Computational Mechanics of the Classical Guitar

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With 65 Figures

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To my parents for their love and support in good and in bad times.
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Preface

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Contents

Glossary of Variables

Coordinates

Ω	domain
Γ	boundary
R_Γ	boundary condition
x	x-coordinate
y	y-coordinate
z	z-coordinate
$\mathbf{u}$	displacement vector {r, s, t}
r or u_x	displacement in x-direction
s or u_y	displacement in y-direction
t or u_z	displacement in z-direction
$\mathbf{n}$	unit outward normal vector

Matrices

$\mathbf{D}$	n $\times$ m matrix of spatial vectors of the central points of the top plate elements
$\mathbf{B}$	n $\times$ m matrix of spatial vectors of the central points of the back plate elements
$\mathbf{Z}$	n $\times$ m matrix of spatial vectors of the central points of the rib elements
$\mathbf{H}$	n $\times$ m matrix of spatial vectors of the central points of the neck elements
$\mathbf{L}$	n $\times$ m $\times$ o matrix of spatial vectors of the central points of the enclosed air space elements
$\mathbf{S}_s$	n $\times$ s matrix of string elements of a string s

$\mathbf{D_u}$ n × m matrix of displacements of the central points of the top plate elements

$\mathbf{B_u}$ n × m matrix of displacements of the central points of the back plate elements

$\mathbf{Z_u}$ n × m matrix of displacements of the central points of the rib elements

$\mathbf{H_u}$ n × m matrix of displacements of the central points of the neck elements

$\mathbf{L_u}$ n × m × o matrix of displacements of the central points of the enclosed air space elements elementmittelpunkte

$\mathbf{S}_s$ n × s matrix of string elements of a string s

$\mathbf{D_v}$ n × m matrix of displacements of the central points of the top plate elements

$\mathbf{B_v}$ n × m matrix of velocities of the central points of the back plate elements .

. .

. .

$\mathbf{S}_v$ n × s matrix of velocities of the string elements of a string s

$\mathbf{D_a}$ n × m matrix of accelerations of the central points of the top plate elements

$\mathbf{B_a}$ n × m matrix of accelerations of the central points of the back plate elements

. .

. .

$\mathbf{S}_a$ n × s matrix of accelerations of string elements of a string s

_ $\mathbf{D_a}$ intermediate memory of the spatial vectors of the central points of the top plate elements

_ $\mathbf{B_a}$ intermediate memory of the spatial vectors of the central points of the back plate elements

. .

. .

_ $\mathbf{S}_a$ intermediate memory of the spatial vectors of string elements of a string s

$\mathbf{G_u}$ rib geometry vectors

Physical Parameter

$\mathbf{D}_m$ mass of each element (in this case in the top plate)

$\mathbf{D}_\varrho$ density of the wood (in this case in the top plate)

$\mathbf{D}_{Ex}$ Youngs modulus in the x direction (in this case in the top plate)

$\mathbf{D}_{Ey}$ Youngs modulus in the y direction (in this case in the top plate)

$\mathbf{D}_h$ height of each element (in this case in the top plate)

$\mathbf{F}$	force
$\mathbf{M}$	moment
$\mathbf{F_{cross\ x\ y}}$	transverse force in the x and y directions
$\mathbf{D_v}$	velocity
$\mathbf{D_a}$	acceleration
$\mathbf{v}$	velocity
$\mathbf{a}$	acceleration
$\mathbf{r}$	radius
δx	separation in the x direction between two neighboring elements
δy	separation in the y direction between two neighboring elements
δz	separation in the z direction between two neighboring elements

Guitar Parameter

ZH	rib height
LK	length of the body in the x direction
BK	width of the body in the y direction
MS	scale length
$SL_{\mathbf{u}}$	position of the sound hole
SL_r	radius of the sound hole
DD	average thickness of the top plate
DB	average thickness of the back plate
DZ	average thickness of the ribs
HB	width of the neck
HD	maximum thickness of the neck

Transformations

$\mathbf{e}_i$	base vectors of the guitar, so $\mathbf{u} = u_i\mathbf{e}_i$ $(\mathbf{u} = \sum_{i=1}^{3} u_i\mathbf{e}_i)$
$\mathbf{Z}^{axis}$	Base vectors of the rib elements
$\mathbf{T}^{i,j}$	Transformation matrix of the rib elements i, j

Time and Analysis

t	time
Δt	time interval
SR	sampling rate

f	frequency
ω	angular frequency $2\pi f$
$F()$	continuous amplitude spectrum
$F[]$	discrete amplitude spectrum
$Z()$	continuous time series
$Z[]$	discrete time series
z^x	Z transformation
CWT	continuous wavelet transformation
DWT	discrete wavelet transformation
FFT	Fast Fourier transformation

1

Introduction

1.1 General Remarks

This book describes a new paradigm in instrument acoustics – one based on time-dependent transient analysis and simulation of complete musical instruments. The prevailing view in instrument acoustics currently remains a static one. Instruments are described in terms of their static characteristic eigenfrequencies or their frequency-dependent properties concerning the dissipation of the sound. However, the music played on musical instruments is never static. On the one hand, amplitudes and/or pitches of the sounds radiating away from an instrument always change steadily, even during what is called the quasi steady-state. On the other hand, it must be borne in mind that musical instruments are systems of individual parts that are linked together, and so their properties are whole complexes that can only be understood through the interactive and coupling properties of the individual subsystems. This complexity of musical instruments cannot be regarded here purely as a combination of static properties of the subsystems; in reality the true vibrational behavior depends on the transient. Without this temporal dimension, investigation of how musical instruments produce their sounds would miss out important parts of the sound, and the instrument as a system cannot be understood in its entirety.

