The physics of the *viola caipira*

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I. Introduction

What is a *viola caipira* ?

- It is a typical Brazilian guitar
- Instrument little studied in musical acoustics

Not every BRAZILIAN GUITAR is a *VIOLA CAIPIRA*

Examples of Brazilian guitars:

Viola Machete *Viola Nordestina* *Viola de Buriti* *Viola de Fandango* *Viola de Cocho*

- Variations of geometries, materials, string arrangements, tuning types, etc…

The *viola caipira* (or the *violas caipiras?*)

Fernando Sodré performing *Luzeiro* from Almir Sater

Musical acoustics context

Viola caipira

Folk guitar

Classical guitar

≠ Structural characteristics

≠ Sounds

RELATIONSHIP ?

Objective approach:
Physical parameters to describe the instrument and its sounds.

Perceptive approach:
Sensory experience of the individual.

- This research: **objective approach** to study the *viola caipira*.

Objectives of the thesis

- Identification and study of the **vibrational and acoustical specificities** of the *viola caipira*.

1. Experimental study

A. High-speed camera analysis

B. Vibration analysis

C. Sound analysis

- Development of a sound synthesis model able to reproduce the specificities of the *viola caipira*.

2. Numerical study

A. Physical modelling

B. Sound simulations

II. Experimental study of *the viola caipira*

The studied *viola caipira:* a representative exemplar

- *Rozini* brand, *Ponteio Profissional* model.
- Smaller body with a narrower waist than those of classical guitars.
- Tuning: *Rio Abaixo*
- **Wood types**
  - Soundboard: *Sitka Spruce*
  - Back and sides: *Indian Rosewood*
  - Neck: *Indian Rosewood*
  - Fretboard: *Ebony*

A. High speed camera analysis: experimental setup

High speed camera: Photron, FASTCAM SA-X2

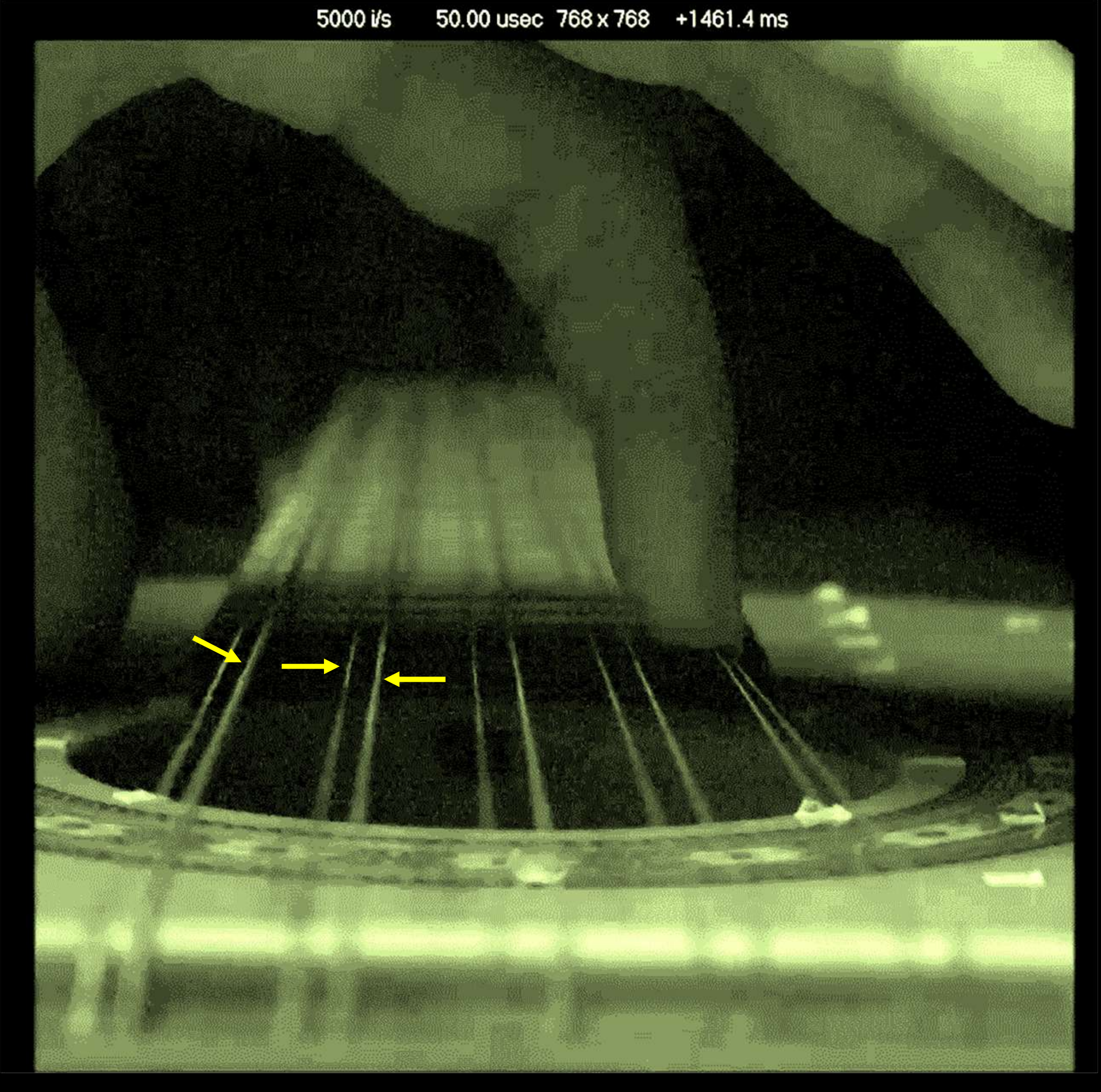
- 1024 × 768 pixels of resolution
- 5000 frames/sec

A. High speed camera analysis

- Particular double pluck
- Non-planar motions
- Collisions between strings

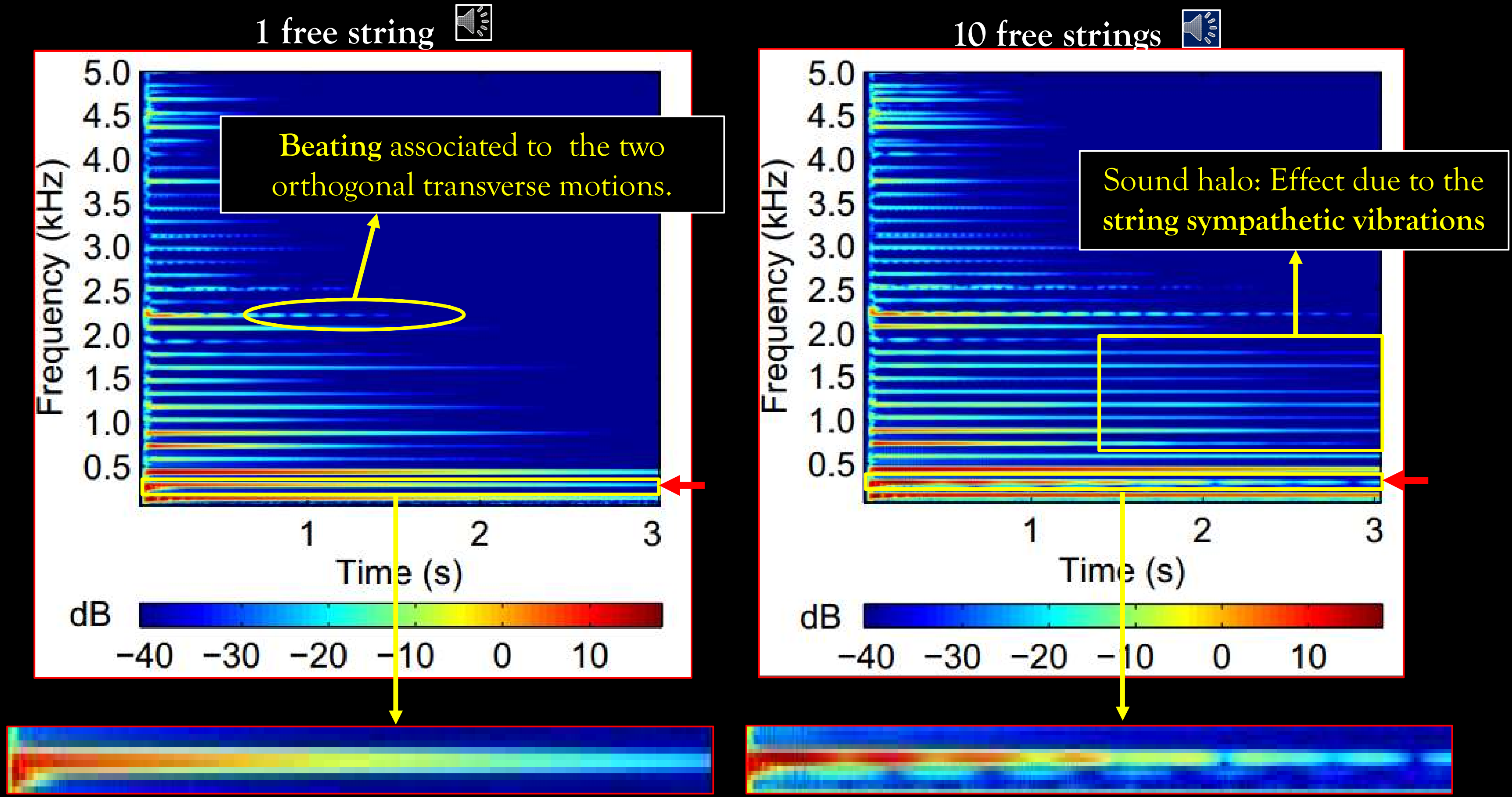
A. High speed camera analysis

- String sympathetic resonances due to the bridge motion.



