IRCAM — STMS :

Quelques approches pour la synthèse sonore par modélisation physique et l'analyse des Sons

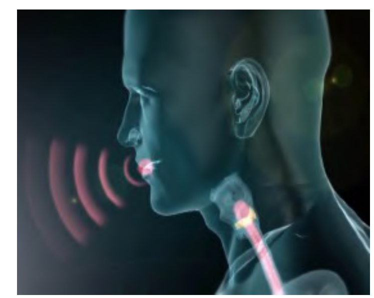
Thomas Hélie, CNRS

Equipe S3AM *(Systèmes et Signaux Sonores: Audio/acoustique, instruMents)*

Laboratoire des Sciences et Technologies de la Musique et du Son

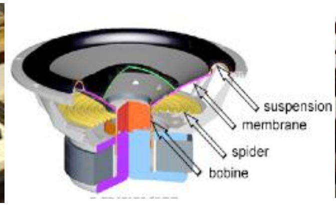
IRCAM — CNRS — Sorbonne Université

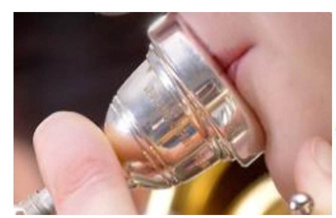
Paris, France



GdR Géométrie Différentielle et Mécanique

Novembre, 2024 — Paris





IRCAM: Institute for Research and Coordination in Acoustics/Music

Creation in 1977 by Pierre Boulez,
associated with the Georges Pompidou Center

Vocation: interaction between

- Scientific research (sound/music)
- Technological development
- Contemporary music creation

Departments (~140 people):

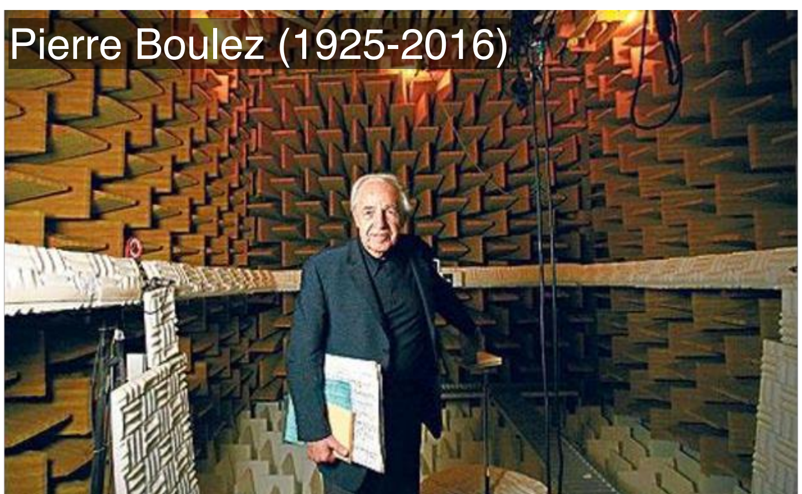
A. STMS laboratory (~100 people + 36 PhDs)

B. Creation & Diffusion (concerts+20 creations/year)

C. Education, Cultural Outreach and Resource Center

- Master ATIAM (sciences for music), Sorbonne Univ.
- Music curriculum (composers), Multimedia Library, …

D. Research/Creation Interface



IRCAM: Institute for Research and Coordination in Acoustics/Music

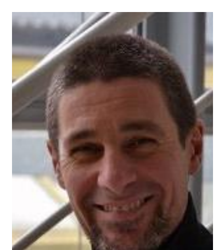
1981: 4X system by G. di Giugno

1994: voice sound processing
by P. Depalle, G. Garcia, X. Rodet

Reconstruction of a castrato voice

- 2 recorded singers:
  - coloratura soprano
  - countertenor
- analysis
- cross-synthesis

1995: creation of the **STMS laboratory**
(unit director, 2024 : N. Misdariis)



STMS laboratory: Sciences and Technologies for Music and Sound

ircam Centre Pompidou · CNRS · Sorbonne Université

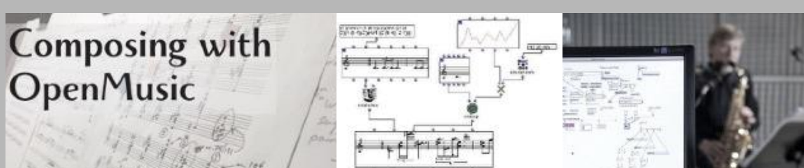
7 teams

Acoustic and Cognitive Spaces

Analysis of Musical Practices

Sound Music Movement Interaction

Musical Representations



Sound Perception and Design

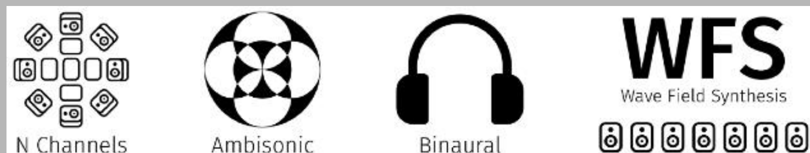
Sound Analysis-Synthesis

Sound Systems and Signals: Audio/Acoustics, Instruments

STMS laboratory: Sciences and Technologies for Music and Sound

7 teams

Acoustic and Cognitive Spaces



Analysis of Musical Practices

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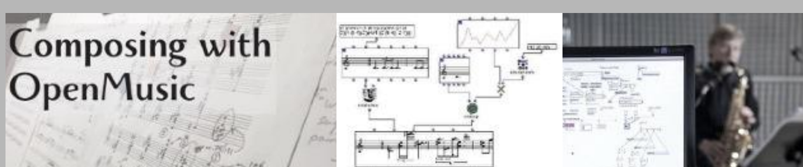


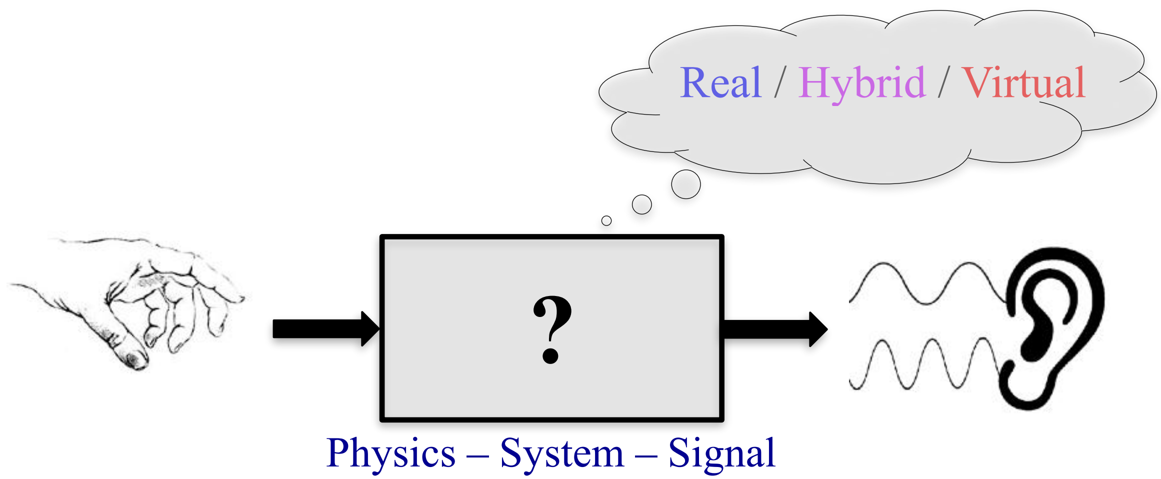
Sound Perception and Design

Sound Analysis-Synthesis

Sound Signals and Systems: Audio/Acoustics, Instruments

Sound Signals and Systems: Audio/Acoustics, Instruments

- Theoretical, technological, and experimental tools
  to address **multiphysics systems** and the sound signals they produce



- **Issues:** sound synthesis, controlled/augmented instruments, optimised design, tools for educational/health purposes

- **Emphasis on 3 points to reach realism**
  - **Nonlinearities:** (1) timbre & complex distortions, (2) self-oscillations & regimes
  - **Damping:** non trivial modelling (spectral colour)
  - **Passivity / power balance:** guarantee physical behaviours

Outline

A. IRCAM and the STMS lab

B. Modelling and simulation
- B1. Volterra series
- B2. Power-balanced multiphysics (Port-Hamiltonian systems)

C. Experimental work

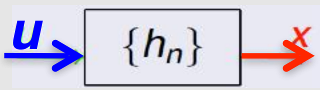
D. Visualisation

B1. Volterra series

Motivation

How to capture the timbre evolution with respect to the sound dynamics ?

→ Combine **weak nonlinearities** and **memory** *(generalised impulse responses)*

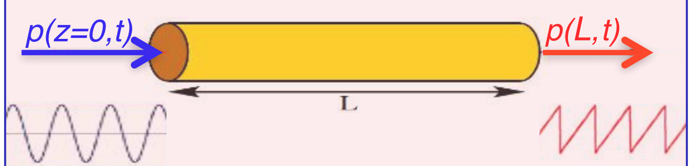


$$x(t) = \underbrace{\sum_{n\in\mathbb{N}^*}}_{\text{Sum}} \underbrace{\int_{\mathbb{R}^n} h_n(\tau_1, \ldots \tau_n)\, u(t-\tau_1)\, \ldots u(t-\tau_n)\, \mathrm{d}\tau_1 \ldots \mathrm{d}\tau_n}_{\text{of multiple convolutions}}$$

Sum of multiple convolutions → *distortions with memory for any input* ***u***

Applications

Brassy effect



$$\partial_x p + \alpha\, \partial_t^{1/2} p = \frac{\beta}{2}\, \partial_t p^2$$

damping nonlinearity

← inspired from [Menguy, Gilbert, 2000]
"Weakly nonlinear gas oscillations in air-filled tubes (…)"

B1. Volterra series

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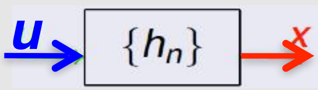

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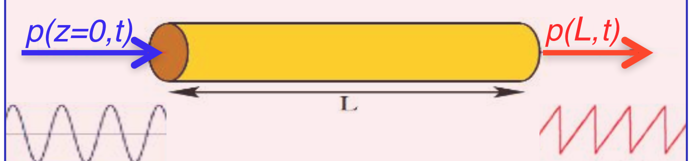

$$\partial_x p + \alpha\, \partial_t^{1/2} p = \frac{\beta}{2}\, \partial_t p^2$$

damping nonlinearity

Moog Ladder Filter

$$\partial_t x = \omega \begin{bmatrix} -\tanh x_1 + \tanh(u - 4 r x_4) \\ -\tanh x_2 + \tanh x_1 \\ -\tanh x_3 + \tanh x_2 \\ -\tanh x_4 + \tanh x_3 \end{bmatrix}$$

String (large displacement)

$$\partial_t^2 u + \alpha \partial_t u - \beta \partial_t \partial_x^2 u - \left(1 + \varepsilon \left[\int_0^1 \left(\partial_x u(x,t)\right)^2 \mathrm{d}x\right]\right) \partial_x^2 u = \Phi\, f_{tot}$$

Sound examples - real-time plugins

1. Chet Baker : without / with **brassy effect**
2. **Moog Ladder Filter** without / with **distortion** (x2)

B1. Volterra series

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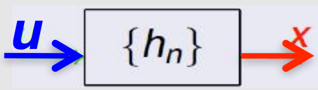

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Other results:

1. Space-time kernels: *Green functions* → *Green-Volterra series*
2. Convergence: computable convergence bounds for classes of systems

Outline

A. IRCAM and the STMS lab

B. Modelling and simulation

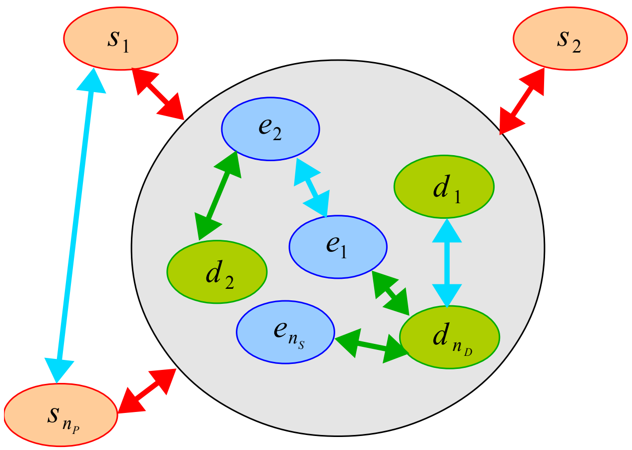
- B1. Volterra series
- B2. Power-balanced multiphysics
  - B2.1. Introduction to Port-Hamiltonian Systems
  - B2.2. Musical applications

C. Experimental work

D. Visualisation

B2.1 Power-balanced systems : Introduction to PHS

A physical system is made of. . .



(i) Energy-storing components
$E = \sum_{n=1}^{N} e_n \geq 0$

(ii) Memoryless passive components
$P_{\textbf{diss}} = \sum_{m=1}^{M} d_m > 0$ (dissipative) or $= 0$ (conservative)

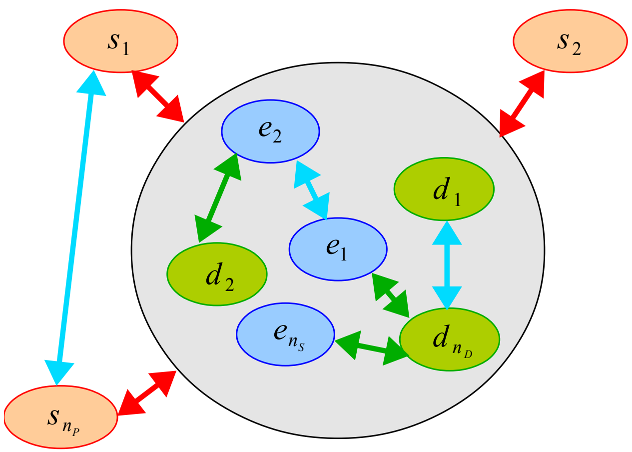
(iii) External components
$P_{\textbf{ext}} = \sum_{p=1}^{P} s_p$

$+$ Conservative connections

B2.1 Introduction to Port Hamiltonian Systems (PHS)

A physical system is made of...

⚠ receiver convention



(i) **Energy-storing components** → *store energy*

$E = \sum_{n=1}^{N} e_n \geq 0$

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$P_{\mathbf{ext}} = \sum_{p=1}^{P} s_p$

\+ Conservative connections → *sum of received powers is zero*

$P_{\mathbf{stored}} + \underbrace{P_{\mathbf{diss}}}_{\geq 0} + P_{\mathbf{ext}} = 0$ with $P_{\mathbf{stored}} = \dot{E}$ **(power balance)**

B2.1 Introduction to Port Hamiltonian Systems (PHS)

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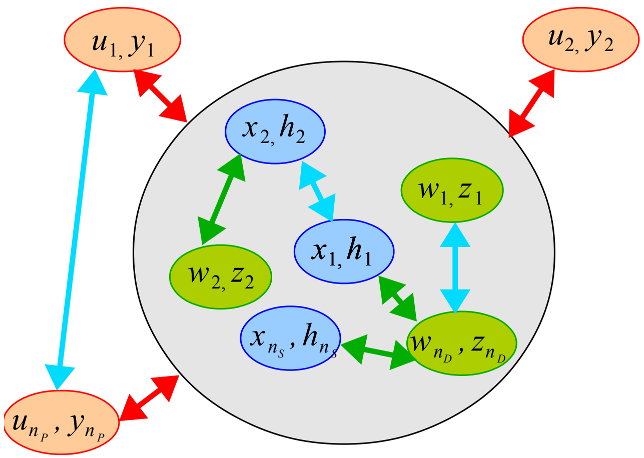
⚠ receiver convention



(i) Energy-storing components → *store energy*

$E = H(\mathbf{x}) = \sum_{n=1}^{N} H_n(x_n) \geq 0$

(ii) Memoryless passive components → *receive power*

$P_{\mathbf{diss}} = \mathbf{z}(\mathbf{w})^\mathsf{T}\mathbf{w} = \sum_{m=1}^{M} z_m(w_m)\, w_m \geq 0$

(effort × flow : force × velocity, voltage × current, etc)

(iii) External components → *receive power*

$P_{\mathbf{ext}} = \mathbf{u}^\mathsf{T}\mathbf{y} = \sum_{p=1}^{P} u_p y_p$

\+ Conservative connections → *sum of received powers is zero*

$$\underbrace{\nabla H(\mathbf{x})^\mathsf{T}\dot{\mathbf{x}}}_{P_{\text{stored}}=\mathrm{d}E/\mathrm{d}t} + \underbrace{\mathbf{z}(\mathbf{w})^\mathsf{T}\mathbf{w}}_{\geq 0} + \mathbf{u}^\mathsf{T}\mathbf{y} = 0 \qquad \textbf{(power balance)}$$

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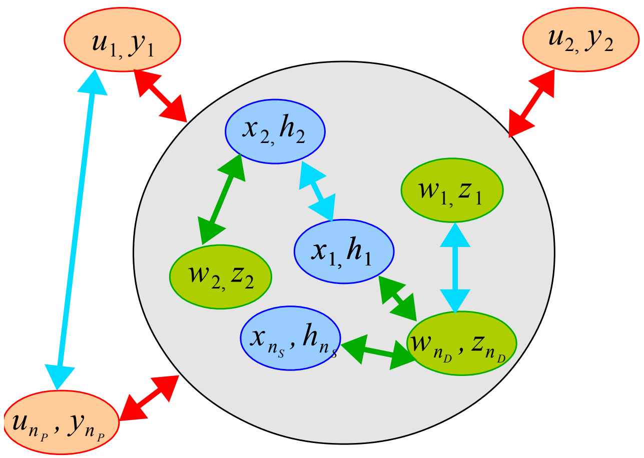

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PHS: Input-State-Output representation (**S**: interconnection matrix)

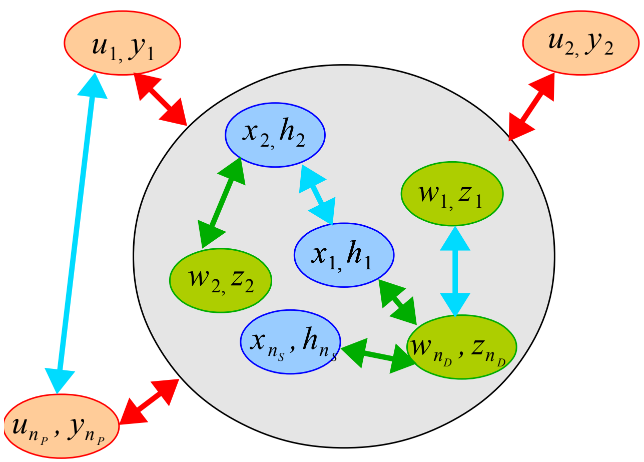
$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}} \\ \mathbf{w} \\ \mathbf{y} \end{bmatrix}}_{\mathbf{f}} = \underbrace{\begin{bmatrix} \mathbf{S_{xx}} & \mathbf{S_{xw}} & \mathbf{S_{xu}} \\ * & \mathbf{S_{ww}} & \mathbf{S_{wu}} \\ * & * & \mathbf{S_{yu}} \end{bmatrix}}_{\text{with } \mathbf{S} = -\mathbf{S}^{\mathsf{T}}} \underbrace{\begin{bmatrix} \nabla H(\mathbf{x}) \\ \mathbf{z}(\mathbf{w}) \\ \mathbf{u} \end{bmatrix}}_{\mathbf{e}} \qquad (1)$$

(*i*) storage → differential eq.
(*ii*) memoryless → algebraic eq.
(*iii*) ports → physical signals

B2.1 Introduction to Port Hamiltonian Systems (PHS)

A physical system is made of...

