis, by the current use of nonlinear iterative solvers in real-time models for tube circuits and the like, in the domain of digital audio effects, particularly those formulated as nonlinear wave digital filters. In the field of computer music, their models were adapted to various branches of digital waveguide synthesis,[9,10] a technology that appeared in commercial digital synthesizers in 1994 with Yamaha's VL-1. While the article itself was focused on

self-sustained oscillations with strong nonlinearities, the reflection-function approach gained significant popularity in the musical acoustics community for both continuously and impulsively excited system modeling.

SUBSEQUENT DEVELOPMENTS

This article and its constituents influenced a wide range of subsequent research investigations, including applications of the reflection-function approach in conical waveguides,[11] brasses,[12,13] and air-jet instruments.[14] Recent developments in understanding bowed-string dynamics still make use of the traveling-wave approach, expanded to include multiple dimensions of string propagation and even bow vibrations.[15] And woodwind models continue to derive, at least in part, from the concepts presented in this article.[16,17]

By GARY SCAVONE[1] and JULIUS O. SMITH[2]
[1]***Computational Acoustic Modeling Laboratory, Schulich School of Music, McGill University, Montreal, Quebec H3A 1E3, Canada***
[2]***Center for Computer Research in Music and Acoustics, Department of Music, Stanford University, Stanford, California 94305, USA***

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