B. Sound analysis

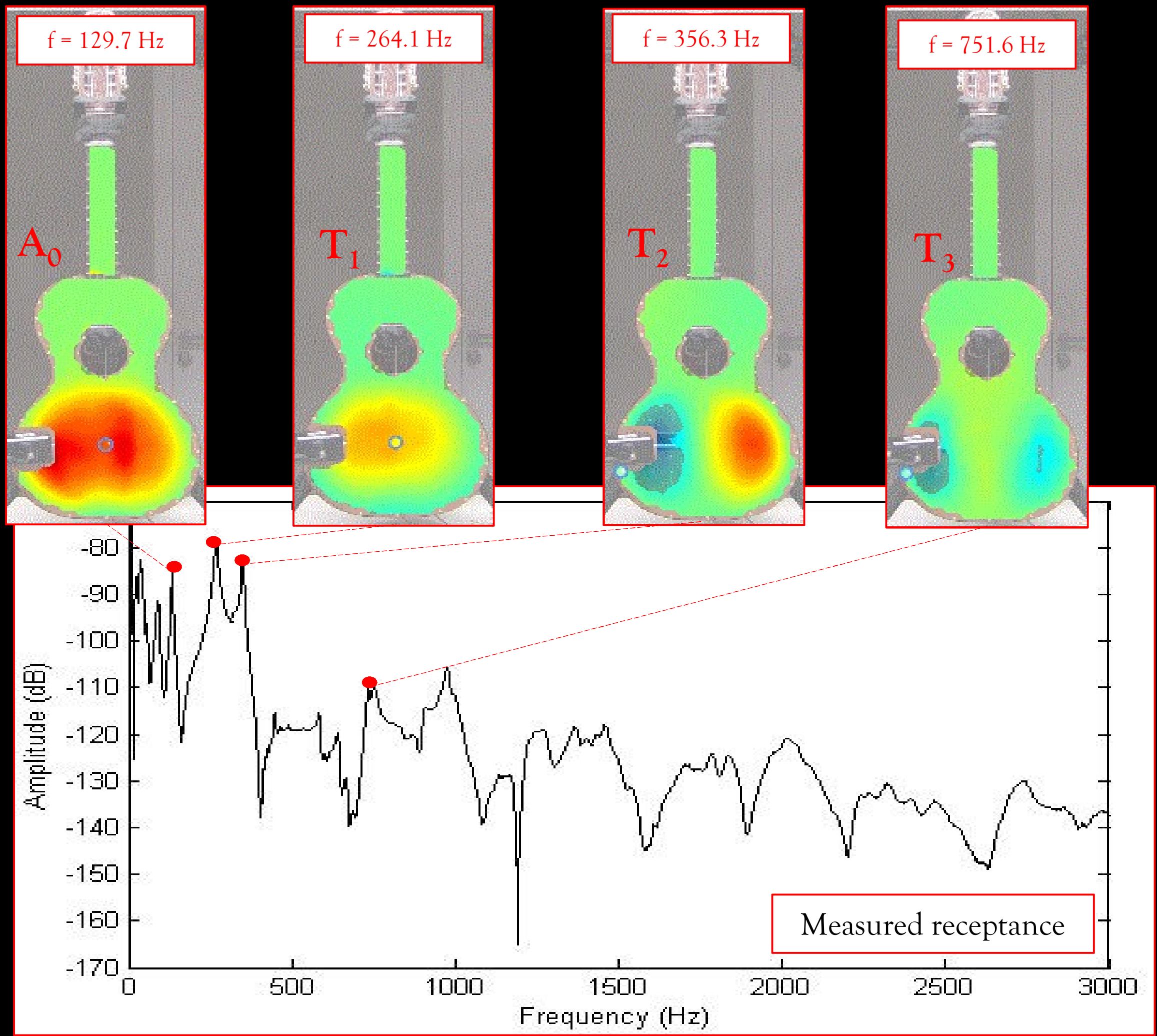
- **Sympathetic resonances and beating** due to the strings coupling through the bridge.



Beating associated to the interaction of multiple strings.

C. Vibration analysis of the body

- **Global vibration map: O**perating deflection shapes (ODSs)

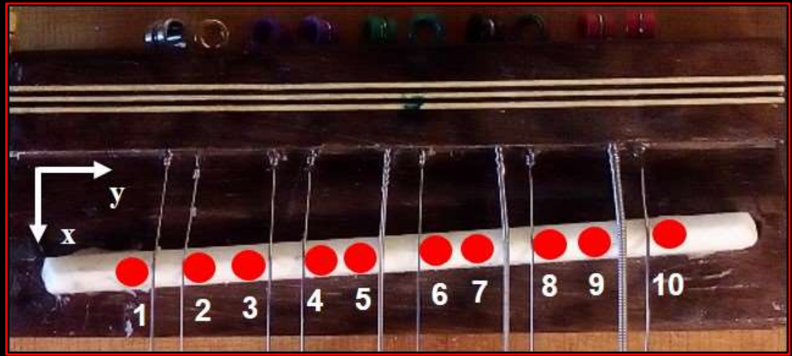


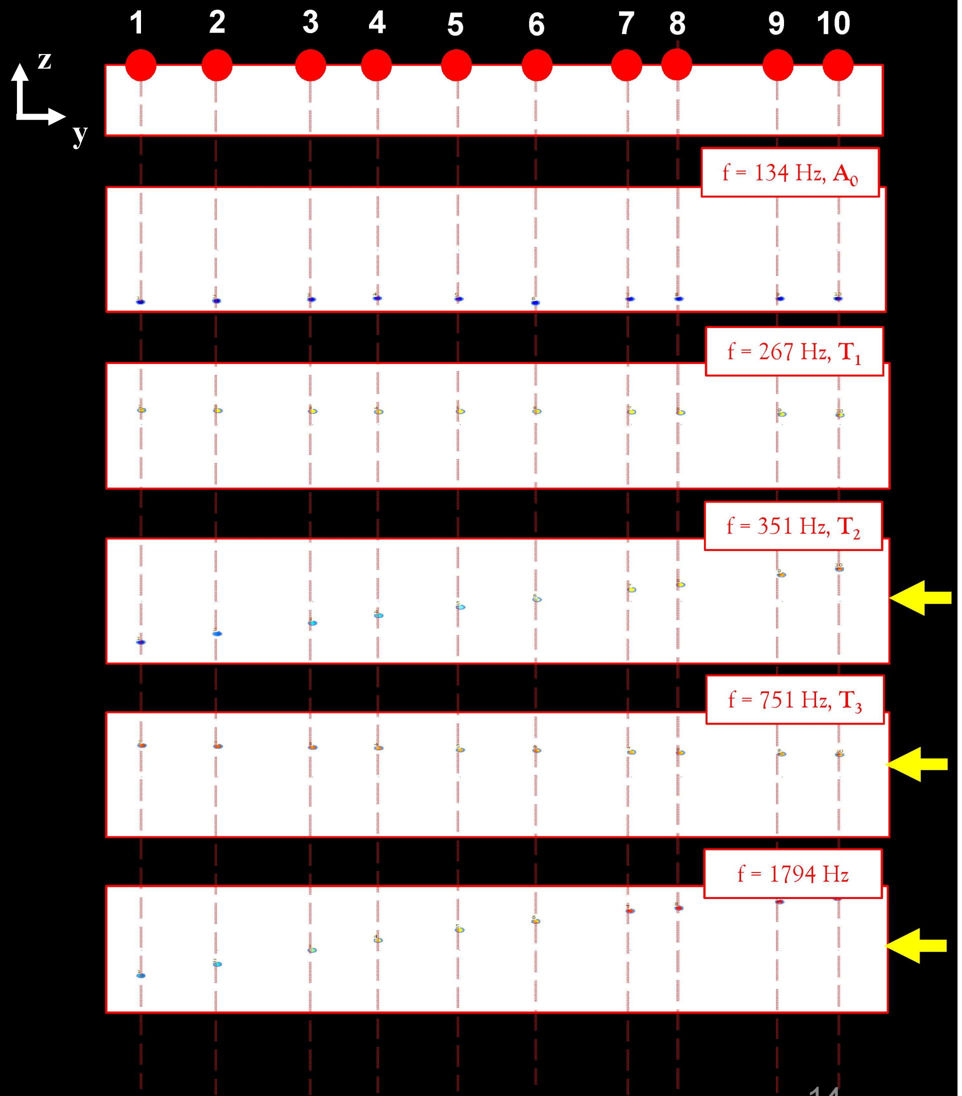
Scanning laser vibrometer

C. Vibration analysis of the body

- ODSs along the bridge using a laser vibrometer

10 string/body coupling points





- At some frequencies, the mobility at the 10 points are significantly different.
- These ODSs reveal the coupling between strings due to the bridge motion.

III. Mobility measurements using the wire-breaking method

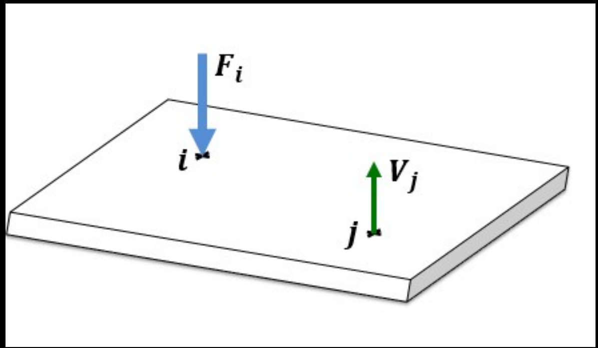
ELSEVIER
Applied Acoustics
Volume 139, October 2018, Pages 140-148

The Roving Wire-Breaking Technique: a low cost mobility measurement procedure for string musical instruments

Guilherme Orelli Paiva [a,b], Frédéric Ablitzer [a], François Gautier [a], José Maria Campos dos Santos [b]

Mobility: definition and why measuring

- **Definition**: transfer function $Y_{ij}(\omega)$



$$Y_{ij}(\omega) = \frac{V_j(\omega)}{F_i(\omega)}$$

- The mobility measured at the bridge quantifies the conversion of **string force** into **bridge velocity** (**degree of coupling** between **strings** and **body**)

Large Mobility → Strong coupling →
- Powerful sound
- Fast decay

Small Mobility → Weak coupling →
- Less powerful sound
- Slower decay

Mobility measurement using the hammer method (classical method)