⚠ receiver convention



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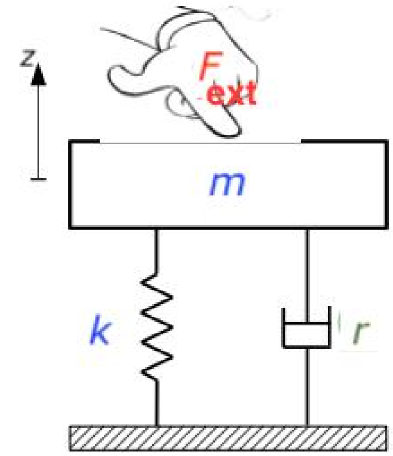
Power balance: $\mathbf{e}^{\mathsf{T}}\mathbf{f} \overset{(1)}{=} \mathbf{e}^{\mathsf{T}}\boldsymbol{S}\mathbf{e} = 0$ as $\boldsymbol{S} = -\boldsymbol{S}^{\mathsf{T}}$ $\Rightarrow \mathbf{e}^{\mathsf{T}}\boldsymbol{S}\mathbf{e} = (\mathbf{e}^{\mathsf{T}}\boldsymbol{S}\mathbf{e})^{\mathsf{T}} = -(\mathbf{e}^{\mathsf{T}}\boldsymbol{S}\mathbf{e})$

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Example: damped mechanical oscillator excited by F_{ext} $(m\ddot{z} + r\dot{z} + kz = F_{\text{ext}})$

(no gravity)

- **4 separate components**



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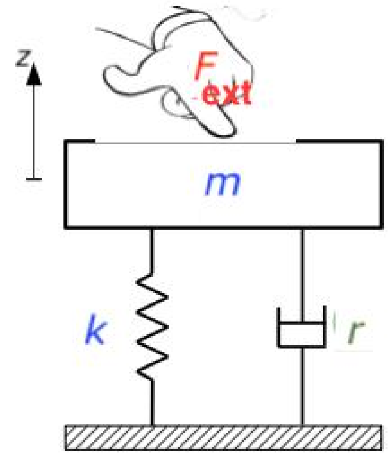

- **4 separate components**

(i$_1$) mass [m] of momentum $\pi = mv$ (energy: $\frac{1}{2}mv^2 = \frac{\pi^2}{2m}$),

	state	energy H_n	flow **f**	effort **e**
m	$x_1 := \pi$	$\pi^2/(2m)$	$\dot{x}_1 = \dot{\pi}$	$H_1'(x_1) = x_1/m$

blue : force

red : velocity

B2. Power-balanced systems

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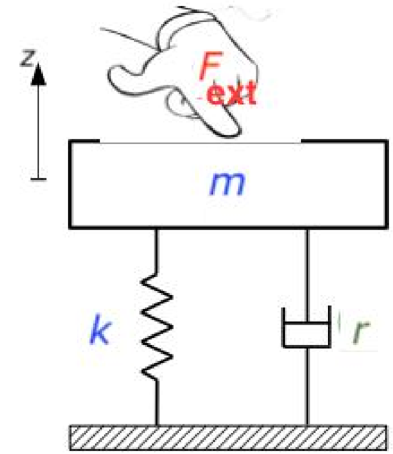

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(i$_2$) spring sp of elongation ξ

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sp	$x_2 := \xi$	$k\,\xi^2/2$	$\dot{x}_2 = \dot{\xi}$	$H_2'(x_2) = k\,x_2$
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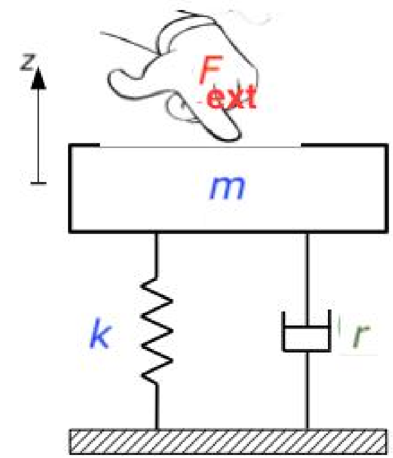

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(ii) damper $\boxed{\mathrm{dp}}$ of velocity V_{dp}

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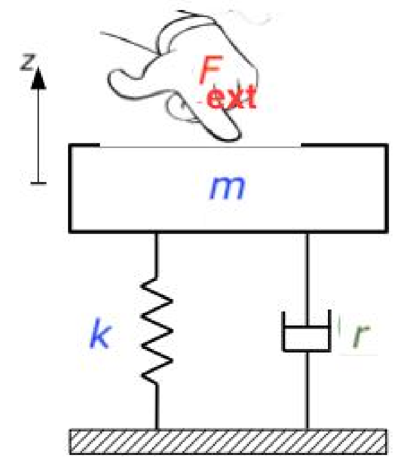

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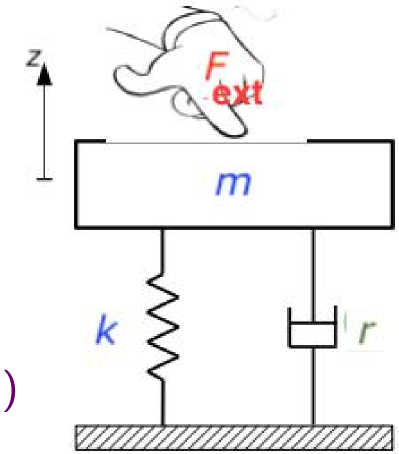

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dp	blue :	force	$w := V_{\mathrm{dp}}$	$z(w) := r\,w$
ext	red :	velocity	$y := V_{\mathrm{ext}}$	$u := -F_{\mathrm{ext}}$

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Example: damped mechanical oscillator excited by F_{ext} ($m\ddot{z} + r\dot{z} + kz = F_{\mathrm{ext}}$)

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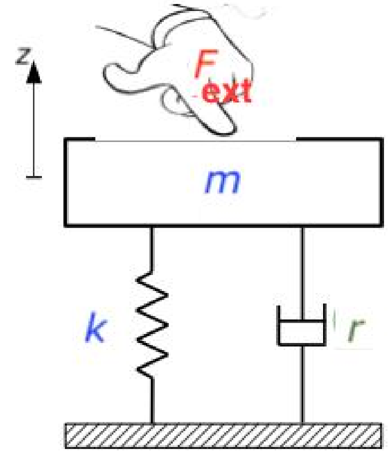

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Example: damped mechanical oscillator excited by $F_{\rm ext}$ $(m\ddot{z} + r\dot{z} + kz = F_{\rm ext})$

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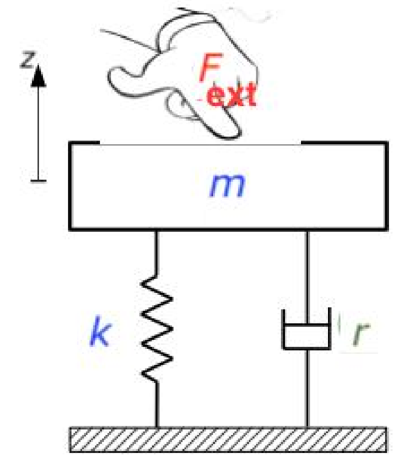
- **4 separate components**

	state	energy H_n	flow **f**	effort **e**
m	$x_1 := \pi$	$\pi^2/(2m)$	$\dot{x}_1 = \dot{\pi}$	$H_1'(x_1) = x_1/m$
sp	$x_2 := \xi$	$k\,\xi^2/2$	$\dot{x}_2 = \dot{\xi}$	$H_2'(x_2) = k\,x_2$
dp		blue : force	$w := V_{\rm dp}$	$z(w) := r\,w$
ext		red : velocity	$y := V_{\rm ext}$	$u := -F_{\rm ext}$



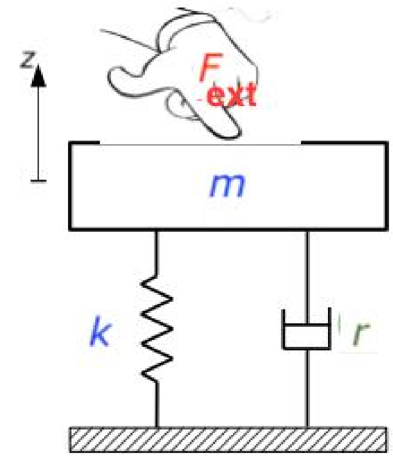
- **assembled with rigid connections**

$$\underbrace{\begin{array}{r} \dot{\pi} = F_{\rm m} \\ \dot{\xi} = V_{\rm sp} \\ \hline V_{\rm dp} \\ \hline V_{\rm ext} \end{array} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ w \\ y \end{bmatrix}}_{\mathbf{f}} = \underbrace{\left[\begin{array}{c|c|c} & & \\ \hline & & \\ \hline & & \end{array}\right]}_{S} \underbrace{\begin{bmatrix} H_1'(x_1) \\ H_2'(x_2) \\ z(w) \\ u \end{bmatrix} \begin{array}{rl} V_{\rm m} = & \pi/m \\ F_{\rm sp} = & k\xi \\ \hline F_{\rm dp} = & r\,V_{\rm dp} \\ \hline -F_{\rm ext} & \end{array}}_{\mathbf{e}}$$

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Example: damped mechanical oscillator excited by F_{ext} $(m\ddot{z} + r\dot{z} + kz = F_{\mathrm{ext}})$

(no gravity)



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dp	blue : force		$w := V_{\mathrm{dp}}$	$z(w) := r\,w$
ext	red : velocity		$y := V_{\mathrm{ext}}$	$u := -F_{\mathrm{ext}}$

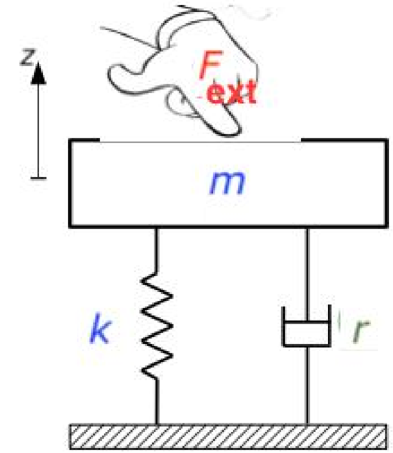
- **assembled with rigid connections**
  - internal forces are balanced $F_{\mathrm{m}} + F_{\mathrm{sp}} + F_{\mathrm{dp}} + (-F_{\mathrm{ext}}) = 0$

$$\underbrace{\begin{array}{r} \dot{\pi} = F_{\mathrm{m}} \\ \dot{\xi} = V_{\mathrm{sp}} \\ \hline V_{\mathrm{dp}} \\ \hline V_{\mathrm{ext}} \end{array} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ w \\ y \end{bmatrix}}_{\mathbf{f}} = \underbrace{\left[\begin{array}{cc|c|c} 0 & -1 & -1 & -1 \\ & & & \\ \hline & & & \\ \hline & & & \end{array}\right]}_{S} \underbrace{\begin{bmatrix} H_1'(x_1) \\ H_2'(x_2) \\ z(w) \\ u \end{bmatrix} \begin{array}{rl} V_{\mathrm{m}} = & \pi/m \\ F_{\mathrm{sp}} = & k\xi \\ \hline F_{\mathrm{dp}} = & r\,V_{\mathrm{dp}} \\ \hline -F_{\mathrm{ext}} & \end{array}}_{\mathbf{e}}$$

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Example: damped mechanical oscillator excited by F_{ext} $(m\ddot{z} + r\dot{z} + kz = F_{\text{ext}})$

(no gravity)



- **4 separate components**

	state	energy H_n	flow **f**	effort **e**
m	$x_1 := \pi$	$\pi^2/(2m)$	$\dot{x}_1 = \dot{\pi}$	$H_1'(x_1) = x_1/m$
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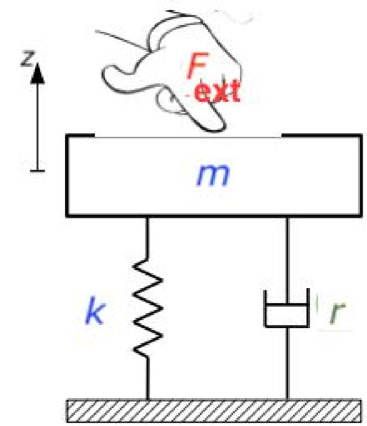
- **assembled with rigid connections**
  - internal forces are balanced $F_{\text{m}} + F_{\text{sp}} + F_{\text{dp}} + (-F_{\text{ext}}) = 0$
  - all velocities are equal $V_{\text{m}} = V_{\text{sp}} = V_{\text{dp}} = V_{\text{ext}}$

$$
\underbrace{\begin{array}{r} \dot{\pi} = F_{\text{m}} \\ \dot{\xi} = V_{\text{sp}} \\ \hline V_{\text{dp}} \\ \hline V_{\text{ext}} \end{array} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ w \\ y \end{bmatrix}}_{\mathbf{f}} = \underbrace{\begin{bmatrix} 0 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 \end{bmatrix}}_{S = -S^{\mathsf{T}}} \underbrace{\begin{bmatrix} H_1'(x_1) \\ H_2'(x_2) \\ z(w) \\ u \end{bmatrix} \begin{array}{rl} V_{\text{m}} = & \pi/m \\ F_{\text{sp}} = & k\xi \\ \hline F_{\text{dp}} = & r\,V_{\text{dp}} \\ \hline -F_{\text{ext}} & \end{array}}_{\mathbf{e}}
$$

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Example: damped mechanical oscillator excited by F_{ext} $(m\ddot{z} + r\dot{z} + kz = F_{\text{ext}})$

(no gravity)



- **4 separate components**

	state	energy H_n	flow **f**	effort **e**
m	$x_1 := \pi$	$\pi^2/(2m)$	$\dot{x}_1 = \dot{\pi}$	$H_1'(x_1) = x_1/m$
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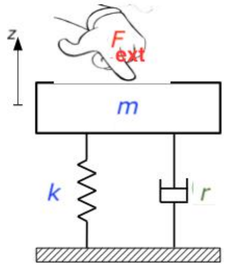
  - internal forces are balanced $F_{\text{m}} + F_{\text{sp}} + F_{\text{dp}} + (-F_{\text{ext}}) = 0$
  - all velocities are equal $V_{\text{m}} = V_{\text{sp}} = V_{\text{dp}} = V_{\text{ext}}$

$$\underbrace{\begin{array}{r} \dot{\pi} = F_{\text{m}} \\ \dot{\xi} = V_{\text{sp}} \\ \hline V_{\text{dp}} \\ \hline V_{\text{ext}} \end{array} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ w \\ y \end{bmatrix}}_{\mathbf{f}} = \underbrace{\begin{bmatrix} 0 & -1 & -1 & -1 \\ 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 \\ \hline 1 & 0 & 0 & 0 \end{bmatrix}}_{\boldsymbol{S} = -\boldsymbol{S}^\intercal} \underbrace{\begin{bmatrix} H_1'(x_1) \\ H_2'(x_2) \\ z(w) \\ u \end{bmatrix} \begin{array}{ll} V_{\text{m}} = & \pi/m \\ F_{\text{sp}} = & k\xi \\ \hline F_{\text{dp}} = & r\,V_{\text{dp}} \\ \hline -F_{\text{ext}} & \end{array}}_{\mathbf{e}}$$