This transient synthesis is demonstrated here by computer-aided modeling using the guitar as an example. The modeling is carried out using the Finite-Difference-Method (FDM). The objective is to simulate the transient behavior of the instrument and to use the analysis to draw conclusions concerning basic properties of the guitar, and also concerning basic mechanical properties. The modeling system used proved to be appropriate for this context.

This investigation was also necessary for other reasons. In earlier works by the same author (Bader 2002a) the initial transients of guitars and other instruments were analyzed in detail using methods of signal processing, fractal dimension analysis and other related methods. However, using purely analytical methods to investigate sounds, it was not possible to clarify what the physical causes of these properties of the initial transients might be. To determine these causes, the concept of a complete simulation of a guitar on a computer appeared to be a suitable method for generating the sounds produced in the tones of guitars. The correctness of this simulation, which is monitored in its individual parameters and stages, allows the causes of the steady-state behavior to be determined with great accuracy. At this point it must be said that many of these causes would be difficult to recognize in an experimental situation, i.e. by manipulating a real instrument. An example of this would be the type of coupling existing between the top plate and the back plate of a guitar via the ribs. The bending wave in the top plate is transformed into a longitudinal wave in the ribs. When this longitudinal wave reaches the back plate, it becomes a transverse wave again. But waves within the guitar that do not have a transverse component cannot be measured directly just anywhere on the guitar body. And if, for example, we wanted to determine the corresponding longitudinal movement at one particular point in the top plate, we would have to saw it open. The chain of transfers outlined here, characterized by the coupling of transverse and longitudinal vibrations, is an important part of the sound of the guitar, as will be explained in more in detail in the chapter on the steady-state. It is this process that allows the ribs to dissipate most of the sound they receive from the top. The result is a type of initial transient with several stages, which initially begins with the attack in the top and which undergoes another change in its sound after about 5 ms. This process (amongst other things) gives the sound extra richness and makes the initial transient slower, and thus longer all of which are beneficial properties for a solo instrument played alone, as is often the case for the guitar. The ribs are a relevant aspect in both the construction and the sound, and go back to citoles in the Middle Ages, and perhaps even the chordophones of the Hethites, ca. 1000 BC, which are possibly the stringed musical instruments depicted on ancient pottery fragments. (For a detailed article on the development of the guitar see (Jahnel 1986)).

The interactions between the vibration in the top plate and that in the ribs brings about a heaviness of the sound that becomes a problem if the instrument plays a solo in a musical context. Two examples of how the rather "weighty" timbre of the concert guitar can be avoided are the flamenco guitar and the electric guitar. The electric guitars of the big-band era were acoustic or semi-acoustic instruments and as such still had ribs, and they sounded very full and muted owing to the relatively thick, polished strings prevailing at the time. However, the height of the ribs decreased progressively in the second half of the 20th century ("thinline" models) until they disappeared altogether from the electric guitar. This also meant that there was no air space any more, which also led to the disappearance of the additional "short, pumping sound" at the onset of the tone. Electric guitars are most commonly used in bands, where they are required to produce sounds within a clearly defined range of frequencies within the overall sound, namely the middle pitches. Any overlap with the frequency ranges of the other instruments, such as the bass or the percussion, often leads to an ill-defined, fuzzy sound. There are numerous musical tasks (principally as an accompaniment) where the electric guitar should provide "patches" or "dabs" of sound within an overall picture spanning a wide range of frequencies. Regarding aspects of sound composition, similar considerations apply to the flamenco guitar – virtually restricted to concerts – but during the period of its development in the nineteenth century it was one of the newest flamenco instruments (appearing later than castanets, for example) and could still be heard in peñ as and bars, where it is very loud. The flamenco guitar also has ribs, but its construction is much lighter overall. Although the effects that the construction and the materials used have on the sound of the flamenco guitar have not been examined in detail, the sound it produces is short and direct. This is probably also the reason for the frequent and rapid repetitions of notes in the rasguedo or tremolo techniques, which are intended to produce a sound which is as penetrating as possible without becoming "heavy".

A second motivation for this detailed investigation of the guitar has to do with questions and methods of observation in the scientific study of music. In musical acoustics, problems with instruments are often approached from a physical point of view whose relevance to actual music is not very obvious to musicians, instrument-makers or music scholars. Many studies of instrument acoustics still start from a physical standpoint, and often serve to confirm physical theories "using delightful music as an example". This state of affairs is characterized by the fact that such analysis of musical instruments hardly ever investigate real plucked, bowed or blown tones. It is much more often the case that the tone or sound which is analyzed in the laboratory is produced by machines playing the instruments (Hutchings 1997) Vol. I p. 499 (Galluzzo and Woodhouse 2003). This is certainly a welcome method, at least initially, for physical reasons. Standardized conditions have to be created in order to exclude interfering variables and to be sure which physical parameters lead to which alterations in the sound. However, after such investigations it is just as advisable to play real sounds and to examine whether the properties found during the physical studies are still relevant in a musical context. This may not be as interesting to physicists, because musical questions then come into play, which by contrast are central to the study of music. Conversely, scholars of music welcome the assistance of physics in clarifying musical, in particular acoustic, problems with sound. As an example in this book I will deal with the coupling between the strings and the top face of the guitar in detail. In the theoretical literature this is described as impedance problem with a first order differential equation. The resulting resonance spectrum, however, only correlated with a resonance spectrum created by artificial stimulation. Only this year has it been discovered that it does not have much in common with the resonance spectrum of a genuine tone played on an instrument at the fundamental pitch/fundamental frequency. The reason for this is explained in this book and a solution to the problem is offered.