Mobility measurement using the wire-breaking method

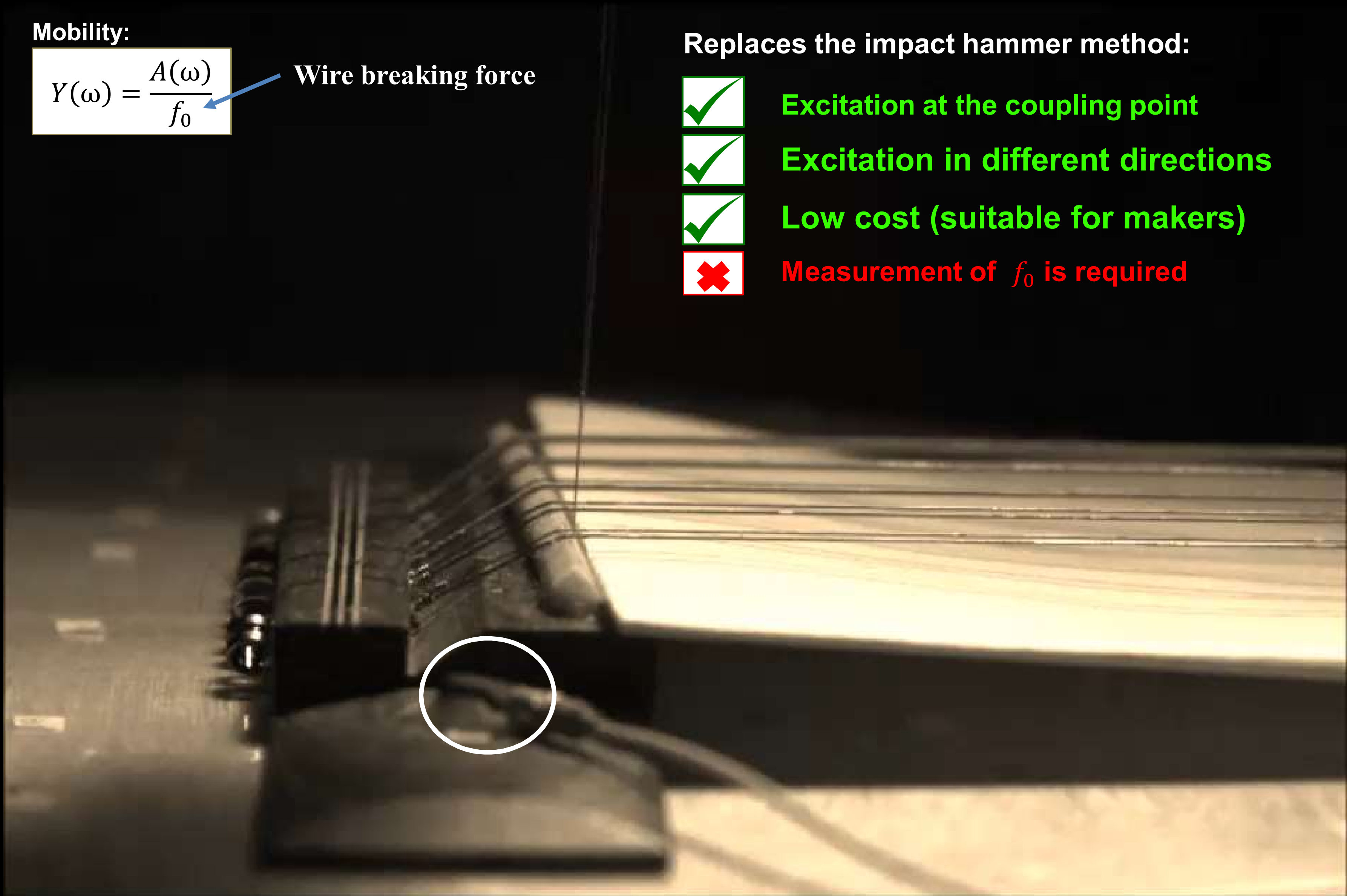
Mobility:

$$Y(\omega) = \frac{A(\omega)}{f_0}$$

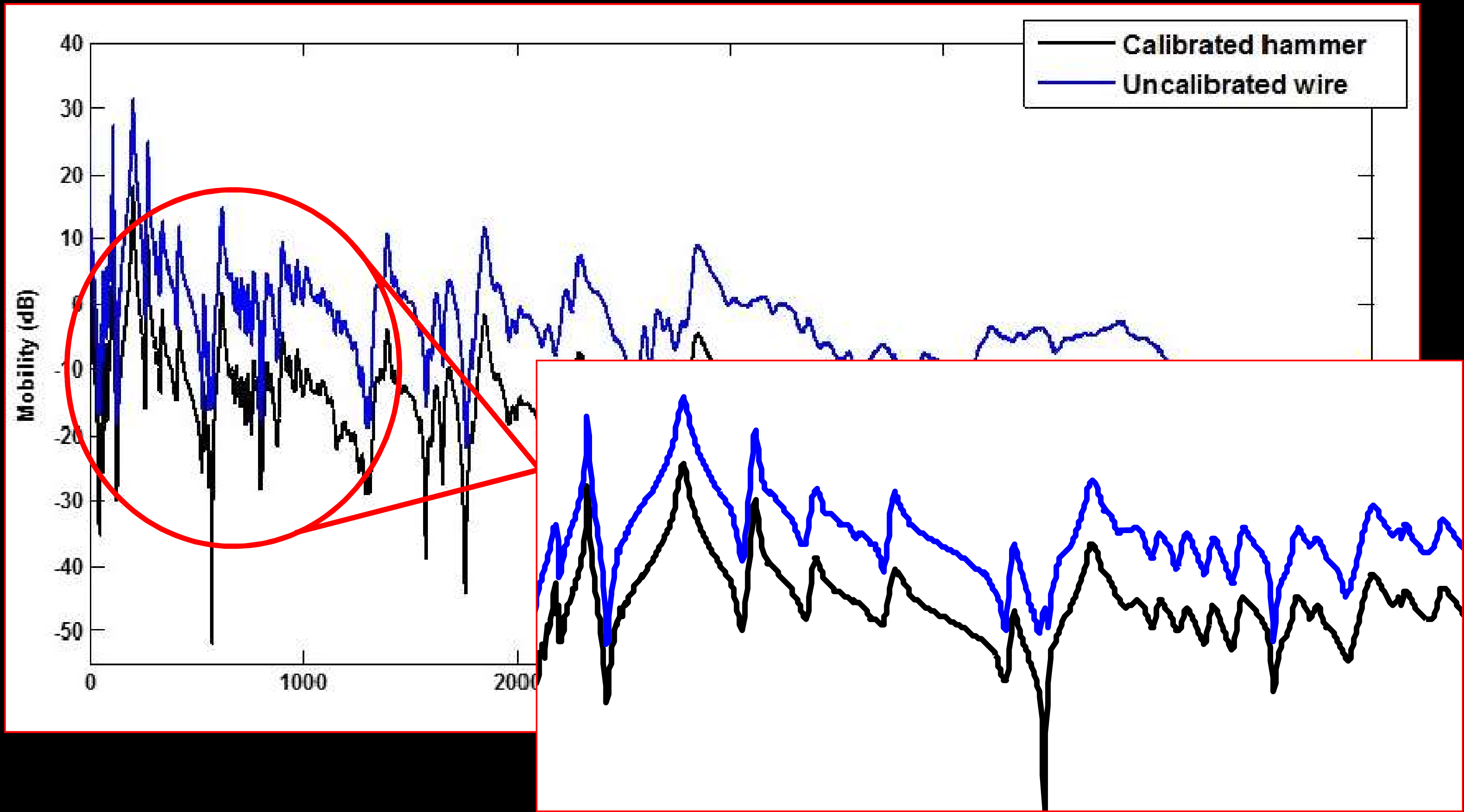
Wire breaking force

Replaces the impact hammer method:

- ✔ Excitation at the coupling point
- ✔ Excitation in different directions
- ✔ Low cost (suitable for makers)
- ✖ Measurement of f_0 is required

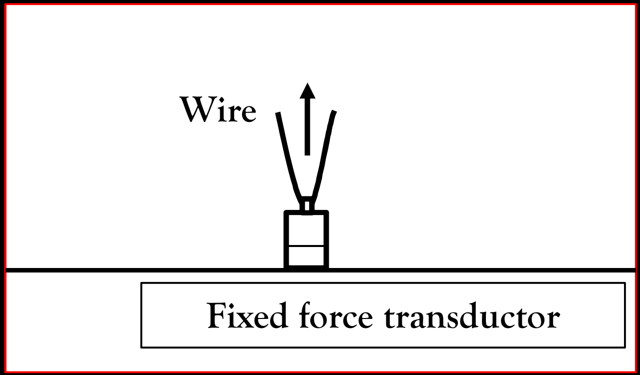


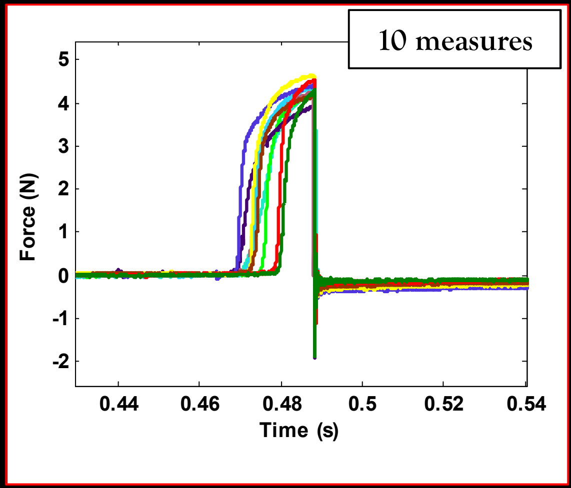
Wire-breaking method vs. Hammer method



Calibration of mobility from f_0 measurement

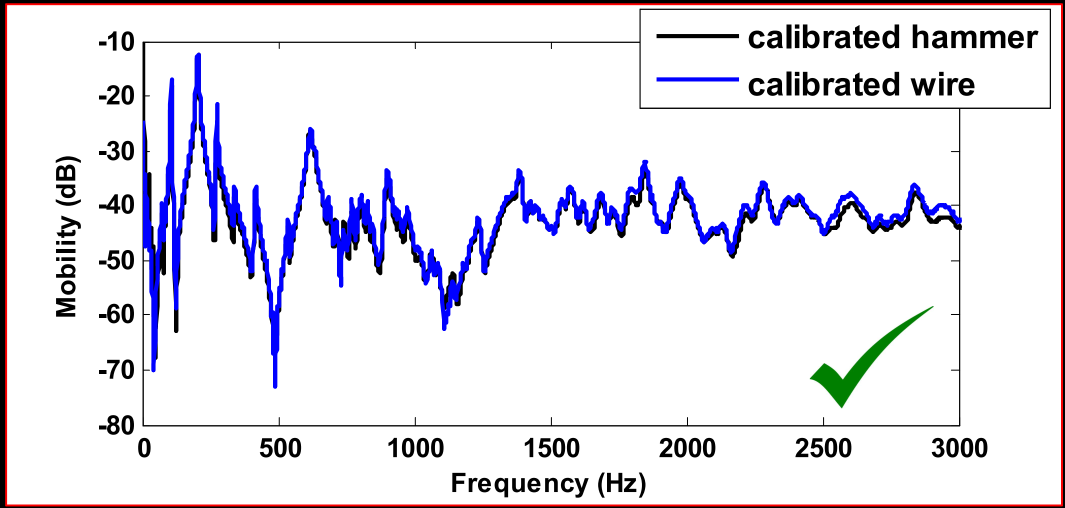
- Wire diameter: 100 µm



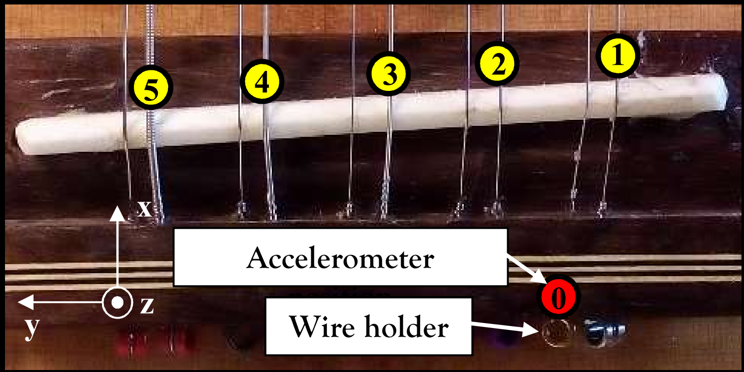


$$f_0 = 4.32 \pm 0.14\ N$$

$$Y(\omega) = \frac{A(\omega)}{f_0}$$



The "Roving Wire-Breaking Technique": modal analysis procedure



- Excitation positions: 0 1 to 5
- Excitation normal and parallel to the soundboard
- Response position: 0
- Wire diameter: 100 µm
- Instrument on a guitar stand