→ Formulation (1) with $H(\mathbf{x}) = H_1(x_1) + H_2(x_2)$ *(ODE: with $z = \xi$)*
→ $\boldsymbol{S} = -\boldsymbol{S}^\intercal$ is canonical *(no mechanical coefficients)*

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Some variations: nonlinear components (modifying H or $\mathbf{z}$) and also...



$$\begin{pmatrix} F_{\rm m} \\ V_{\rm sp} \\ \hline V_{\rm dp} \\ \hline V_{\rm ext} \end{pmatrix} = \left(\begin{array}{cc|c|c} 0 & -1 & -1 & -1 \\ +1 & 0 & 0 & 0 \\ \hline +1 & 0 & 0 & 0 \\ \hline +1 & 0 & 0 & 0 \end{array}\right) \cdot \begin{pmatrix} V_{\rm m} \\ F_{\rm sp} \\ \hline F_C \\ \hline -F_{\rm ext} \end{pmatrix}$$

Hamiltonian systems (conservative, autonomous)

$$\begin{pmatrix} F_{\rm m} \\ V_{\rm sp} \\ \hline . \\ \hline . \end{pmatrix} = \left(\begin{array}{cc|c|c} 0 & -1 & . & . \\ +1 & 0 & . & . \\ \hline . & . & . & . \\ \hline . & . & . & . \end{array}\right) \cdot \begin{pmatrix} v_M \\ F_{\rm sp} \\ \hline . \\ \hline . \end{pmatrix}$$

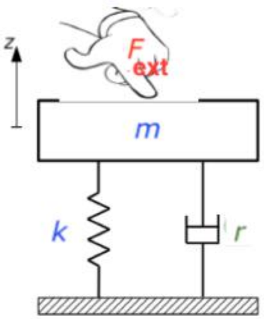
"Mass+Damper+Excitation" (spring removed)

$$\begin{pmatrix} F_{\rm m} \\ \hline . \\ \hline V_{\rm dp} \\ \hline V_{\rm ext} \end{pmatrix} = \left(\begin{array}{cc|c|c} 0 & . & -1 & -1 \\ \hline . & . & . & . \\ \hline +1 & . & 0 & 0 \\ \hline +1 & . & 0 & 0 \end{array}\right) \cdot \begin{pmatrix} V_{\rm m} \\ . \\ \hline F_C \\ \hline -F_{\rm ext} \end{pmatrix}$$

"Mass+Excitation"

$$\begin{pmatrix} F_{\rm m} \\ . \\ \hline . \\ \hline V_{\rm ext} \end{pmatrix} = \left(\begin{array}{cc|c|c} 0 & . & . & -1 \\ \hline . & . & . & . \\ \hline . & . & . & . \\ \hline +1 & . & . & 0 \end{array}\right) \cdot \begin{pmatrix} V_{\rm m} \\ . \\ \hline . \\ \hline -F_{\rm ext} \end{pmatrix}$$

B2.1 Introduction to Port Hamiltonian Systems (PHS)



$$\begin{matrix} F_{\mathrm{m}} \\ V_{\mathrm{sp}} \\ V_{\mathrm{dp}} \\ V_{\mathrm{ext}} \end{matrix} \quad \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \hline w \\ \hline y \end{pmatrix} = \left(\begin{array}{cc|c|c} 0 & -1 & -1 & -1 \\ +1 & 0 & 0 & 0 \\ \hline +1 & 0 & 0 & 0 \\ \hline +1 & 0 & 0 & 0 \end{array}\right) \cdot \begin{pmatrix} \partial_{x_1} H(\mathbf{x}) \\ \partial_{x_2} H(\mathbf{x}) \\ \hline z(w) = r\,w \\ \hline u \end{pmatrix} \quad \begin{matrix} V_{\mathrm{m}} \\ F_{\mathrm{sp}} \\ F_C \\ -F_{\mathrm{ext}} \end{matrix}$$

$$F_C = -\,r\,\partial_{x_1} H(\mathbf{x})$$

$$\begin{matrix} F_{\mathrm{m}} \\ V_{\mathrm{sp}} \\ V_{\mathrm{ext}} \end{matrix} \quad \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ y \end{pmatrix} = \left(\left(\begin{array}{cc|c} 0 & -1 & -1 \\ +1 & 0 & 0 \\ \hline +1 & 0 & 0 \end{array}\right) - \left(\begin{array}{cc|c} r & 0 & 0 \\ 0 & 0 & 0 \\ \hline 0 & 0 & 0 \end{array}\right) \right) \cdot \begin{pmatrix} \partial_{x_1} H(\mathbf{x}) \\ \partial_{x_2} H(\mathbf{x}) \\ \hline u \end{pmatrix} \quad \begin{matrix} V_{\mathrm{m}} \\ F_{\mathrm{sp}} \\ -F_{\mathrm{ext}} \end{matrix}$$

Differential formulation of PHS in "J-R"

$$\underbrace{\begin{bmatrix} \dot{\mathbf{x}} \\ \mathbf{y} \end{bmatrix}}_{\mathbf{f}} = \Bigg(\underbrace{\begin{bmatrix} J_{\mathrm{xx}} & J_{\mathrm{xu}} \\ * & J_{\mathrm{yu}} \end{bmatrix}}_{=:\; J = -J^{\mathsf{T}}} - \underbrace{\begin{bmatrix} R_{\mathrm{xx}} & R_{\mathrm{xu}} \\ * & R_{\mathrm{yu}} \end{bmatrix}}_{=:\; R = R^{\mathsf{T}} \succeq 0} \Bigg) \underbrace{\begin{bmatrix} \nabla H(\mathbf{x}) \\ \mathbf{u} \end{bmatrix}}_{\mathbf{e}} \rightarrow$$

power balance with $P_{\mathrm{diss}} = \mathbf{e}^{\mathsf{T}} R\, \mathbf{e} \geq 0$

+ Power-balanced numerical methods

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Power-balanced numerical method : discrete gradient

Classical numerical schemes for $\frac{\mathrm{d}x}{\mathrm{d}t} = f(x)$:

- efficiently approximate $\frac{\mathrm{d}.}{\mathrm{d}t}$ and exploit f
- *a posteriori* analysis of stability

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Power-balanced numerical method : discrete gradient

Classical numerical schemes for $\frac{\mathrm{d}x}{\mathrm{d}t} = f(x)$:

- efficiently approximate $\frac{\mathrm{d}.}{\mathrm{d}t}$ and exploit f
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A discrete power-balanced method (PHS)

Exploit differentiation chain rule

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \sum_n \frac{\partial H}{\partial x_n}\frac{\mathrm{d}x_n}{\mathrm{d}t} \simeq \sum_n \underbrace{\frac{H_n(x_n[k+1]) - H_n(x_n[k])}{x_n[k+1]-x_n[k]}}_{\left[\nabla_D H\left(x[k],\delta x[k]\right)\right]_n} \underbrace{\frac{x_n[k+1]-x_n[k]}{\delta t}}_{[\delta x[k]/\delta t]_n} = \frac{E[k+1]-E[k]}{\delta t}$$

Jointly substitute $\dot{\mathbf{x}} \to \delta\mathbf{x}/\delta t$ and $\nabla H(\mathbf{x}) \to \nabla_D H(\mathbf{x}, \delta\mathbf{x})$:

$$\underbrace{\begin{pmatrix} \frac{\delta \mathbf{x}}{\delta t} \\ \mathbf{w} \\ -\mathbf{y} \end{pmatrix}}_{\mathbf{f}[k]} = \mathbf{S} \underbrace{\begin{pmatrix} \nabla_D H(\mathbf{x},\delta\mathbf{x}) \\ \mathbf{z}(\mathbf{w}) \\ \mathbf{u} \end{pmatrix}}_{\mathbf{e}[k]}$$

Simulation : solve $(\delta\mathbf{x}, w)$ at each time step k (e.g. Newton-Raphson algo.)

B2.1 Introduction to Port Hamiltonian Systems (PHS)

Power-balanced numerical method : discrete gradient

Classical numerical schemes for $\frac{\mathrm{d}x}{\mathrm{d}t} = f(x)$:

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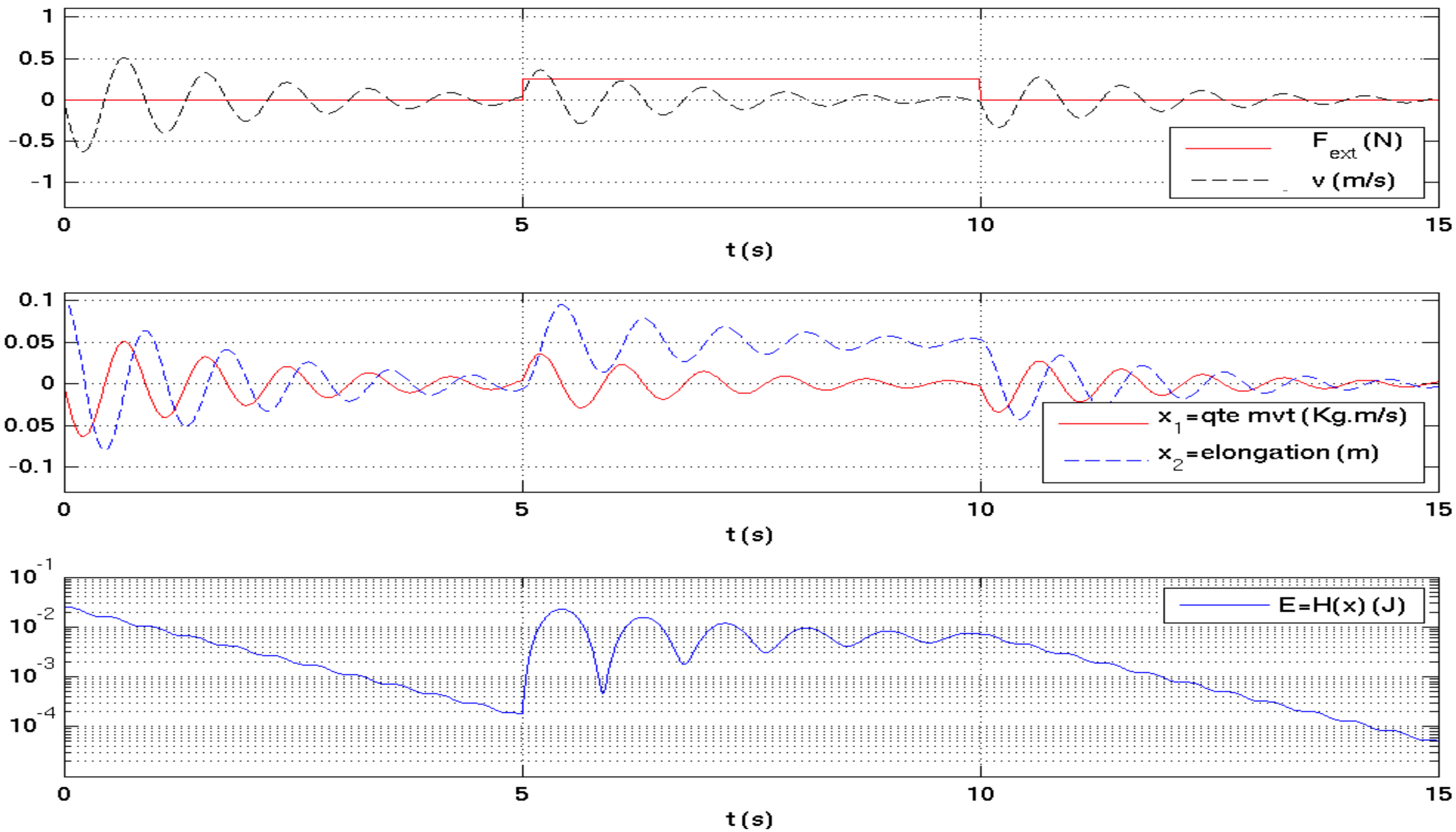
Simulation : solve $(\delta\mathbf{x}, w)$ at each time step k (e.g. Newton-Raphson algo.)

- Skew-symmetry of S preserved $\Rightarrow$ $0 = \mathbf{e}^T\mathbf{S}\mathbf{e} = \mathbf{e}^\mathsf{T}\mathbf{f} = \delta E/\delta t + \mathbf{z}(\mathbf{w})^T\mathbf{w} + \mathbf{u}^T\mathbf{y}$
- For **linear systems**, $\nabla_D H(\mathbf{x},\delta\mathbf{x}) = \nabla H(\mathbf{x}+\delta\mathbf{x}/2)$ restores the **mid-point scheme**.
- Method also applies to nonlinear components and non separate Hamiltonian
- Power-balanced Runge-Kutta scheme (non iterative) [Lopes et al., LHMNC'2015]

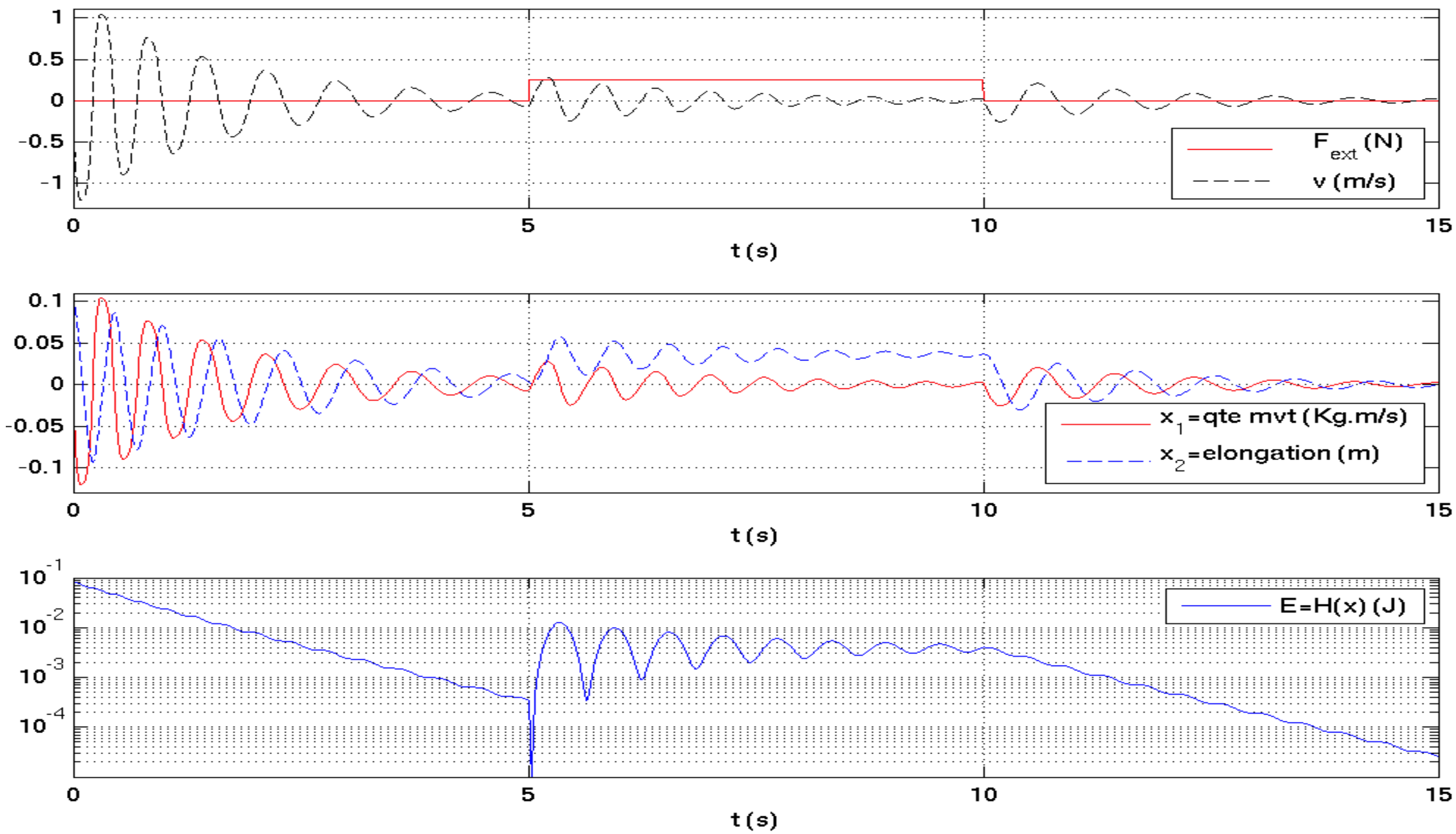
Simulation 1: mass-spring-damper

- **Parameters:** $M = 100\,\mathrm{g}$, $K = 5\,\mathrm{N/m}$, $C = 0.1\,\mathrm{N.s/m}$ et $\delta t = 5\,\mathrm{ms}$
- **Initial conditions:** $x_0 = \left[m v_0 = 0,\ \ell_0 = 10\,\mathrm{cm} \right]^T$
- **Excitation:** $F_{\mathrm{ext}}(t) = F_{\mathrm{max}}\, \mathbf{1}_{[5s,10s]}(t)$ with $F_{\mathrm{max}} = K\ell_0/2 = 0.25\,\mathrm{N}$



Simulation 2: idem with a hardening spring

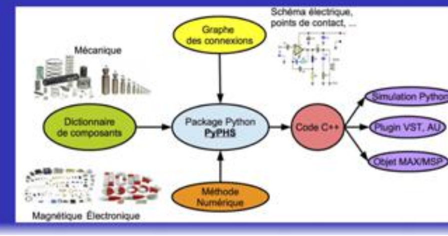
- **Potential energy:** $H_2^{\mathrm{NL}}(x_2) = K\,L^2\left[\cosh(x_2/L) - 1\right] \quad \left(\sim k\,x_2^2/2\right)$
- **Physical law:** $F_2 = \left(H_2^{\mathrm{NL}}\right)'(x_2) = K\,L\,\sinh(x_2/L) \quad \left(\sim K\,x_2\right)$
- **Reference elongation:** $L = \ell_0/4 = 25\,\mathrm{mm}$



B2.2a Musical Applications (PHS)

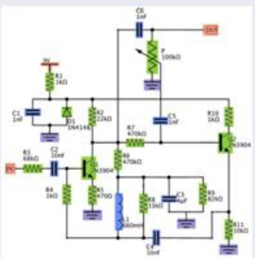
PhD, July 2016: Antoine Falaize

Passive modelling, simulation, code generation and correction of audio multi-physical systems



→ librairie open-source : https://pyphs.github.io/pyphs

Wah pedal (CryBaby): netlist → PyPHS → LateX eq. & Simulation C code



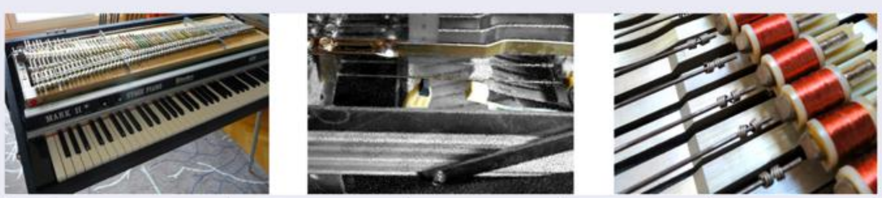
Components	Number
Storage	7 linear
Dissipative	18 (5 NL, 2 modulated)
Ports	3 (IN, OUT, battery)

Audio PlugIn:

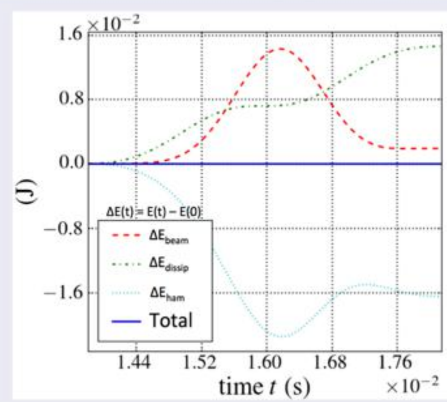
Sound 1 : dry

Sound 2 : wah

A simplified Fender-Rhodes Piano



Components	Hammer	1 beam	Pickup/RC-circuit
Storage	2 NL	$2M$ lin.	2 lin. (+ NL connection)
Dissipative	1 NL	M lin.	1 lin.
Ports	2	1	1



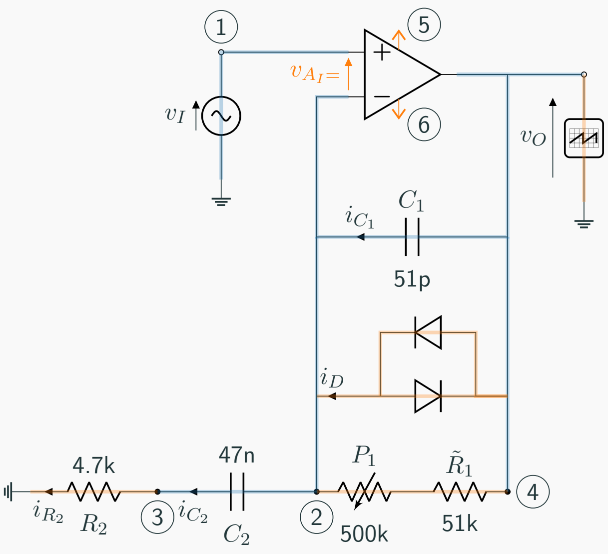
B2.2b Musical Applications (PHS)

PhD, July 2021: Rémy Müller

Time-continuous power-balanced simulation of nonlinear audio circuits: realtime processing framework and aliasing rejection

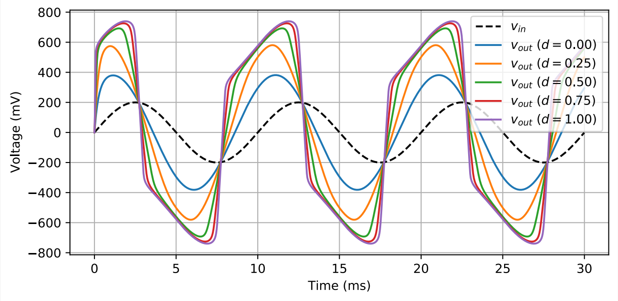
Tube screamer effect

Circuit



- 13 branches
- **PH-ODE** simulation

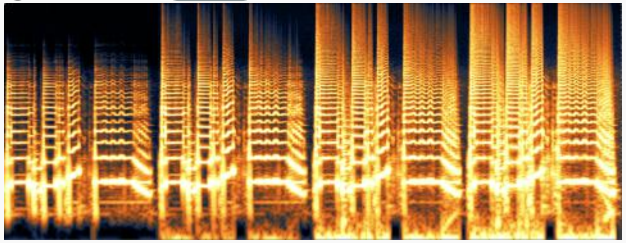
Simulation



projection $\equiv$ **RPM(1,0)**

Newton method: avg 1.52 iteration

Sounds ▸ play



Dry $\rightarrow$ Drive$= 0 \rightarrow 50 \rightarrow 100$ %

(constant loudness: -14dBLKFS)

B2.2e Musical Applications (PHS)

2D Berger plate + fluid damping + nonlinearity *[CFA'18 with D. Roze, STMS]*

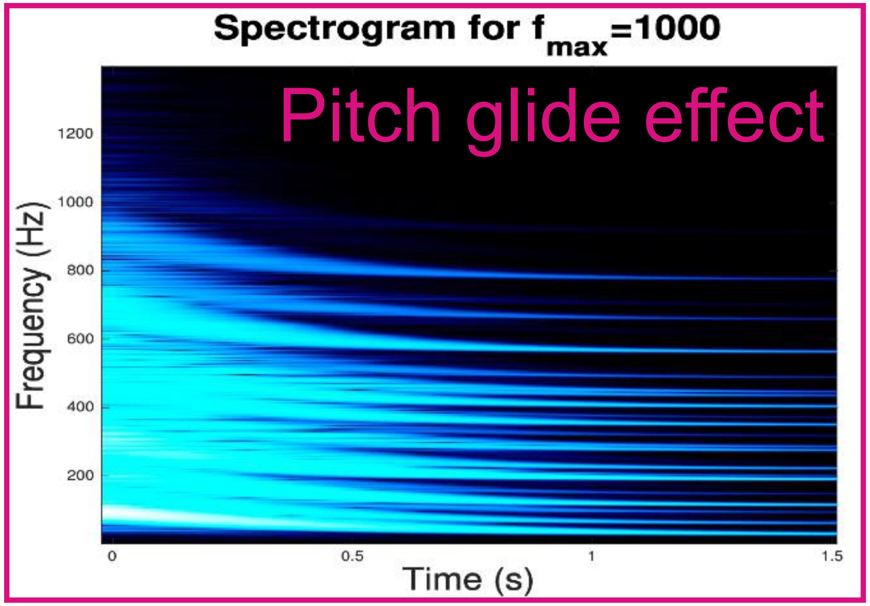
$$\partial_t^2 w + \alpha \partial_t w + \Delta\Delta w - \epsilon \int\int |\nabla w|^2 \mathrm{d}S \Delta w = f$$

+ Boundary Conditions (simply supported)

$$\begin{cases} \partial_t x &= (\mathcal{J} - \mathcal{R}) & \delta_x \mathcal{H}(x) & + \mathcal{G}\, u \\ y &= & \mathcal{G}^* \quad \delta_x \mathcal{H}(x) \end{cases}$$

Exact modal reduction

$$\partial_t X = (J - R)\nabla H(X) + G\,U$$



B2.2f Musical Applications (PHS)

$M(z)\ddot{w}(z,t) + \mathcal{K}(z)w(z,t) = f(z,t) \quad \text{for all} \quad (z,t) \in \Omega \times \mathbb{R}_+$

Linear conservative mechanical boundary problems

+ linear damping models preserving eigenmodes (generalise Caughey series)

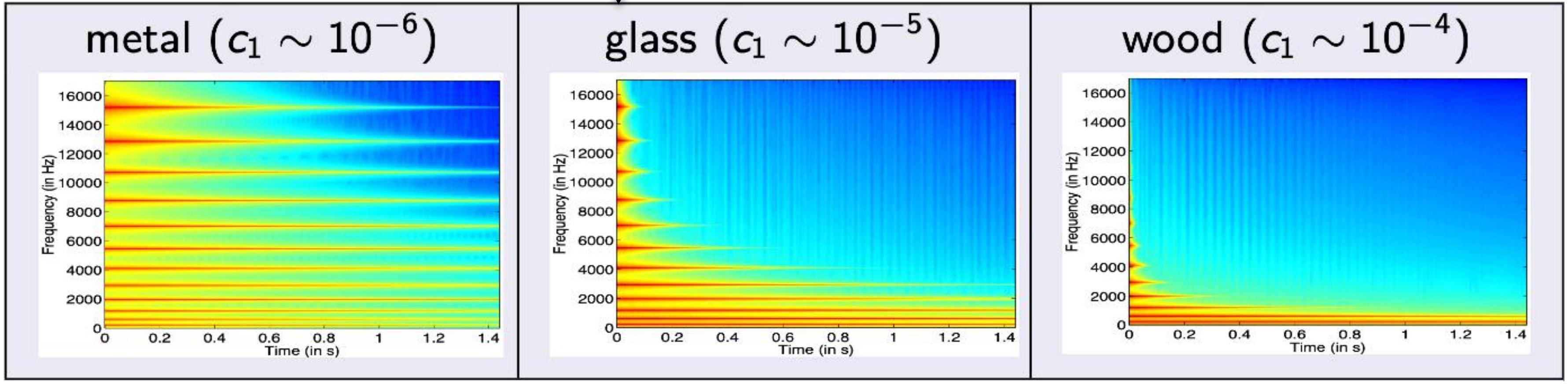
= musical instruments for various materials *[with D. Matignon, Sup'Aéro]*

Linear Beam

$$\underbrace{\partial_t^2 q}_{\mathcal{M}\equiv Id} + \underbrace{(c_0 + c_1 \partial_\ell^4)}_{\mathcal{C}} \partial_t q + \underbrace{\partial_\ell^4}_{\mathcal{K}} q = f_{\text{ext}}$$

+ Boundary Conditions (simply supported)

PHS
+ modal decomposition
+ power-balanced simulation



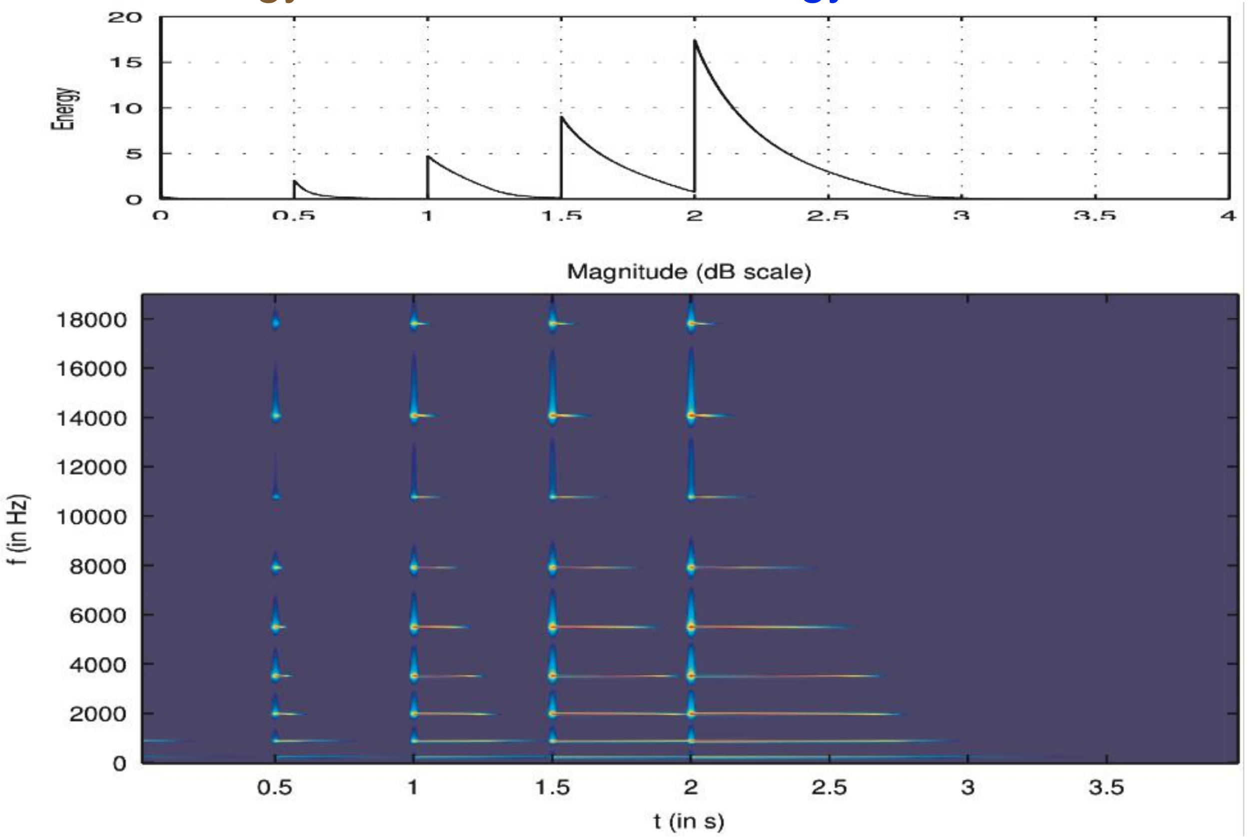
B2.2f Musical Applications (PHS)

Linear conservative mechanical boundary problems

+ nonlinear damping models preserving eigenmodes (generalises Caughey series)

= musical instruments with material morphing *[with D. Matignon, Sup'Aéro]*

Energy<<1 → wood Energy>>1 → metal



B2.2f Musical Applications (PHS)

Idem for a 2D plate

	PDE	Hamiltonian
Function	w	$X := \begin{bmatrix} \vec{q} := \vec{\mathrm{grad}}\, w \\ p := \rho_0 \partial_t w \end{bmatrix}$
Energy	E	$= H(X) = \frac{1}{2} \int_\Omega (T_0 \vec{q}^{\,2} + p^2/\rho_0)\, \mathrm{d}x\mathrm{d}y$
Formal dyn. eq	$M\ddot{w} + \mathcal{K}w = f$	$\partial_t X = \begin{bmatrix} 0 & \mathcal{J}_{qp} \\ -\mathcal{J}_{qp}^* & 0 \end{bmatrix} \underbrace{\delta_X H(X)}_{\mathcal{L}X} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} f$
Membrane equation	$\rho_0 \ddot{w} - T_0 \Delta w = f$	$\partial_t X = \begin{bmatrix} 0 & \vec{\mathrm{grad}} \\ \mathrm{div} & 0 \end{bmatrix} \begin{bmatrix} T_0 I_2 & 0 \\ 0 & \frac{1}{\rho_0} \end{bmatrix} X + \begin{bmatrix} 0 \\ 1 \end{bmatrix} f$