- 12 inertance curves
- Single-Input-Multiple-Output

High-resolution modal analysis

1st step. Estimation of poles: **ESPRIT** (Roy & Kailath, 1989)

- Time domain method

$$s[n] = \underbrace{\boxed{\sum_{k=1}^{2K} a_k e^{-\alpha_k n} e^{j(2\pi f_k n + \varphi_k)}}}_{\text{Signal subspace}} + \underbrace{\boxed{w[n]}}_{\text{Noise subspace}}$$

- The **signal subspace** verifies the rotational invariance property:

$$\boldsymbol{W}_{\uparrow}(2K) = \boldsymbol{W}_{\downarrow}(2K)\boldsymbol{R}(2K)$$

$\boldsymbol{W}(2K)$: basis of the signal subspace

$\boldsymbol{R}(2K)$: matrix whose eigenvalues are the poles $z_k = e^{-\alpha_k + 2\pi f_k}$

2nd step. Estimation of the mode shapes components

- Fit in the frequency domain (**collocated mobility**)

$$Y_{0z,0z}(\omega) = \sum_{k=1}^{K} A_k \underbrace{\frac{j\omega}{\omega_k^2 + \omega^2 + j2\xi_k\omega_k\omega}}_{H_k(\omega),\ \text{computed from poles!}}$$

$A_k = \phi_{0z,k}\phi_{0z,k}$

Constraint 1: A_k is positive

Constraint 2: A_k is real

- Non-Negative Least Square Procedure (NNLS)

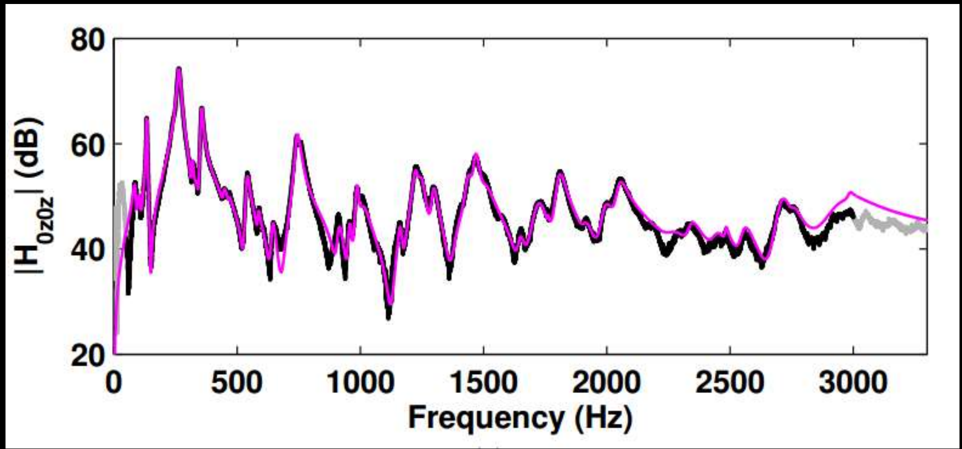
$$\min_{\boldsymbol{x}} \|\boldsymbol{C}\boldsymbol{x} - \boldsymbol{d}\|_2^2 \quad \boldsymbol{x} = [A_1 \dots A_K]^{\boldsymbol{T}}, x_k \geq 0 \ \ \forall k$$

- Provides intrinsically the modal order

- Other modal amplitudes: Standard Least Square

The "Roving Wire-Breaking Technique": modal analysis procedure

Modal fit

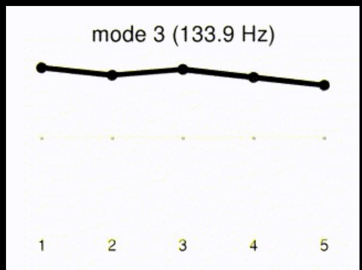


Modal identification

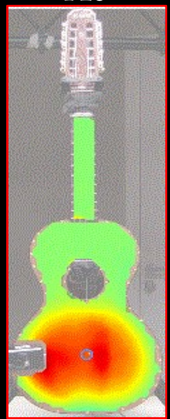
- 47 modes between 50 Hz and 3000 Hz

Mode shapes at the string/body coupling points

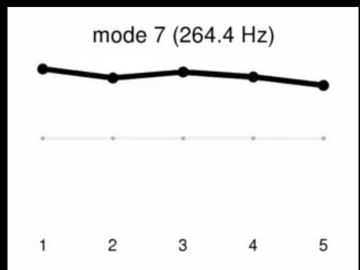
f = 133.9 Hz



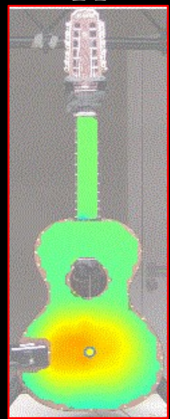
A0



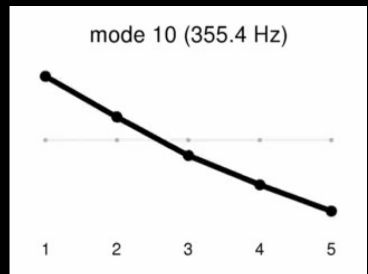
f = 264.4 Hz



T1



f = 355.4 Hz



T2

VI. Physical modelling

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Journal of Sound and Vibration

Volume 443, 17 March 2019, Pages 178-197

Collisions in double string plucked instruments: Physical modelling and sound synthesis of the *viola caipira*

Guilherme Orelli Paiva [a, b], Frédéric Ablitzer [a], François Gautier [a], José Maria Campos dos Santos [b]

Principle of the model: hybrid modal approach

Uncoupled string modes (Analytical)

- Modal basis of a stiff string

Pinned ends

+

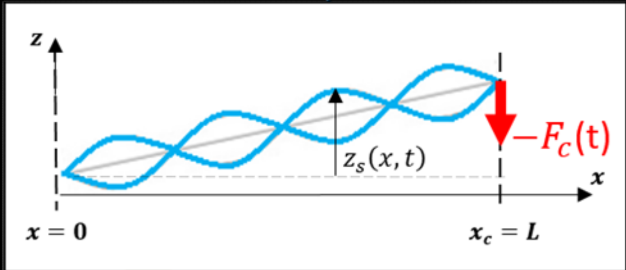
Interface mode

Uncoupled body modes (Experimental or Numerical)

- Mobility at the coupling points

$$Y(\omega) = \frac{V(\omega)}{F(\omega)} = \sum_{k=1}^{N_b} \frac{\phi_k^b(p_c)\phi_k^b(p_c)}{m_k(\omega_k^2 + 2i\omega_k\zeta_k - \omega^2)}$$

- Methods of parameters extraction: LSCE, ESPRIT



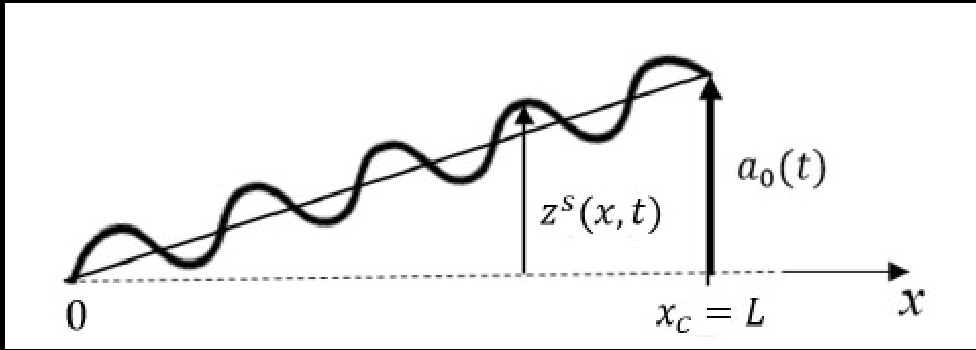
Finite differences temporal scheme

Kinematic coupling — t_{i+1}

Computation of the coupling force F_c — t_i

Time-step

Simplified case: 1 string,1 polarization



String displacement

$$z^s(x,t) = \sum_{j=1}^{N_s} a_j(t) sin\left(\frac{j\pi x}{L}\right) + a_0(t)\left(\frac{x}{L}\right)$$