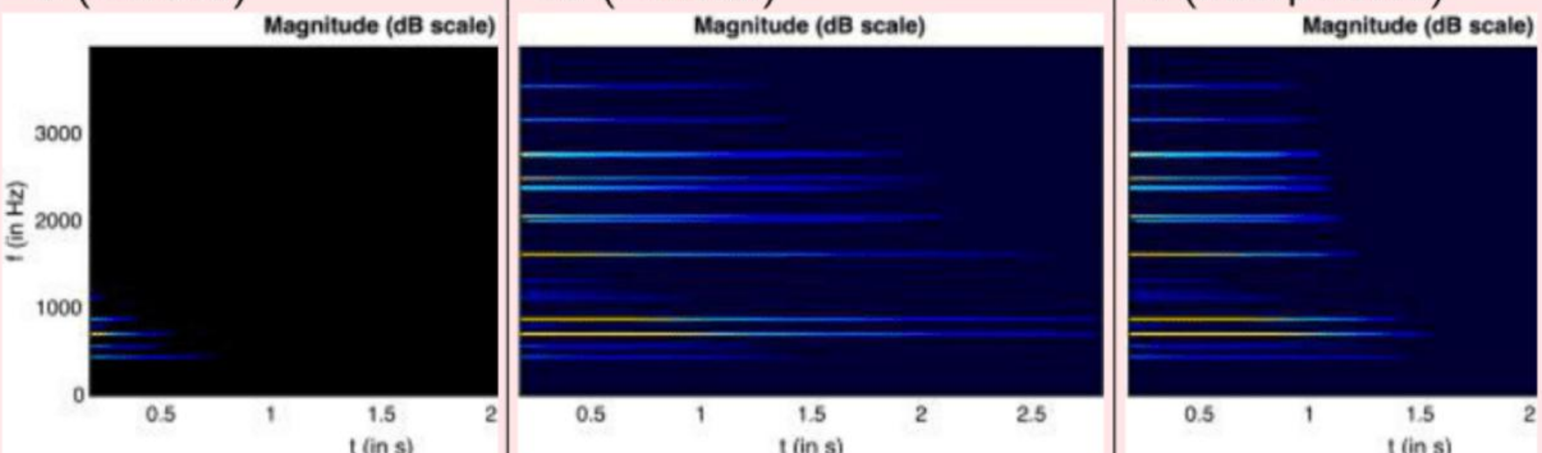
PHS +NL damping R

$$\partial_t X = (\mathcal{J} - \mathcal{R})\, \mathcal{L}X + [0, 1]^\intercal f$$

$$\mathcal{L}\mathcal{R} = \underbrace{\begin{bmatrix} 0_{qq} & 0_{qp} \\ 0_{pq} & I_{pp} \end{bmatrix}}_{\text{momentum selection}} \mathbb{P}\big[(\mathcal{L}\mathcal{J})^* (\mathcal{L}\mathcal{J}) \big]$$

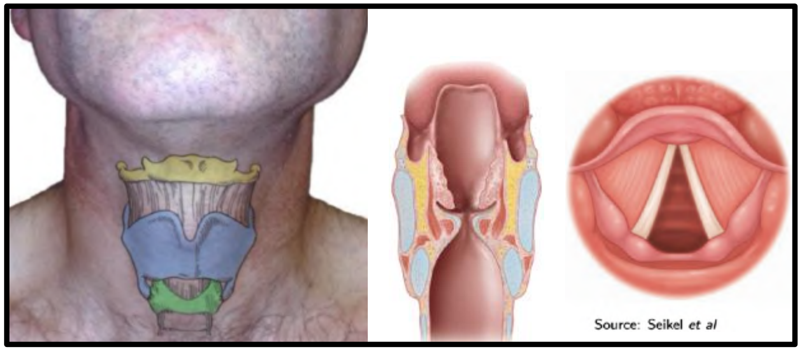
Simulation & Spectrograms

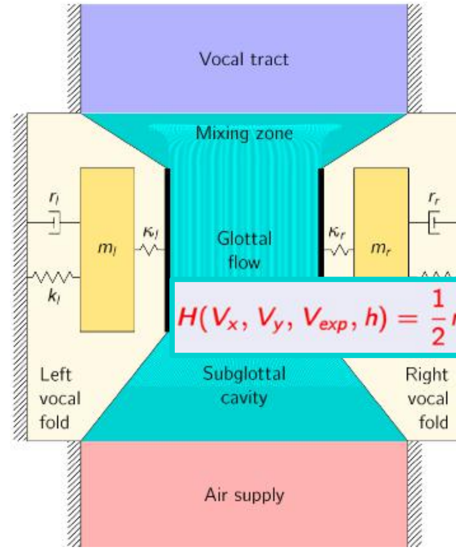
0 (∼wood) | ∞ (∼metal) | c (interpolated)



B2.2g Minimal power-balanced Vocal Apparatus

[with F. Silva, LMA-Marseille]





$$H(V_x, V_y, V_{exp}, h) = \frac{1}{2} m(h) \left(V_x^2 + V_y^2\right) + \frac{1}{2} m_e(h) V_{exp}^2$$

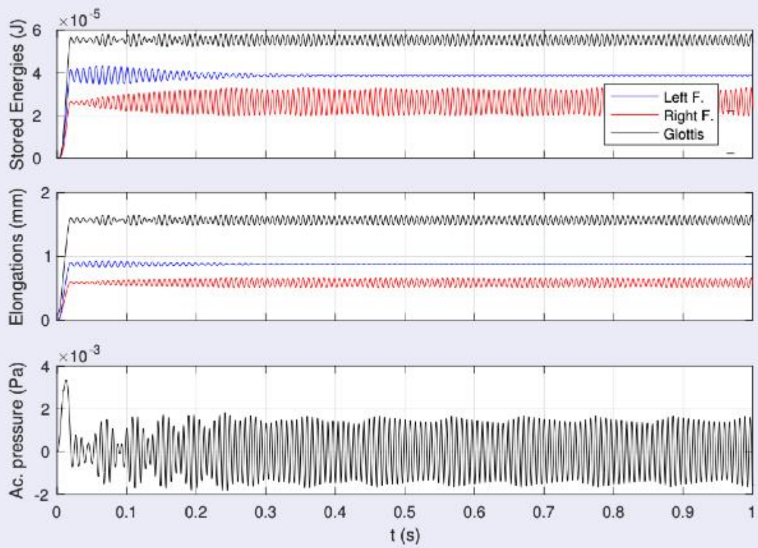
PHS with dimension = 12

$$
\begin{array}{c}
\text{Right vocal fold} \\ \text{Left vocal fold} \\ \text{Glottal flow} \\ \text{Vocal tract} \\ \text{Mixing} \\ \text{Port}
\end{array}
\quad
\begin{pmatrix}
\dot{\xi}_r \\ \dot{\pi}_r \\ \dot{\eta}_r \\ \hline \dot{\xi}_l \\ \dot{\pi}_l \\ \dot{\eta}_l \\ \hline \dot{\Pi}_x \\ \dot{\Pi}_y \\ \dot{\Pi}_{exp} \\ \dot{h} \\ \hline \dot{X}_1^{ac} \\ \dot{Y}_1^{ac} \\ \hline w_{mix} \\ \hline -Q_{sub}
\end{pmatrix}
=
\left(\begin{array}{ccc|ccc|cccc|cc|c|c}
 & 1 & & & & & & & & & & & & \\
-1 & -r_r & 1 & & & & & & & & -S^r_{sup} & & & -S^r_{sub} \\
 & -1 & & & & & & \frac{h_0}{h} & -1 & & & & & \\
\hline
 & & & & 1 & & & & & & & & & \\
 & & & -1 & -r_l & 1 & & & & & -S^l_{sup} & & & -S^l_{sub} \\
 & & & & -1 & & & -\frac{h_0}{h} & -1 & & & & & \\
\hline
 & & & & & & & & & & -L_0 h_0 & & -L_0 h_0 & L_0 h_0 \\
 & & -\frac{h_0}{h} & & & \frac{h_0}{h} & & & & & & & & \\
 & & 1 & & & 1 & & & & -2 & 2L_0\ell_0 & & 2L_0\ell_0 & 2L_0\ell_0 \\
 & & & & & & & & 2 & & & & & \\
\hline
 & S^r_{sup} & & & S^l_{sup} & & L_0 h_0 & & -2L_0\ell_0 & & -R_{ac} & -1 & & \\
 & & & & & & & & & & 1 & & & \\
\hline
 & & & & & & L_0 h_0 & & -2L_0\ell_0 & & & & & \\
\hline
 & S^r_{sub} & & & S^l_{sub} & & -L_0 h_0 & & -2L_0\ell_0 & & & & &
\end{array}\right)
\begin{pmatrix}
\partial_{\xi_r} H \\ \partial_{\pi_r} H \\ \partial_{\eta_r} H \\ \hline \partial_{\xi_l} H \\ \partial_{\pi_l} H \\ \partial_{\eta_l} H \\ \hline \partial_{\Pi_x} H \\ \partial_{\Pi_y} H \\ \partial_{\Pi_{exp}} H \\ \partial_h H \\ \hline \nabla_{X_1^{ac}} H \\ \nabla_{Y_1^{ac}} H \\ \hline z_{mix} \\ \hline P_{sub}
\end{pmatrix}
$$

B2.2g Minimal power-balanced Vocal Apparatus

Strong asymmetry

$k_l = 100\,\mathrm{N\,m^{-1}}$ (112 Hz)
$k_r = 149\,\mathrm{N\,m^{-1}}$ (137 Hz)
with adduction ($h_r = 0.1\,\mathrm{mm}$)

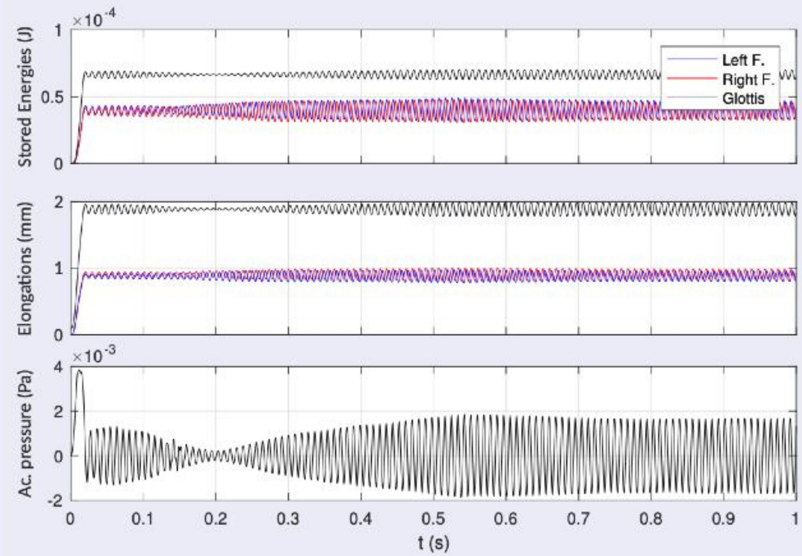


Quasi-periodic oscillations:

- starting on the left (lax) vocal fold,
- transferred to the right (stiffer) fold for the steady state regime.

Adduction (nearly closed, $h_r = 0.1\,\mathrm{mm}$)

Slightly detuned vocal folds
$k_l = 100\,\mathrm{N\,m^{-1}}$ (112 Hz)
$k_r = 97\,\mathrm{N\,m^{-1}}$ (110 Hz)



Periodic oscillations:

- Oscillation stabilized after some transient
- Synchronized folds vibrations even without contact between folds

☞ *Self-oscillation threshold & Phonation & Dysphonia*

+ [V. Wetzel, PhD'21] + [T. Risse, PhD'25] + [ANR AVATARS 2023-2027]

Outline

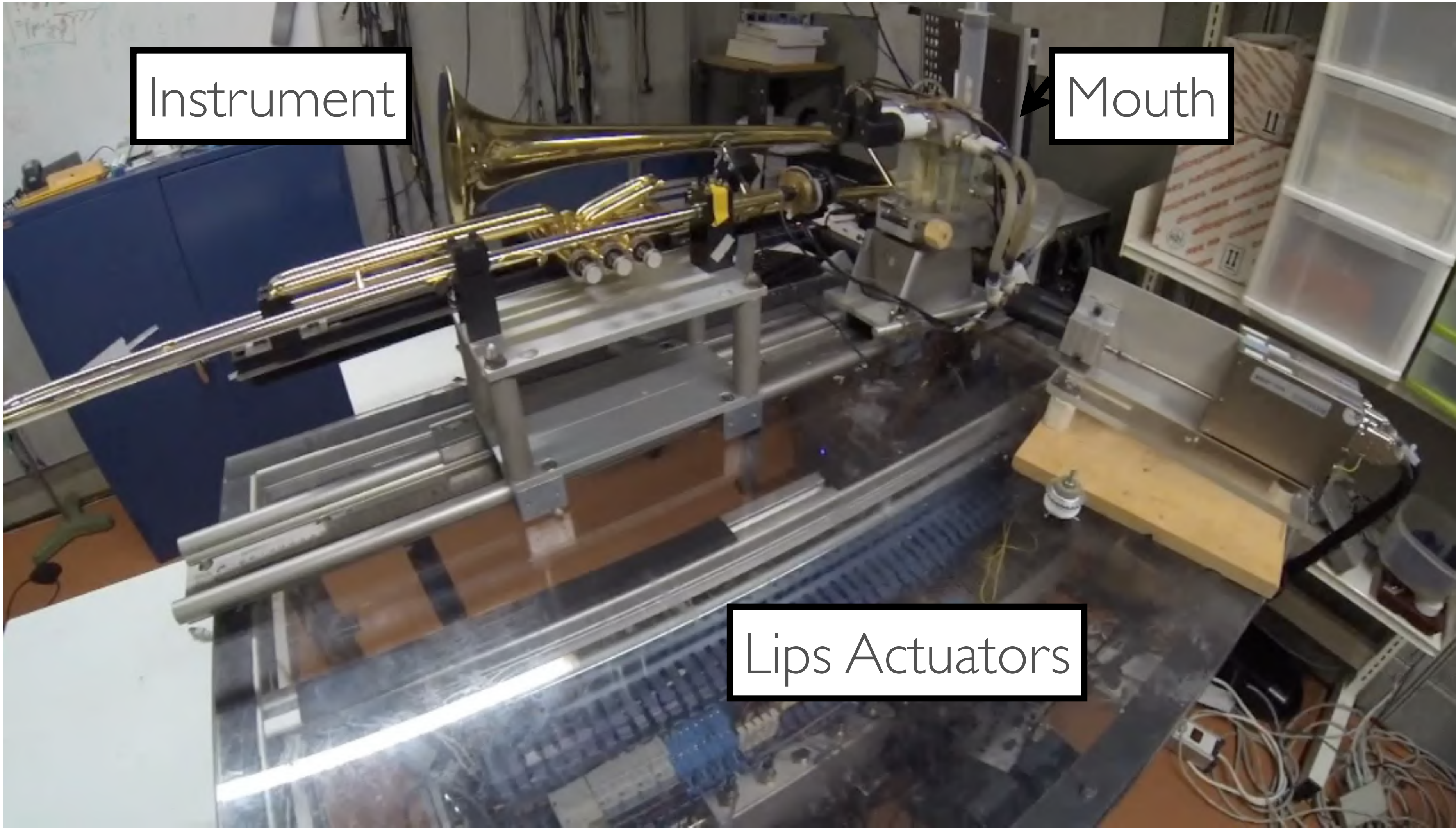
A. IRCAM and the STMS lab

B. Modelling and simulation

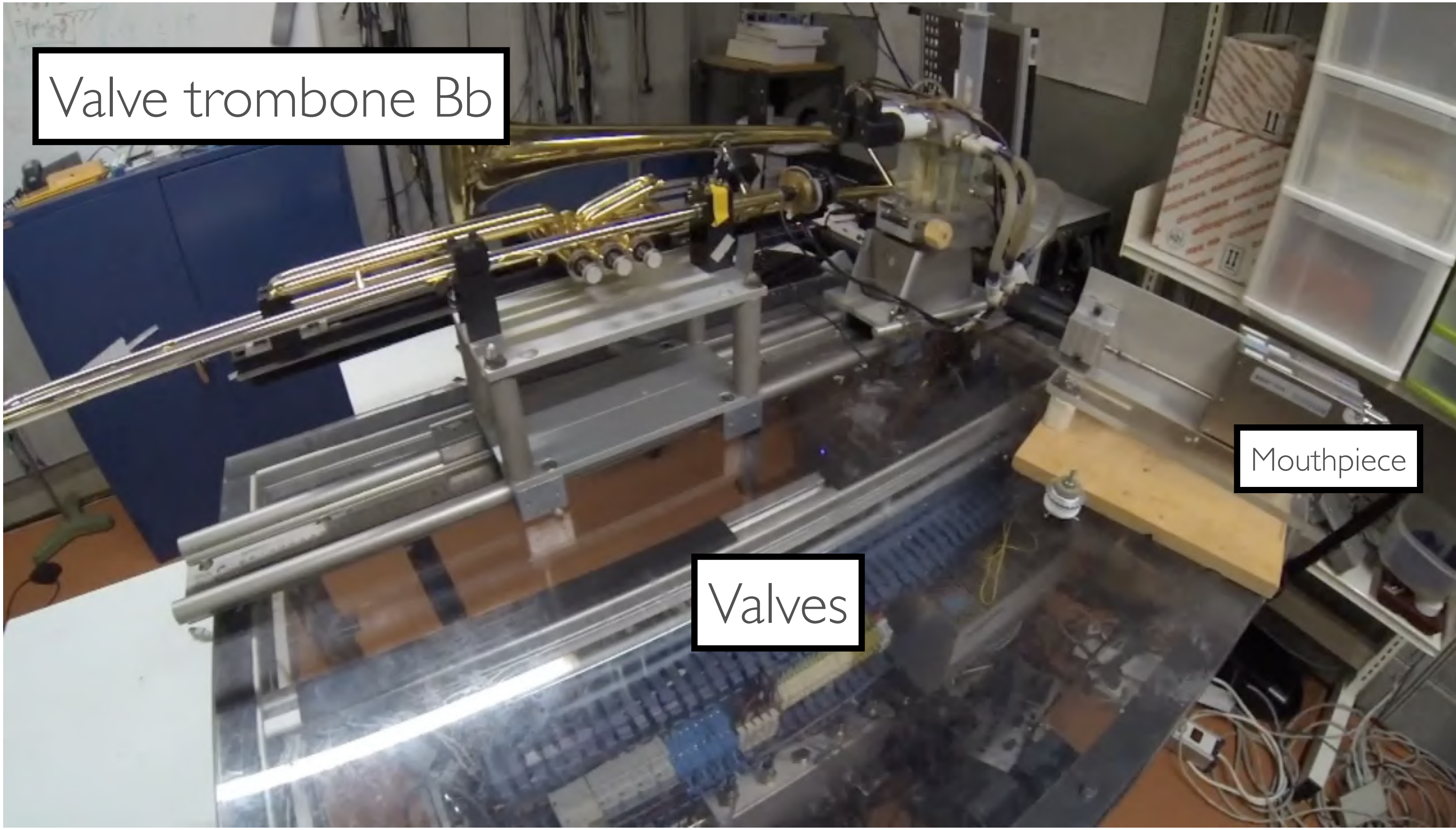
C. Experimental work
   Robotised artificial mouth for brass instruments

D. Visualisation

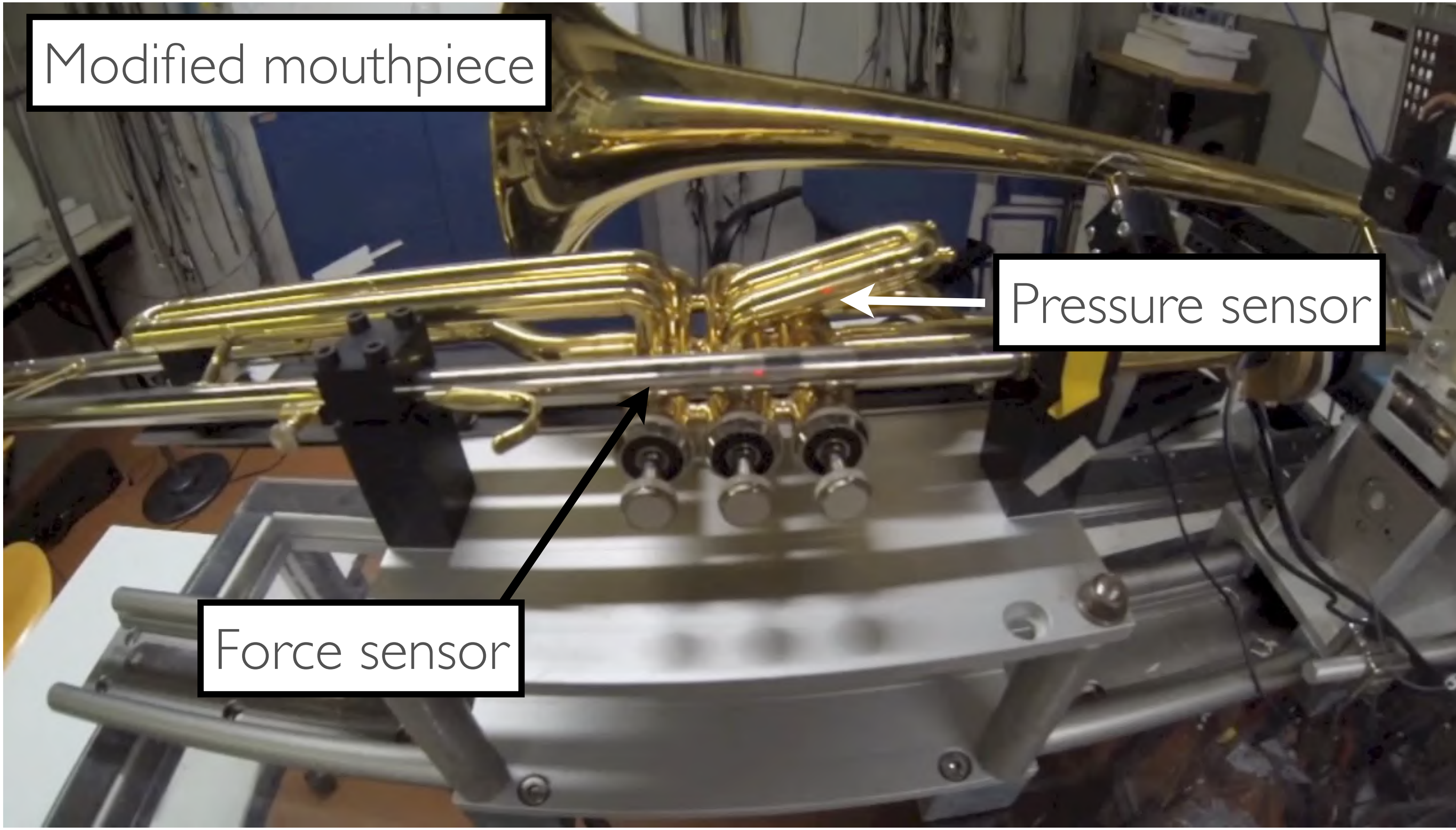
Robotised Artificial Mouth for brass instruments



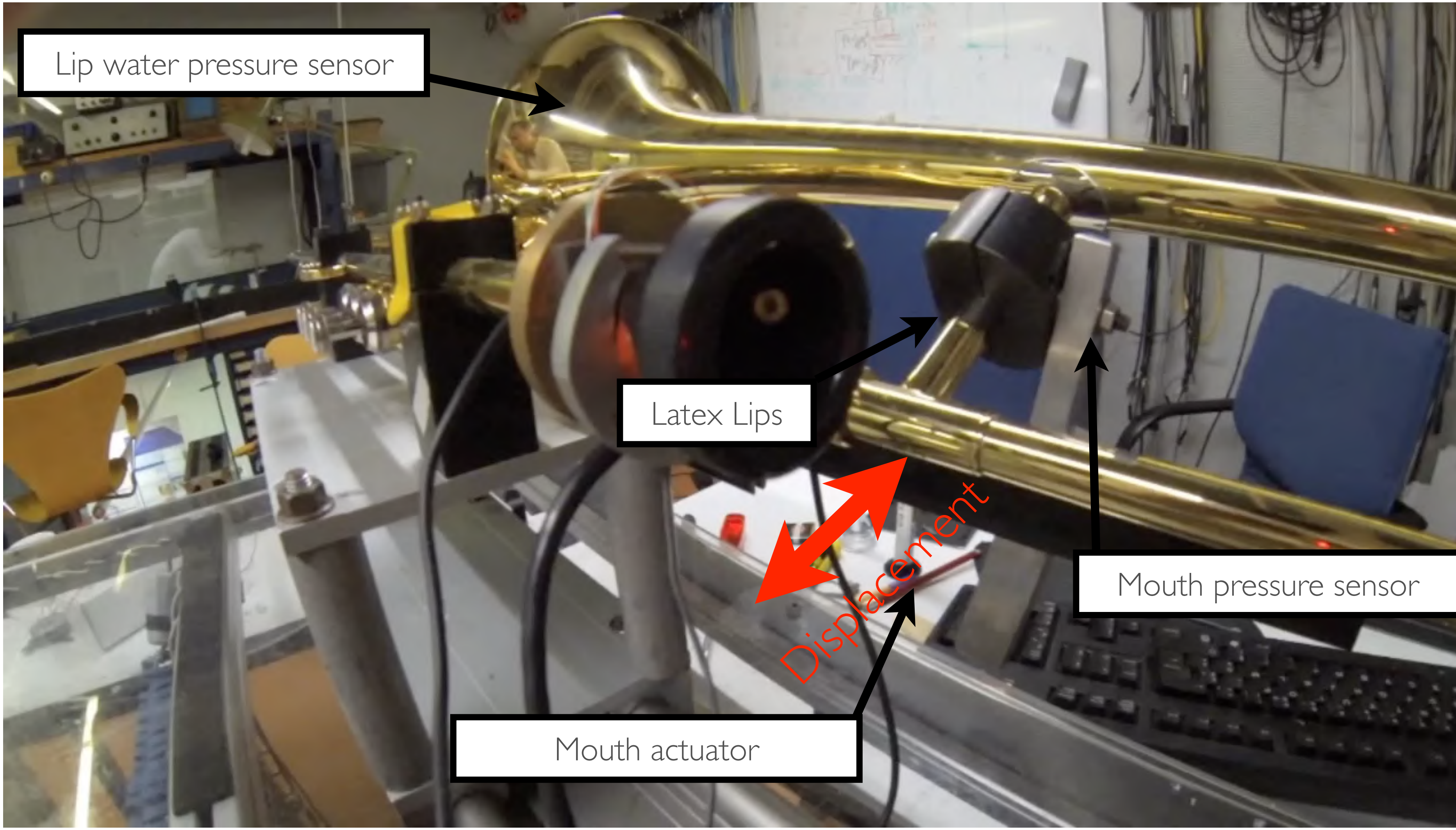
Robotised Artificial Mouth for brass instruments



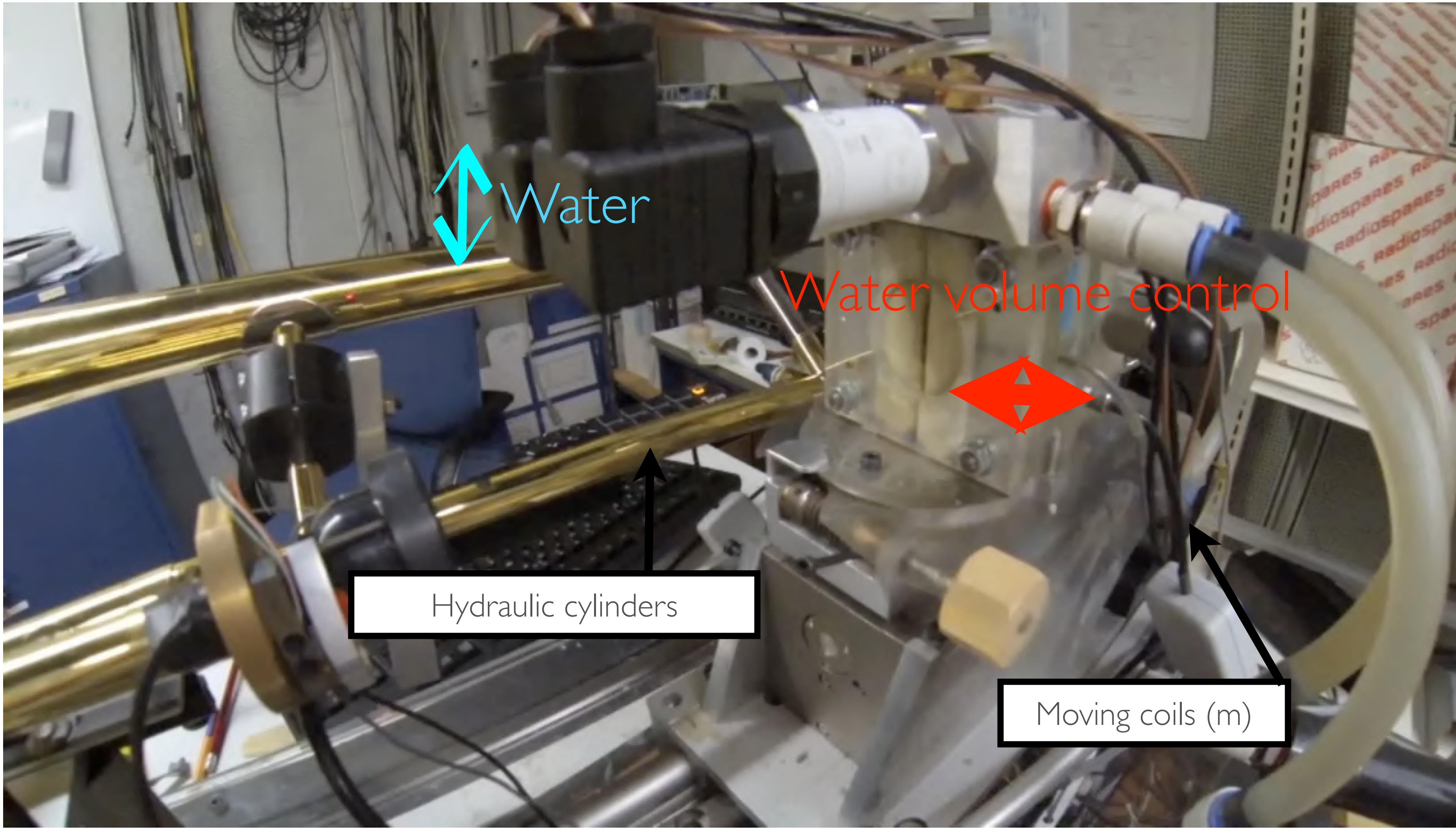
Robotised Artificial Mouth for brass instruments



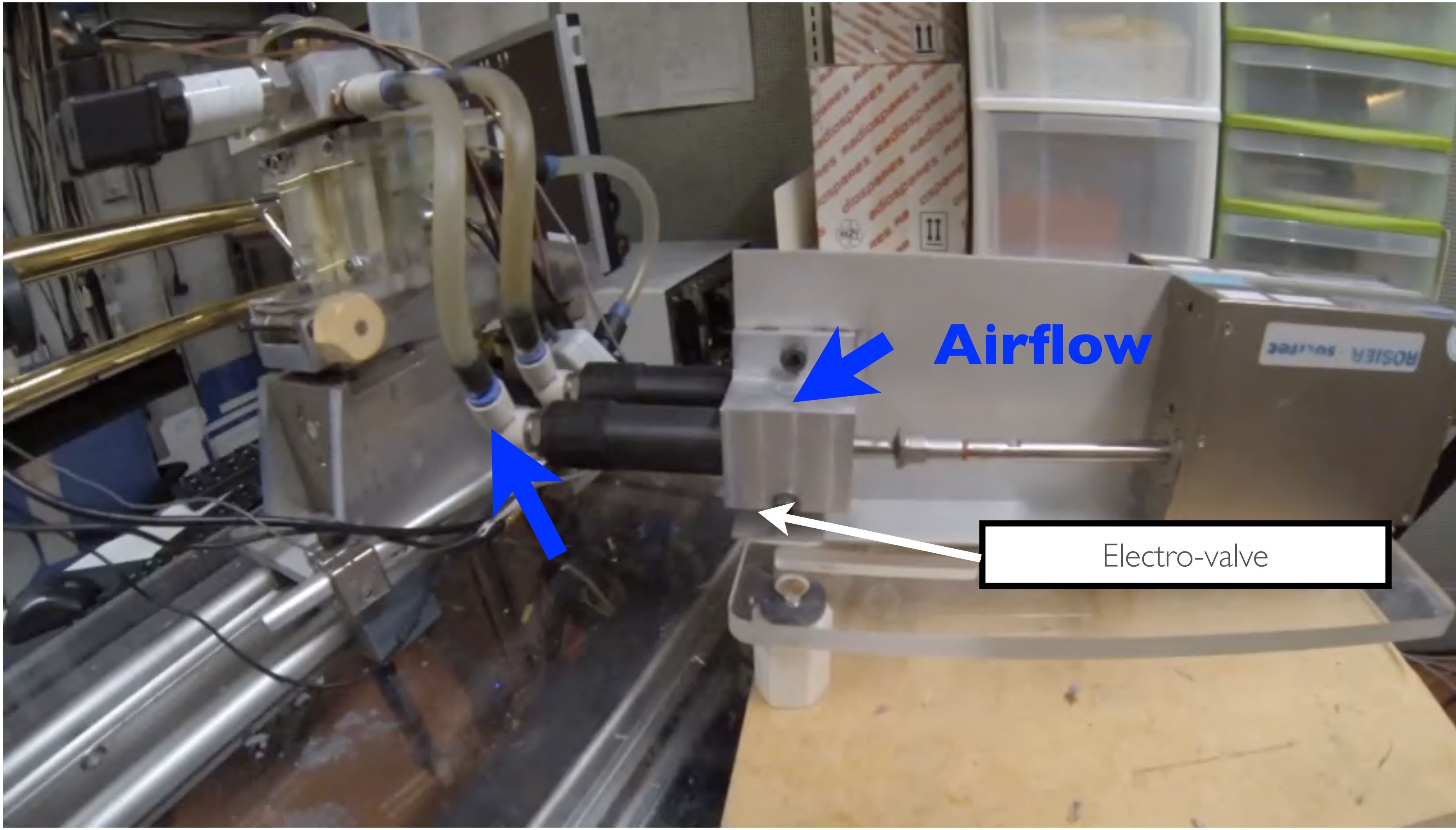
Robotised Artificial Mouth for brass instruments