At the string/bridge coupling point, x = L:

$$z^s(L,t) = a_0(t)$$

Displacement continuity:
$z^s(L,t) = z^b(L,t)$

String motion equation (modal)

$$\boldsymbol{M}^s\ddot{\boldsymbol{a}} + \boldsymbol{C}^s\dot{\boldsymbol{a}} + \boldsymbol{K}^s\boldsymbol{a} = \boldsymbol{f}^e + \boldsymbol{f}^c$$

$$\boldsymbol{f}^e = (\boldsymbol{\Phi}_e^s)^t F^e(t)$$

Force continuity

$$\boldsymbol{f}^c = (\boldsymbol{\Phi}_c^s)^t F^c(t)$$

Bridge displacement

$$z^b(L,t) = \sum_{k=1}^{N_b} b_k(t)\phi_k^b(L)$$

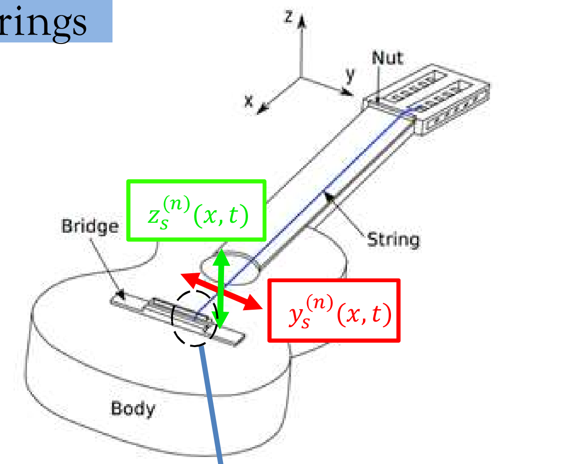
Bridge motion equation (modal)

$$\boldsymbol{M}^b\ddot{\boldsymbol{b}} + \boldsymbol{C}^b\dot{\boldsymbol{b}} + \boldsymbol{K}^b\boldsymbol{b} = -\boldsymbol{f}^c$$

$$-\boldsymbol{f}^c = -(\boldsymbol{\Phi}_c^b)^t F^c(t)$$

Fully coupled system: 10 strings, 2 polarizations

Strings

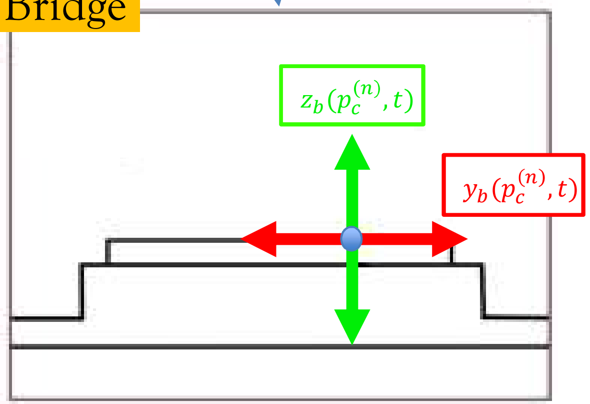


STRING displacements

$$\phi_s^{1z}(x) = \left(\frac{x}{L}, \sin\left(\frac{1\pi x}{L}\right), \dots, \sin\left(\frac{N_s \pi x}{L}\right)\right) \qquad \boldsymbol{a}^{1z}(t) = \left(a_0^{1z}(t), a_1^{1z}(t), \dots, a_{N_s}^{1z}(t)\right)^T$$

$$\underbrace{\begin{pmatrix} z_s^1(x,t) \\ y_s^1(x,t) \\ \vdots \\ z_s^{10}(x,t) \\ y_s^{10}(x,t) \end{pmatrix}}_{\boldsymbol{D_s}(x,t)} \equiv \underbrace{\begin{pmatrix} \boldsymbol{\phi}_s^{1z}(x) & & & & (\boldsymbol{0}) \\ & \boldsymbol{\phi}_s^{1y}(x) & & & \\ & & \ddots & & \\ & (\boldsymbol{0}) & & \boldsymbol{\phi}_s^{10z}(x) & \\ & & & & \boldsymbol{\phi}_s^{10y}(x) \end{pmatrix}}_{\boldsymbol{\Phi}^s(x)} \underbrace{\begin{pmatrix} \boldsymbol{a}^{1z}(t) \\ \boldsymbol{a}^{1y}(t) \\ \vdots \\ \boldsymbol{a}^{10z}(t) \\ \boldsymbol{a}^{10y}(t) \end{pmatrix}}_{\boldsymbol{a}(t)}$$

Bridge



BODY displacement

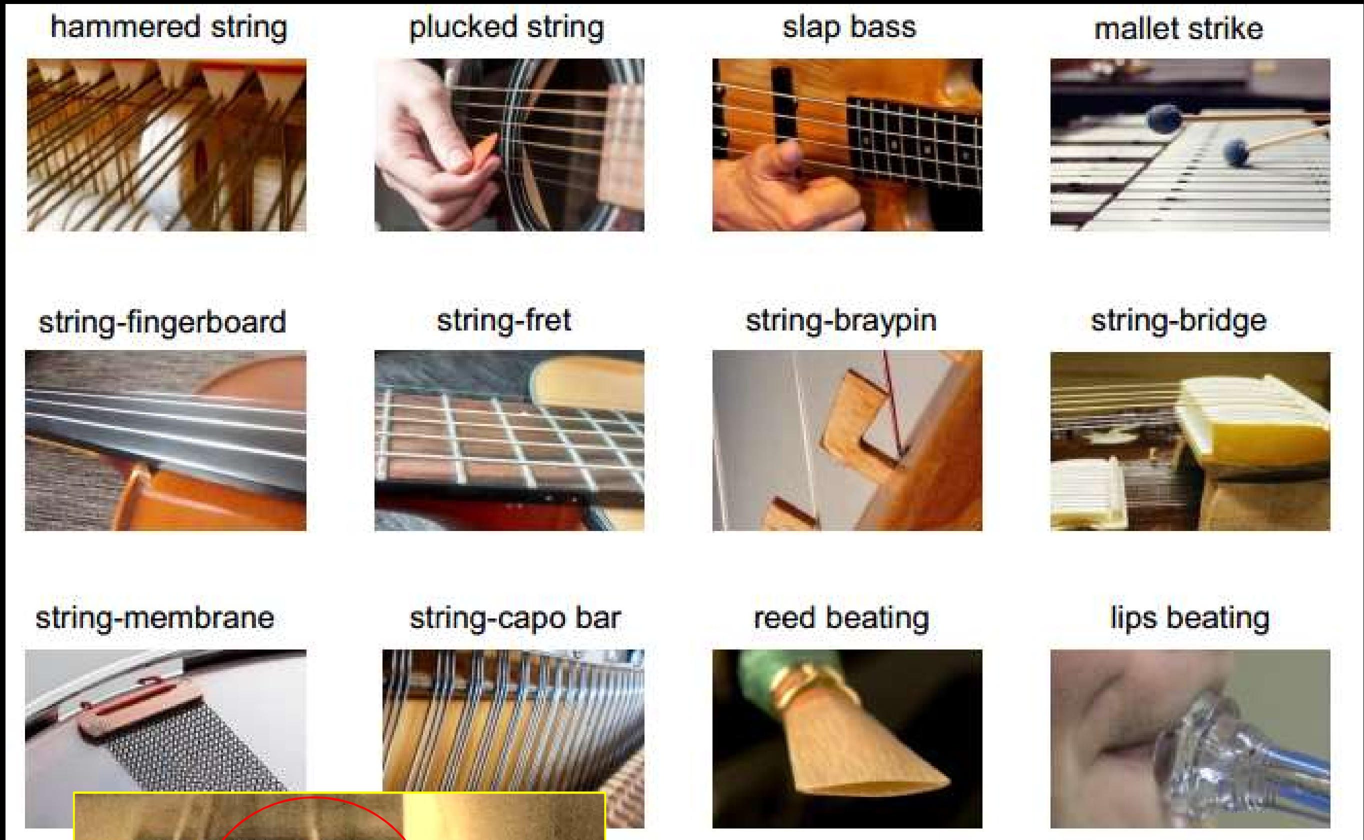
$$\boldsymbol{\phi}_b^z(p_c^1) = \left(\phi_1^{bz}(p_c^1), \dots, \phi_{N_b}^{bz}(p_c^1)\right)$$

$$\underbrace{\begin{pmatrix} z_b(p_c^1,t) \\ y_b(p_c^1,t) \\ \vdots \\ z_b(p_c^{10},t) \\ y_b(p_c^{10},t) \end{pmatrix}}_{\boldsymbol{D_b}(p_c,t)} \equiv \underbrace{\begin{pmatrix} \boldsymbol{\phi}_b^z(p_c^1) \\ \boldsymbol{\phi}_b^y(p_c^1) \\ \vdots \\ \boldsymbol{\phi}_b^z(p_c^{10}) \\ \boldsymbol{\phi}_b^y(p_c^{10}) \end{pmatrix}}_{\boldsymbol{\Phi}^b(x)} \underbrace{\begin{pmatrix} b_1(t) \\ \vdots \\ b_{N_b}(t) \end{pmatrix}}_{\boldsymbol{b}(t)}$$

- Resolution in time domain
- Centered finite differences
- Explicit matricial formulation

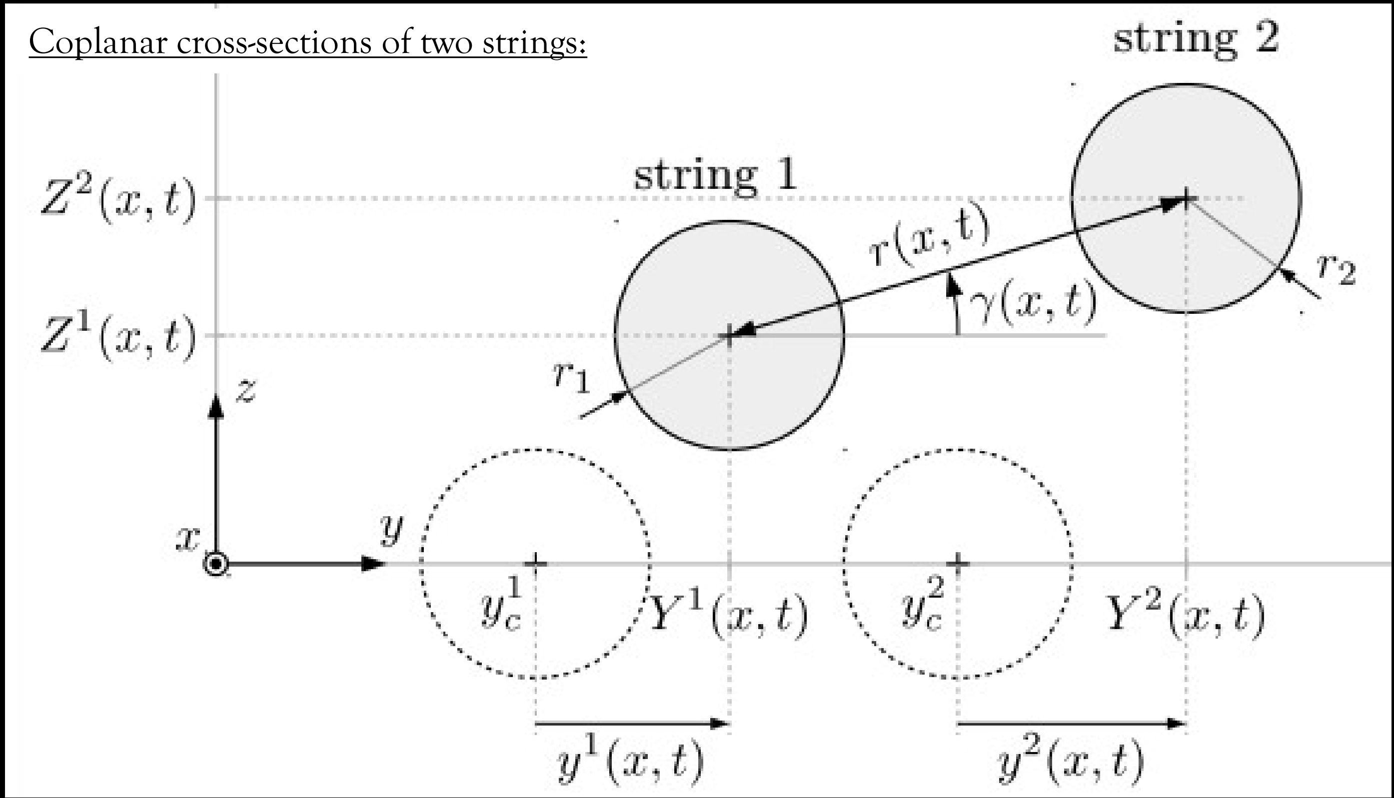
String/string collisions modelling

Collisions in musical instruments



(Walstijn, 2017)