Robotised Artificial Mouth for brass instruments



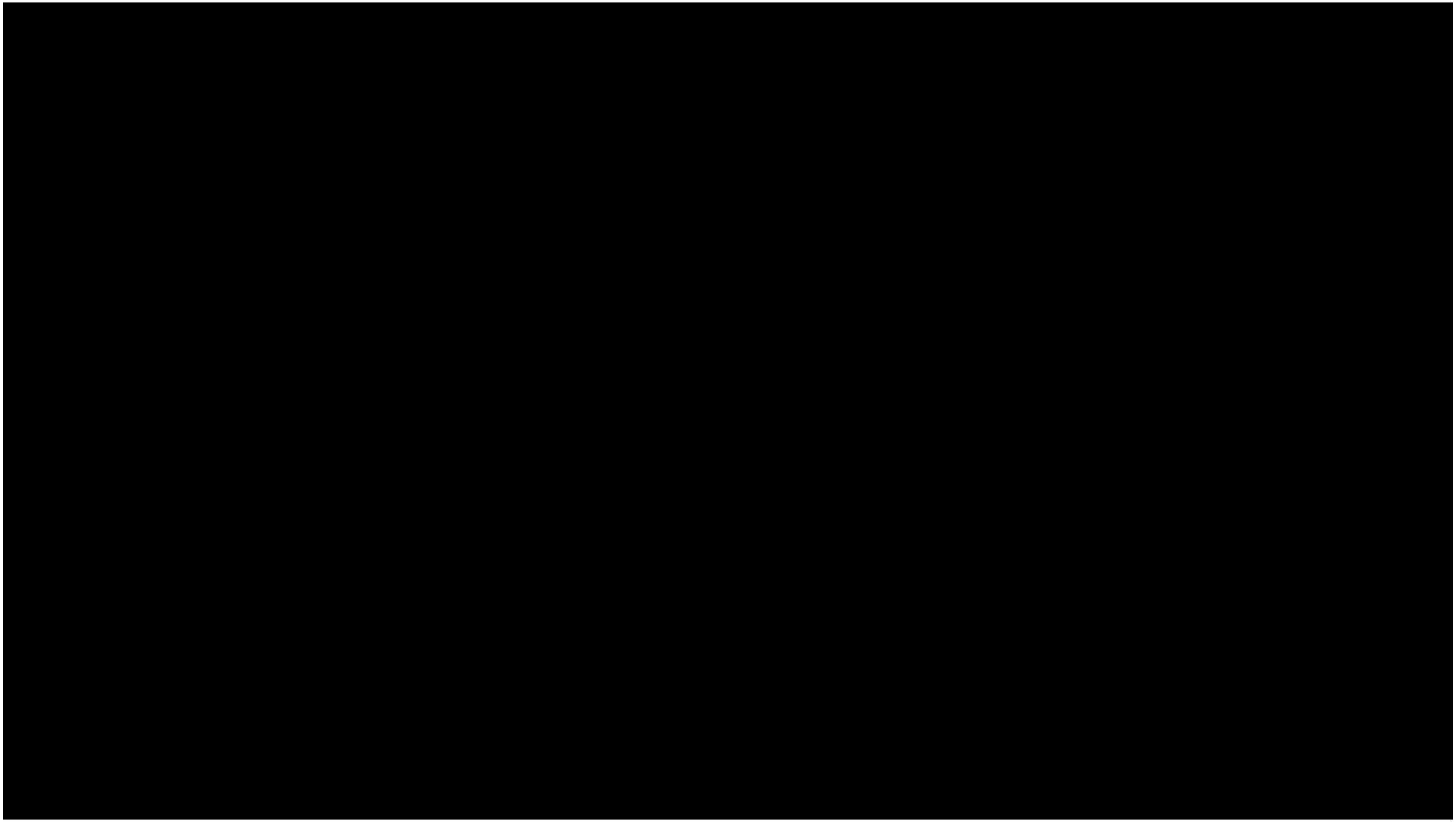
Robotised Artificial Mouth for brass instruments



Robotised Artificial Mouth for brass instruments

First experiment on a trumpet (2009)

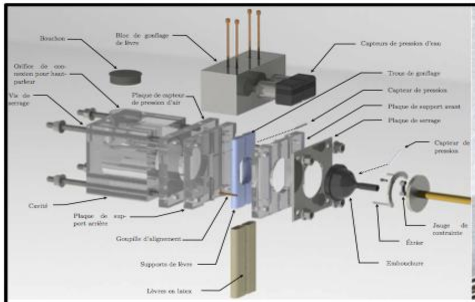
- Fixed: all the lip parameters
- Open control: airflow *(servo-valve)*



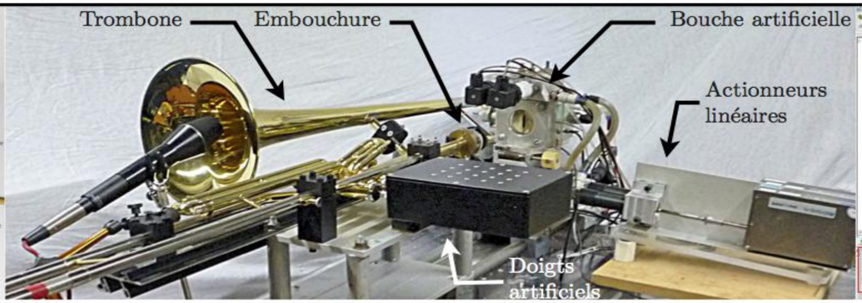
Robotised Artificial Mouth for brass instruments

PhD, June 2016: Nicolas Lopes

Passive modelling, simulation and experimental study
of a robotised artificial mouth playing brass instruments



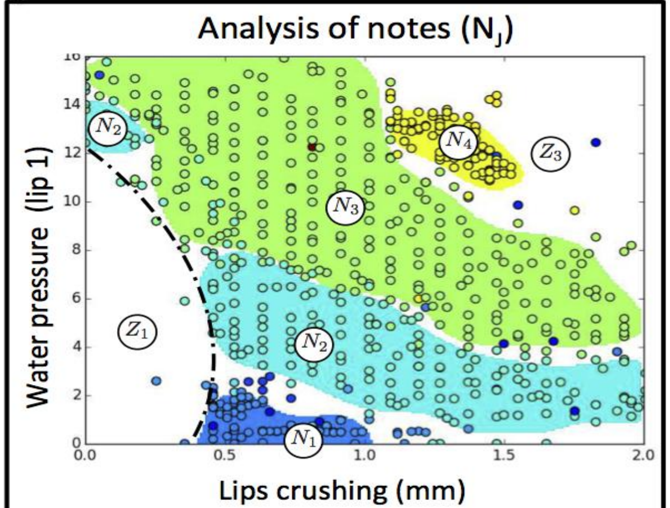
Instrumented mouth, lips and mouthpiece



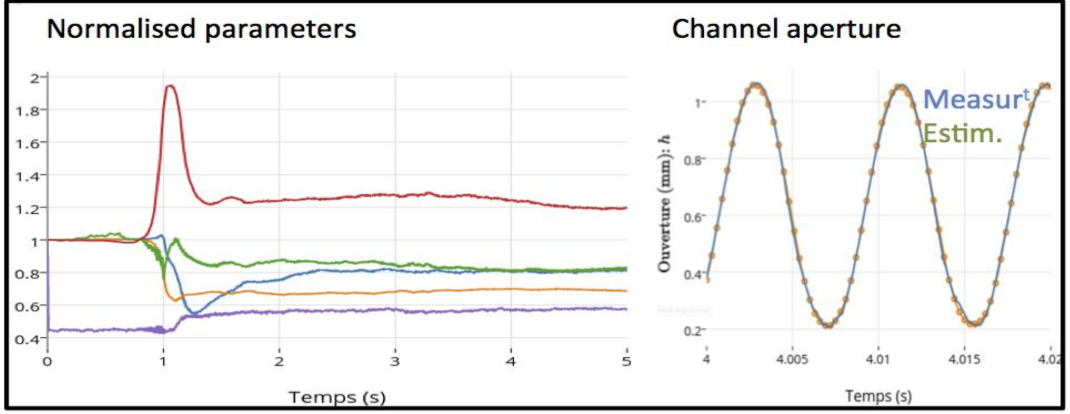
Robotised testbed

HMI *(dSpace & Python)*

2. Automated exploration



3. Estimation/Observation: extended Kalman filter on PHS
(5 estimated parameters: lip mass, stifness, *etc*)



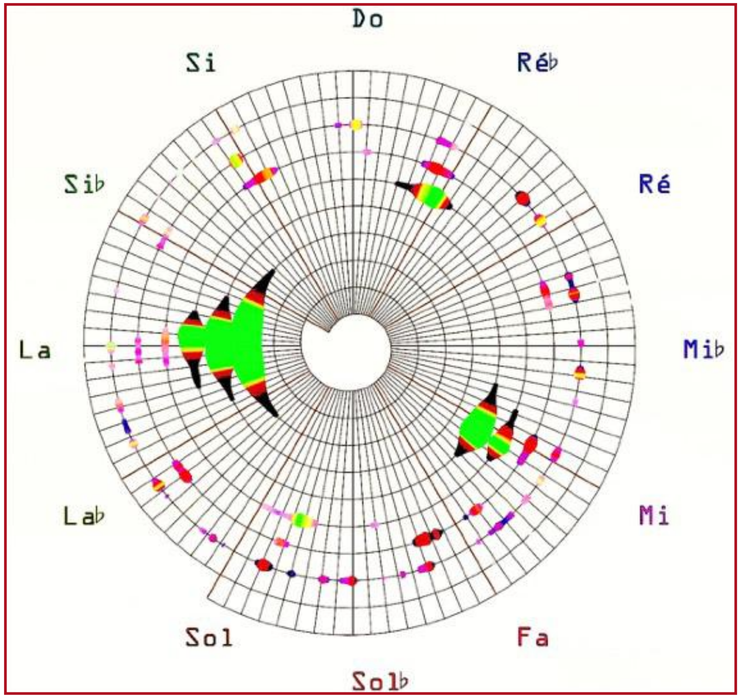
Outline

A. IRCAM and the STMS lab

B. Modelling and simulation

C. Experimental work

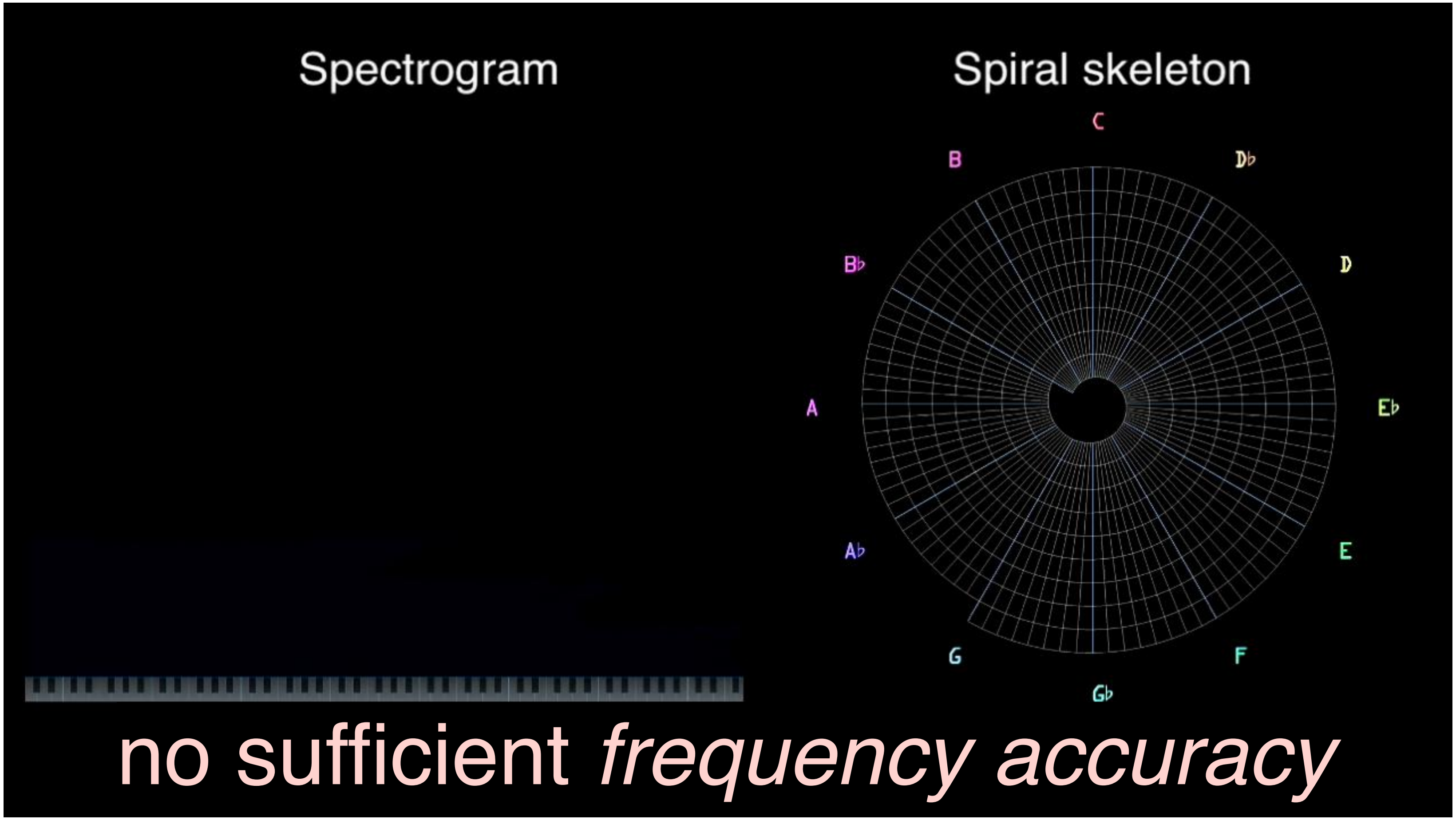
D. Visualisation
- D1. Principle (snail-analyser)
- D2. Views



D1. Principle (1/2)

1. Musical representation of the spectrum on a spiral skeleton

- +1 round = +1 octave
- angle = chroma *(note name)*

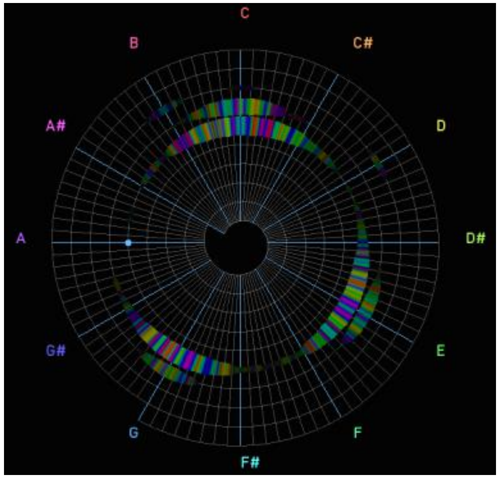


D1. Principle (2/2)

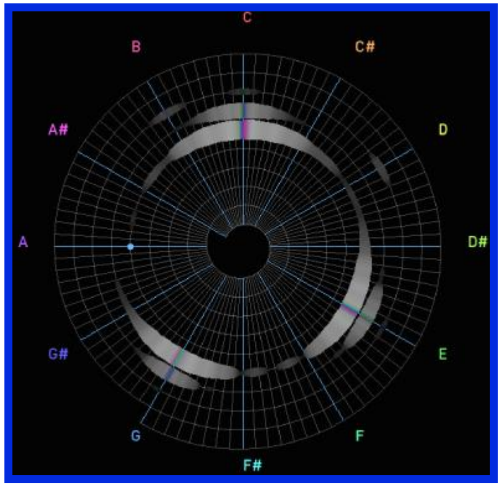
2. **Algorithm** to improve the <u>frequency accuracy</u>