String/string collision modelling



- Absolute coordinates:

$$Y^{(s)}(x,t) = y_c^{(s)} + y^{(s)}(x,t)$$

$$Z^{(s)}(x,t) = z_c^{(s)} + z^{(s)}(x,t)$$

- Distance between centroids:

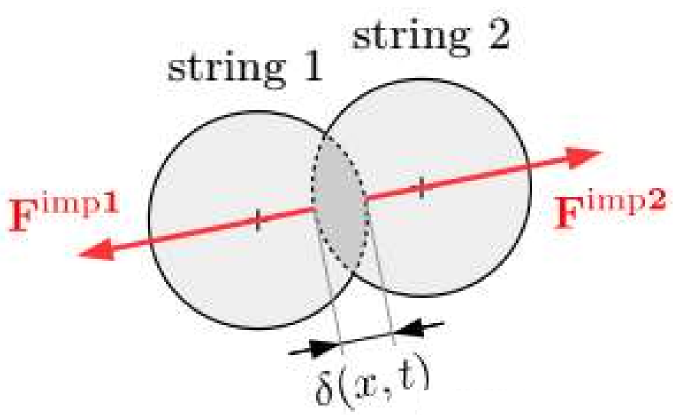
$$r(x,t) = \sqrt{(Y^2 - Y^1)^2 - (Z^2 - Z^1)^2}$$

- Impact angle:

$$\gamma(x,t) = arctan\left(\frac{Z^2 - Z^1}{Y^2 - Y^1}\right)$$

String/string collision modelling

Two colliding cross-sections:



- **Nonlinear model with hysteresis damping (Hunt and Crossley, 1975)**

Interpenetration   Compliance exponent

$$\left|\boldsymbol{F}^{imp(s)}(x,t)\right| = K_c\delta(x,t)^p + \lambda_d\delta(x,t)^p\dot{\delta}(x,t)$$

Contact stiffness   Damping coefficient

V. Sound synthesis of the *viola caipira:* numerical experiments

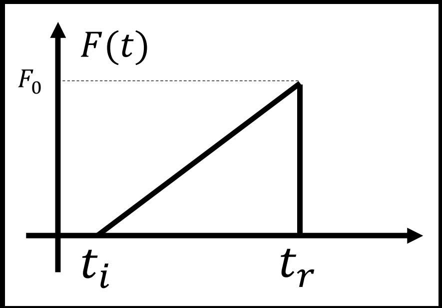
Simulation parameters

Number of modes

- **Strings:** modes up to 5000 Hz
- **Body:** 20 modes between 0 Hz and 1000 Hz

Excitation model

Ramp function



Maximum amplitude

Release time

$$|\mathbf{F}^{\mathbf{e(s)}}(t)| = \frac{F_0^{(s)}}{(t_r^{(s)} - t_i^{(s)})}(t - t_i^{(s)})(H(t - t_i^{(s)}) - H(t - t_r^{(s)}))$$

Initial time

- $t_r^{(s)} - t_i^{(s)} = 8\ ms$
- $F_0^{(s)} = 3\ N$

Excitation position: 8.5 cm from the bridge

Impact parameters

Table 1. Impact model parameters

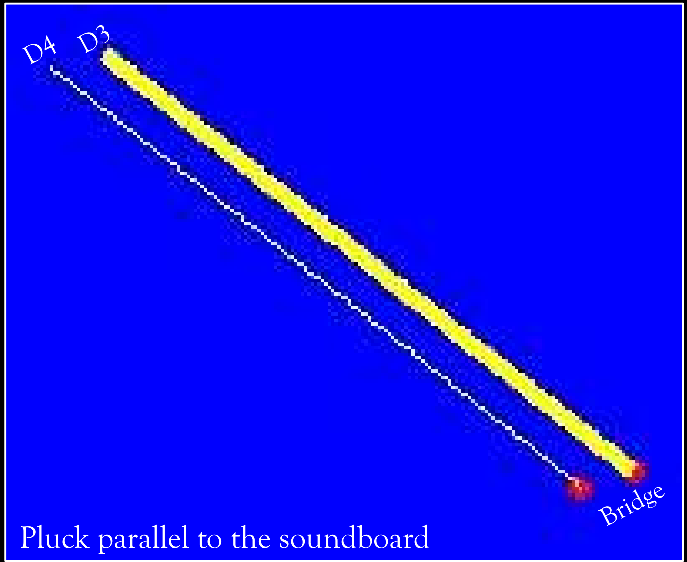
λ_d $[N.s/m^{p+2}]$	K_c $[N/m^{p+1}]$	p
10^8	10^9	1.5

Sampling frequencies (after convergence tests)

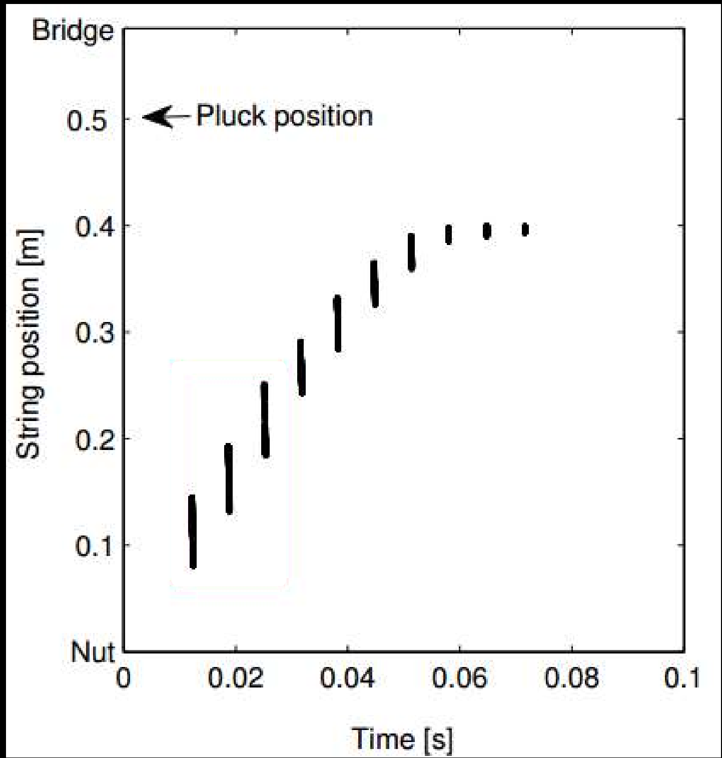
A. Without collisions: 220.5 kHz

B. With collisions: 441.5 kHz

Organization of collisions in space and time



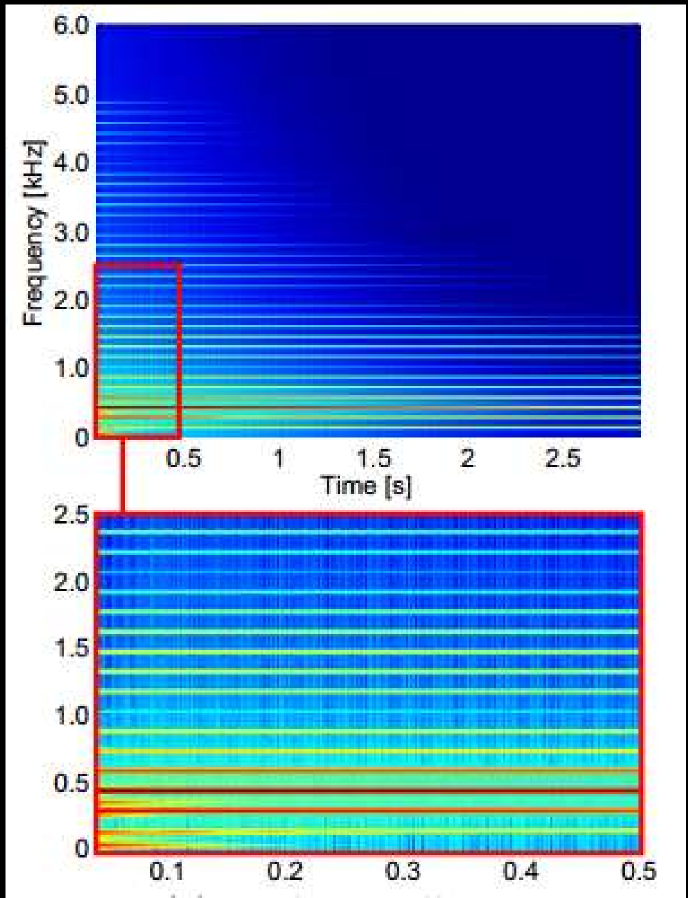
Collisions space-time diagram



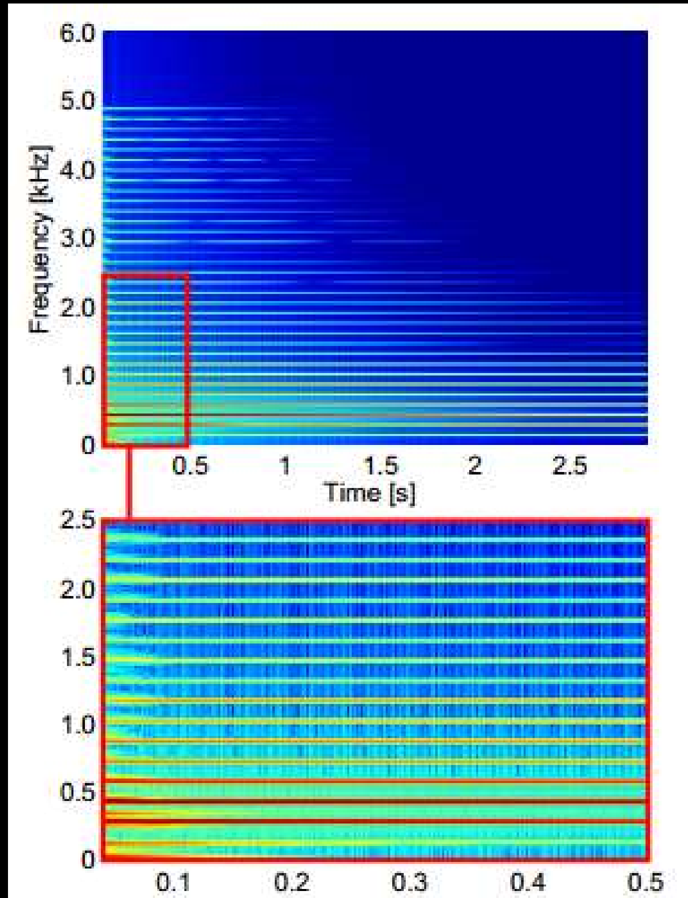
- Collision point moves along the string length.
- Collisions occur only in the immediate transient phase just after the pluck.

Collisions effects on the sound: <u>buzzing and spectral enrichment</u>

<u>Without collision</u>



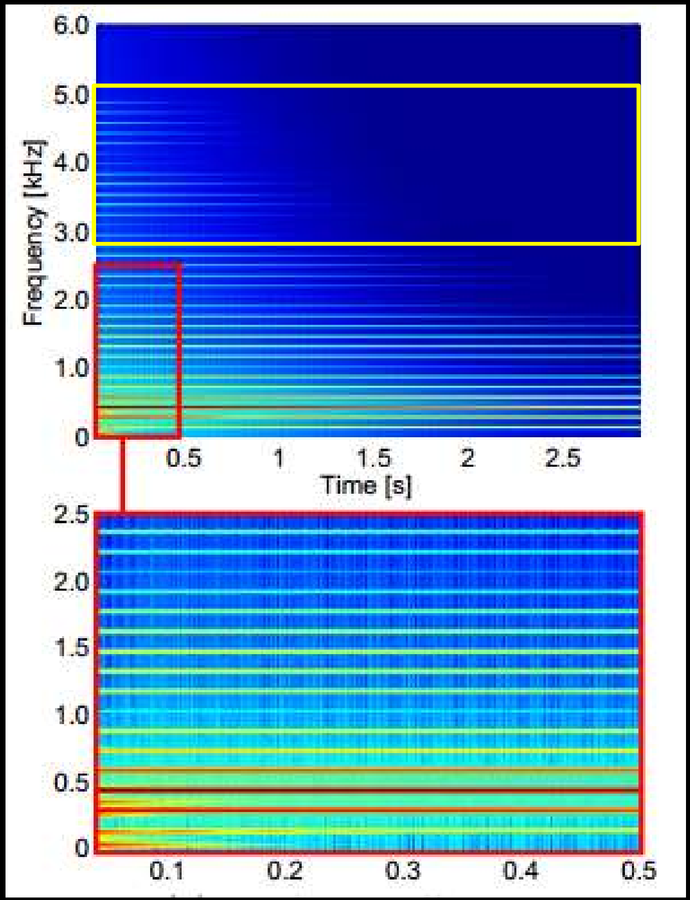
<u>With collision</u>



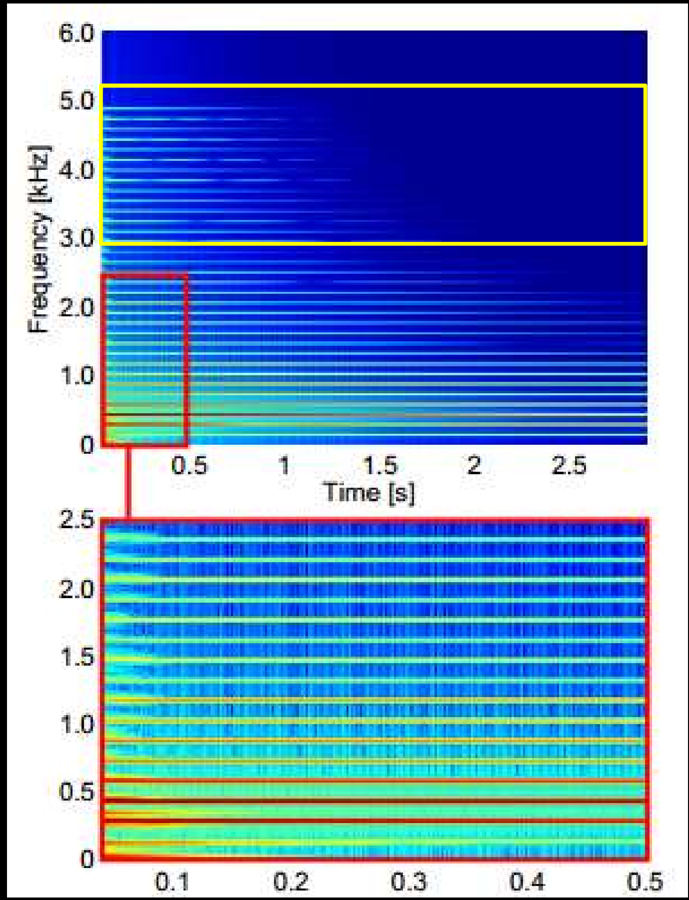
- <u>Buzzing effect:</u> induced by the repeated collisions in the early transient phase.
- <u>Spectral enrichment:</u> spectral rays are broadened during the collisions .

Collisions effects on the sound: redistribution of the spectral components

Without collision



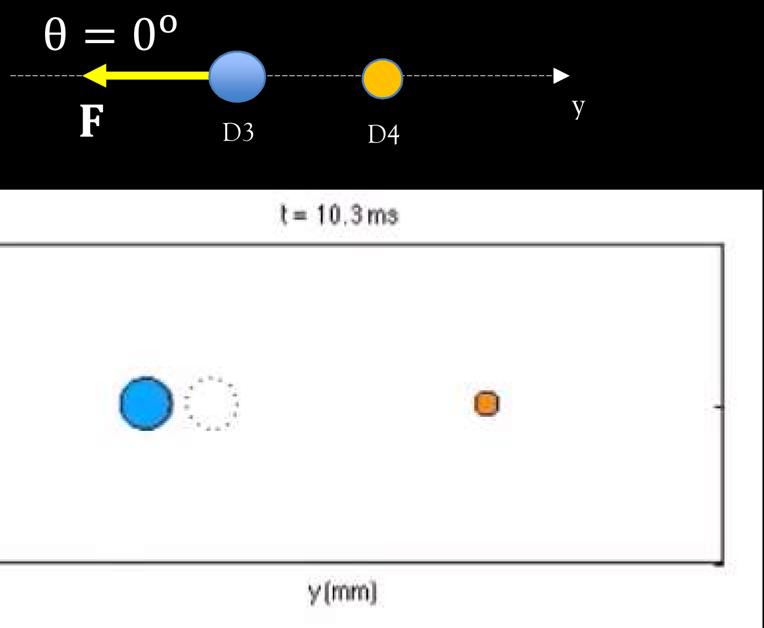
With collision



- The filtering related to the plucking position is cancelled since the collision point moves.

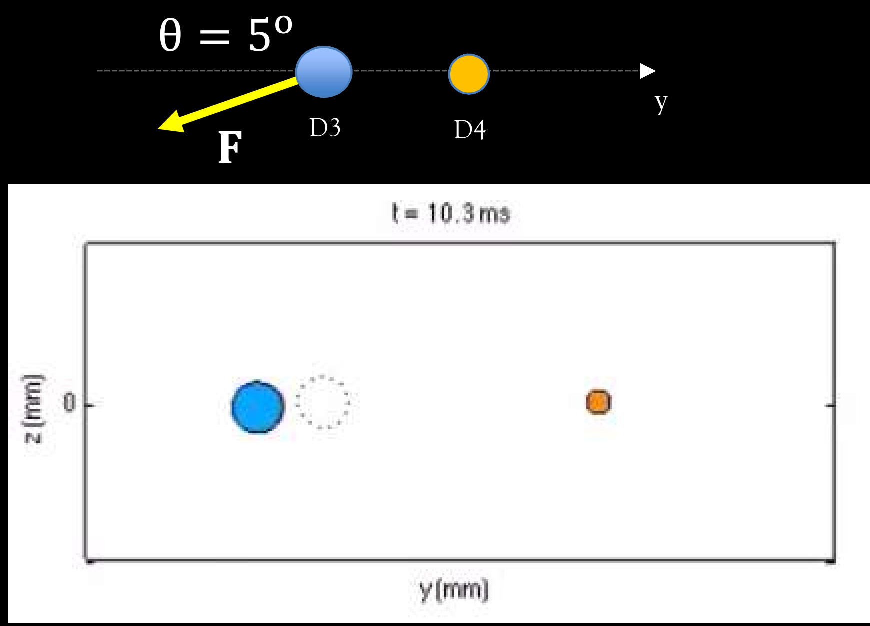
Collisions effects on the vibration: polarization change mechanism

Parallel pluck



Polarization remains in the plane

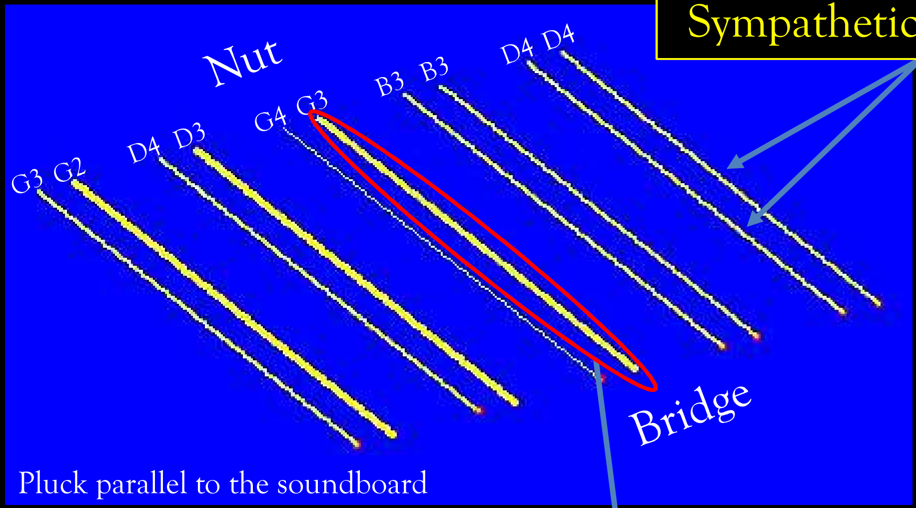
Inclined pluck



Polarization changes

- The plucking angle plays an important role in the polarization change.