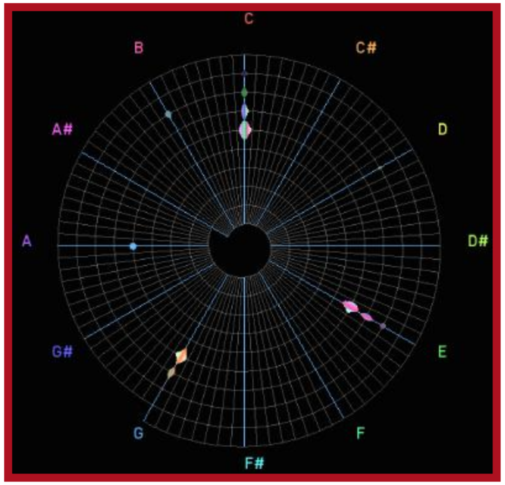
➡ build the **demodulated phase**

$$\phi_d(t, f) = \phi_{Fourier}(t, f) - 2\pi f t$$

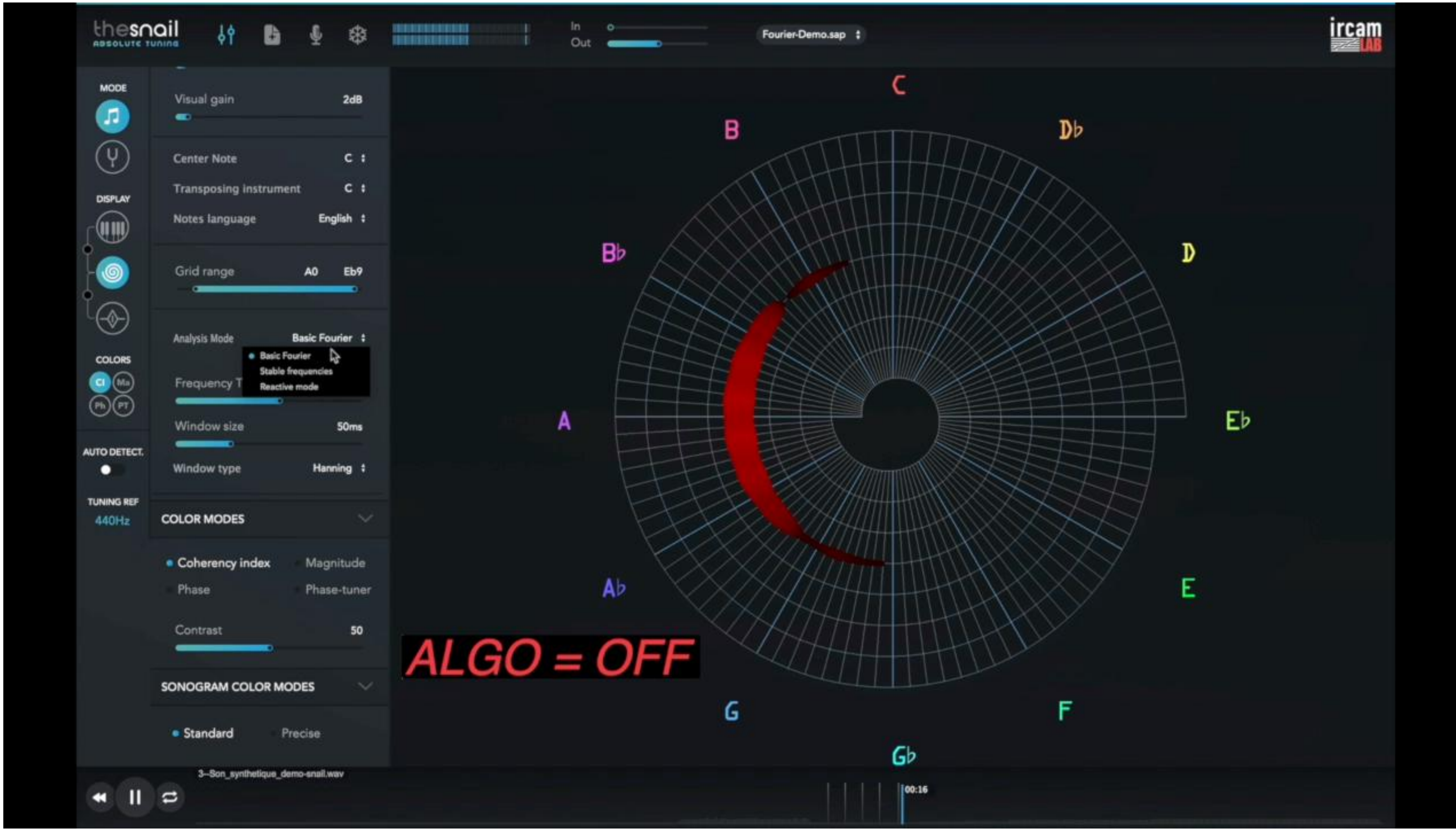


➡ only the slowly oscillating phases $\phi_d(t, f)$ are selected

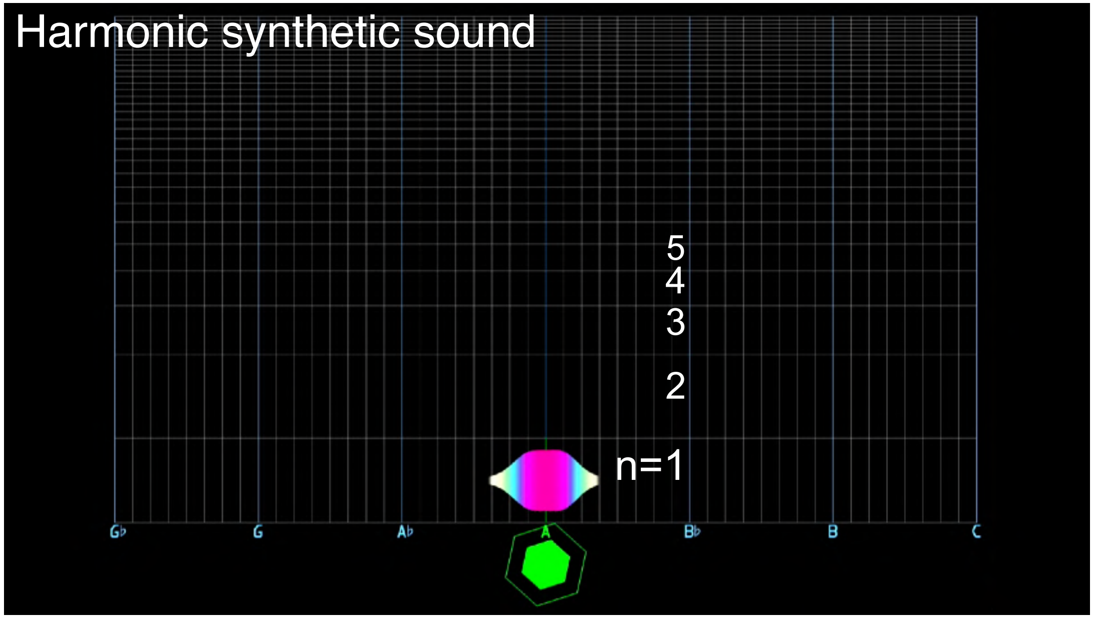




D2. Views: demonstration



D2. Views: harmonic representation



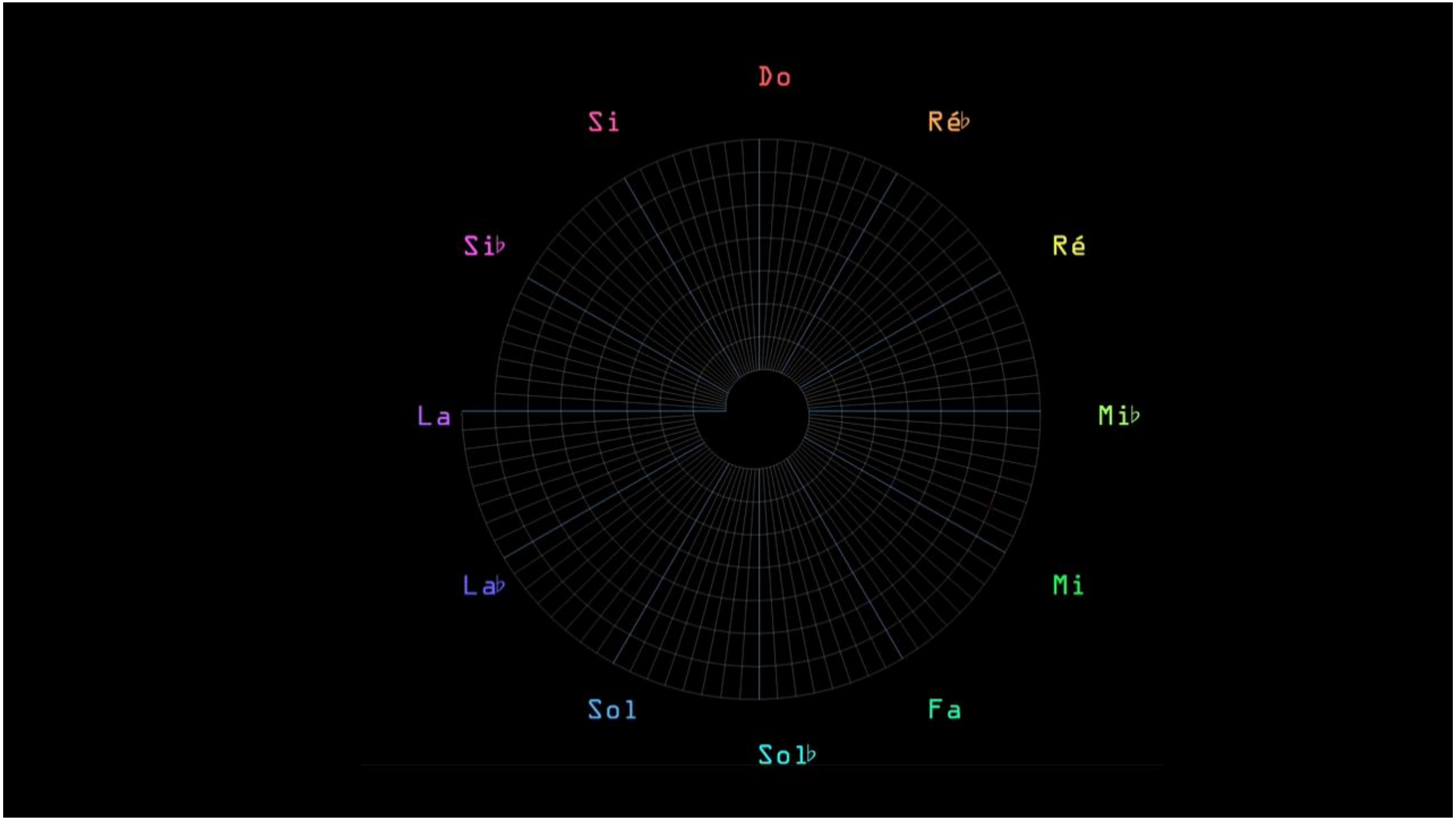
Stage n = Harmonic n

Harmonicity
= vertical alignment

Inharmonicity
= deviation with n

Illustration of a sound illusion

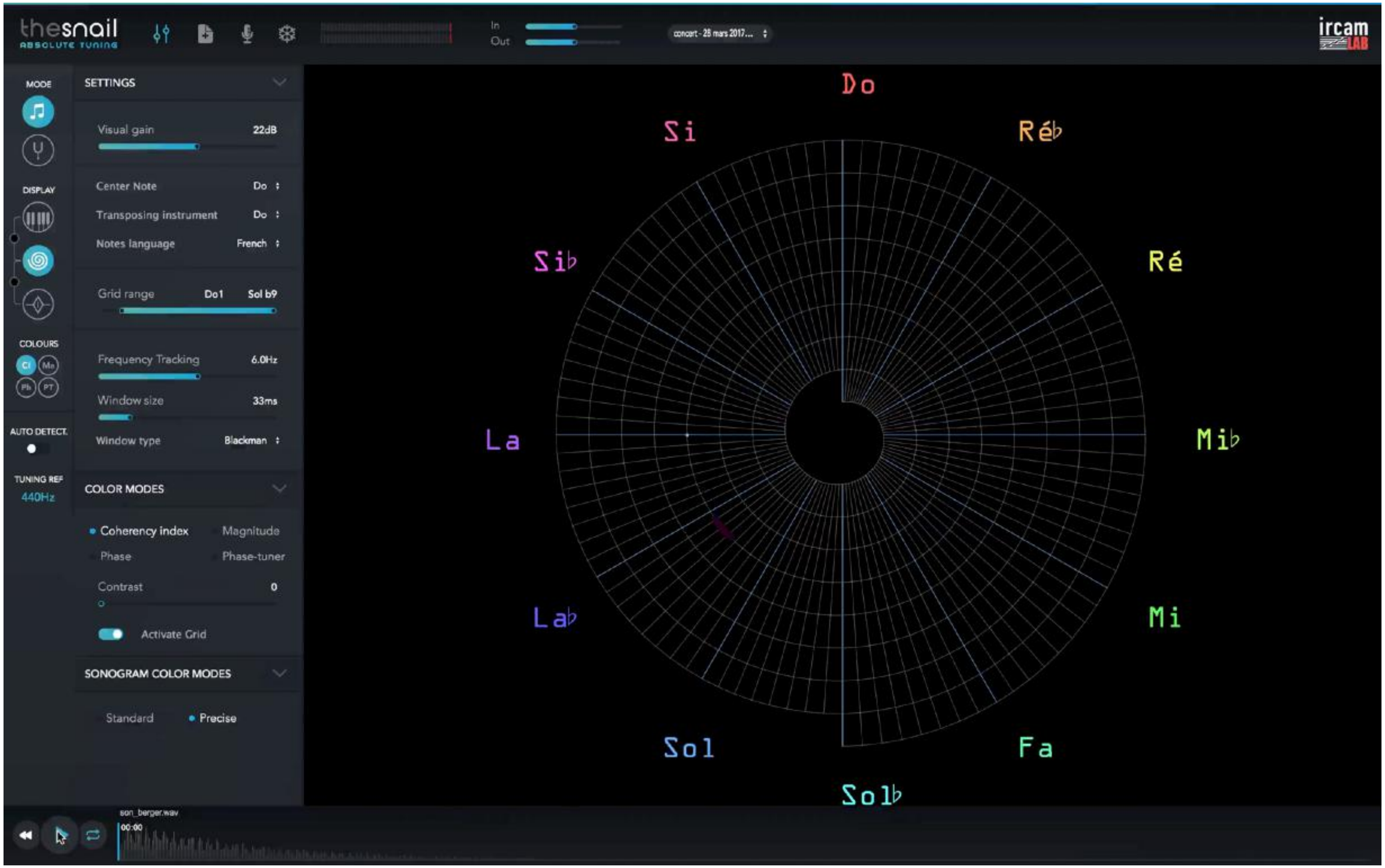
Infinite continually ascending glissando (continuous Risset scale)



D2. Views

Simulation of the nonlinear Berger membrane

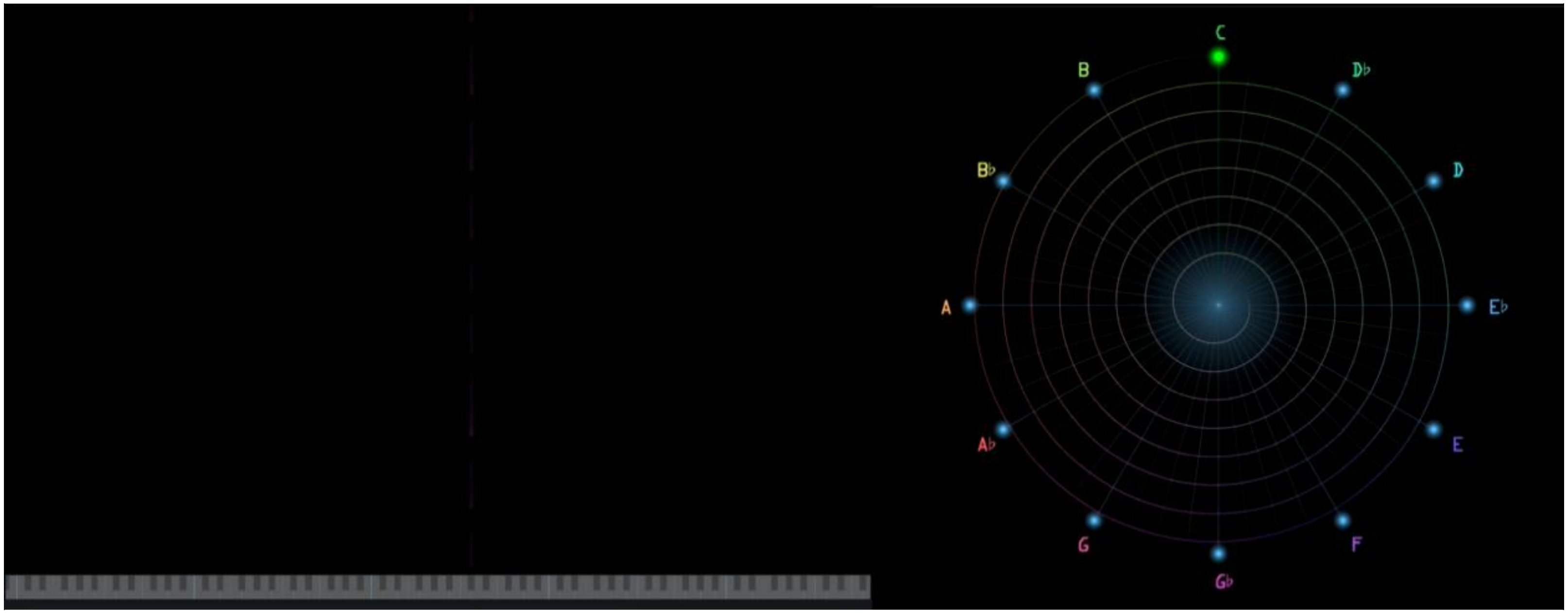
[CFA'2018 with David Roze]

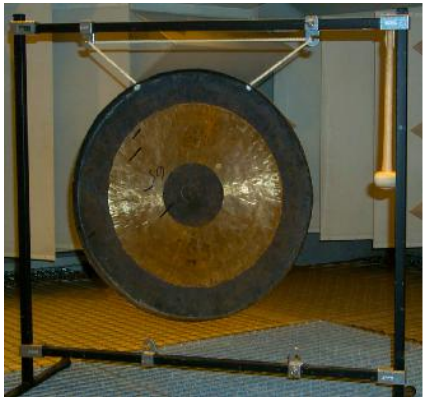


D2. Views

Sound of a gong excited by a sinusoid with increasing amplitude

Courtesy of A. Chaigne, O. Thomas, C. Touzé





Thank you for your attention

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- **Snail Analyser:** Q. Lamerand, C. Picasso, R. Piéchaud, F. Rousseau *& Plugivery & Buffet*
- ***Gong sound:** courtesy of A. Chaigne, O. Thomas, C. Touzé*
- ***& Ongoing work on 4D-PHS :** E. Rouhaud (UTT) et coll.*