Fully coupled system simulations: sympathetic resonances and beating



Sympathetic resonances!

Single string (D4)

10 strings (D4)

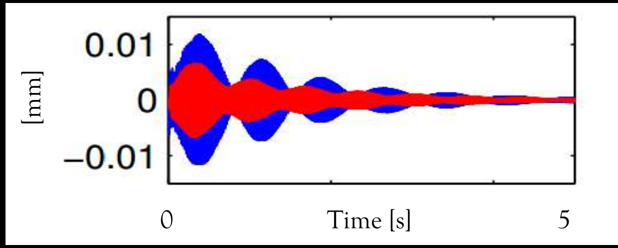
Without collisions

10 strings (D4)

With collisions

- Strings couplings through the bridge induce **sympathetic resonances.**

Time-history of string 5 (G3)

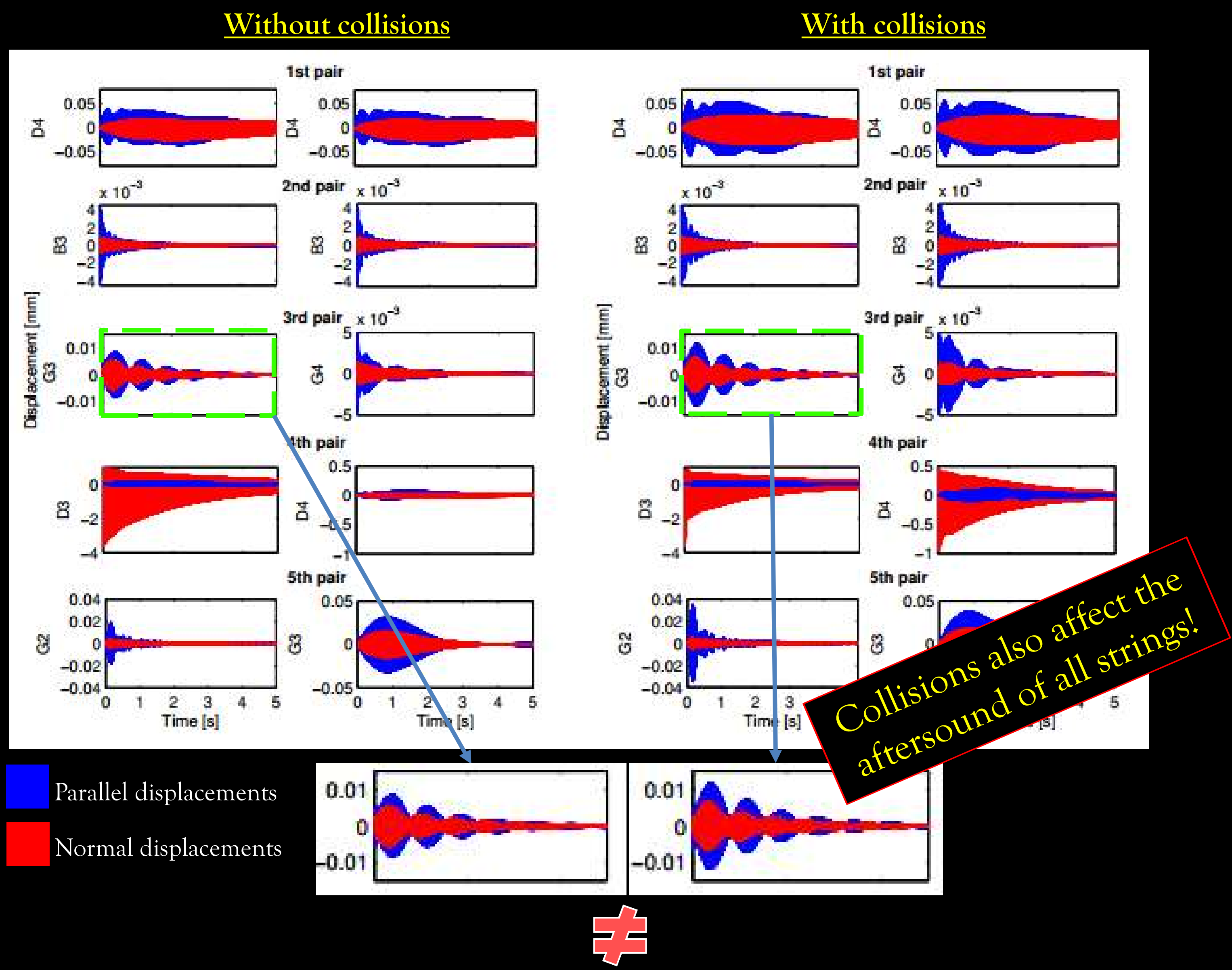


Parallel displacement

Normal displacement

- **Beating phenomena** are also observed on some strings.

Fully coupled system simulations: influence of collisions on the aftersound



Fully coupled system simulations: effect of the pluck direction

Ten strings (D4)

Parallel pluck

Ten strings (D4)

Normal pluck

- The sound halo is much more perceptible for an excitation normal to the soundboard.

VI. Application to the instrument making: tools for makers

Goal

- Collaboration with pafi : Music Instrument Making Platform
- http://pafi.univ-lemans.fr
- Integration to the platform

  i/ Wire technique: low cost technique for measuring mobilities

  ii/ Sound synthesis tool

VII. Conclusions and perspectives

Conclusions

- Specificities of the *viola caipira* :
  i) Particular double pluck
  ii) Sympathetic resonances and beating phenomena
  iii) **Collisions between strings.**

- A physical model for sound synthesis including **string/string collisions**. It reproduces the main sound features of the *viola caipira*.

- Collision effects on the sound:
  - Buzzing effect/spectral enrichment
  - Redistribution of spectral components
  - Polarization change

- The Roving Wire-Breaking Technique:
  - Novel procedure for modal analysis
  - Low cost and suitable for instrument makers

Perspectives

- Parameters adjustment and experimental validation of the sound synthesis model
- Inclusion of string non-linearities
- Sound radiation model

Turbonius

R&D Projects

- **URUTAU PROJECT**: “Cloud environment for design, analysis and simulation of musical instruments”.
- **XURI PROJECT**: “Small room acoustic correction – web application for optimal treatment”.

Acoustic consulting ...

Acoustic panels manufacturing ...

Contact: **pitupaiva@gmail.com**

The synthesized viola caipira!

Thank you for your attention.

O Violeiro by Almeida Júnior, 1899.

Scientific production

Articles

- G. Paiva, F. Ablitzer, F. Gautier and J. M. C. dos Santos, "Collisions in double string plucked instruments: physical modelling and sound synthesis of the *viola caipira*", Journal of Sound and Vibration.
- G. Paiva, F. Ablitzer, F. Gautier and J. M. C. dos Santos, "The Roving Wire-Breaking Technique: a low cost mobility measurement pro cedure for string musical instruments", Applied Acoustics.

Yamaha Music Internship

- Numerical Analysis of Electric Guitars, March/2017 – July/2017.

Conference papers

- G. Paiva, J. M. C. dos Santos, Modelling Fluid-Structure Interaction in a Brazilian Guitar Body. In: International Congress on Mechanical Engineering, Ribeirão Preto, Brazil, 2013.
- G. Paiva, J. M. C. dos Santos, Vibroacoustic Modal Analysis of a Brazilian Guitar Resonance Box. In: International Conference on Structural Engineering Dynamics, Sesimbra, Portugal, 2013.
- G. O. Paiva, J. M. C. dos Santos, Modal Analysis of a Brazilian Guitar Body. In: International Symposium on Musical Acoustics, 2014, Le Mans, France, 7-12 July 2014.
- G.O. Paiva, F.Gautier, F.Ablitzer, J.M.C dos Santos, M. Sécail-Géraud, Measuring the Mobility Matrix at the Bridge of Stringed Instruments by the Wire Breaking Method, 2016, Le Mans, France, 11-15 April 2016.
- F. Gautier, F. Ablitzer, G. Paiva, B. David, M. Curtit, M. Sécail, E. Brasseur, G. Michelin, Methodologies and tools for characterising stringed musical instruments in the maker's workshop, Making wooden musical instruments: an integration of different forms of knowledge, 7-9 September, Barcelona, 2016.

Poster presentations

- G.O. Paiva, F.Gautier, F.Ablitzer, J.M.C dos Santos, Modélisation physique et synthèse sonore d'une guitare brésilienne Part. 1, Forum Jeunes Recherche, Université du Maine, Le Mans, France, 2016.
- G.O. Paiva, F.Gautier, F.Ablitzer, J.M.C dos Santos, Modélisation physique et synthèse sonore d'une guitare brésilienne Part. 2, JJCAB2016 : Journées Jeunes Chercheurs en vibration, Acoustique et Bruit 17-18 nov. Marseille, France, 2016.
- G. O. Paiva, J. M. C. dos Santos, Modal Analysis of a Brazilian Guitar Body. In: International Symposium on Musical Acoustics, 2014, Le Mans, France, 7-12 July 2014.

Oral presentations

- G. O. Paiva, J. M. C. dos Santos, Vibroacoustic Numerical Analysis of a Brazilian Guitar Resonance Box. In: ESSS CONFERENCE ANSYS USERS MEETING, Atibaia, Brazil, 2013.
- G. O. Paiva, F. Gautier, F. Ablitzer, J. M. C. dos Santos, Time Domain Simulations of a Ten-String Brazilian Guitar, ViennaTalk2015, Vienna, Austria, 16-19 September 2015.
- G. O. Paiva, F. Ablitzer, F. Gautier, M. Sécail-Géraud and J. M. Campos Dos Santos, Physical Modelling and Sound Synthesis of a Viola Caipira, In: International Symposium on Musical Acoustics, Montreal, Canada, 18-22 June 2017.