Title:
Machine learning and sound simulations by physical models to help the design of musical instruments.

Supervisors:
Advisor: Jean-François PETIOT (Professor, Ecole Centrale de Nantes, LS2N (UMR CNRS 6004)) – Jean-Francois.Petiot@ec-nantes.fr
Co-advisor: Vincent FREOUR (Yamaha R&D division / LMA (UMR CNRS 7031)) – vincent.freour@music.yamaha.com

Place of internship:
Laboratoire des Sciences du Numérique de Nantes, LS2N (UMR CNRS 6004) – Ecole Centrale de Nantes, 1 rue de la Noë, BP92101, 44321 NANTES Cedex 3
2 or 3 missions to the Laboratory of Mechanics and Acoustics (LMA) in Marseille must be planned during the internship
Regular online meetings with YAMAHA corporation (Japan) will be organized during the internship

Duration: 6 months (between March and September 2025)
Gratification: in agreement with the minimum required (4,35€/h)
Language: English

Skills: numerical methods, machine learning, acoustic of brasses

Abstract

Sound simulations by physical models are interesting to transcribe the physics underlying the functioning of a musical instrument. These simulations make it possible to listen to a virtual instrument with a mode of operation representative of the interaction musician/instrument (driving a sound by the causes that create it). But the computation times of these simulations is heavy and only few designs are possible to represent the physical behavior of a musical instrument. The idea, implemented in 2 previous projects (2023 and 2024), is to train a machine learning model (ML) on a dataset of simulated designs [1, 2]. Random forest and elastic net regression were implemented with success in the two previous projects. The results show that the fitting of the ML models is satisfying and that accurate predictions of the behavior of instruments can be made on the whole design space [3]. The application carried out concerns the brass instruments (trumpet, trombone), for which the input of the ML model is the geometry of the resonator and the outputs are descriptors characterizing the sound and playability (intonation and pressure threshold).
The main objective of this project is to improve the previous process in order to support the design of brass instruments. In particular, the goals will be:

- to analyze the ML models in order to understand the relationships between the input variables of the models and the sound descriptor. In this context, sensitivity analysis [4] can be performed, to understand the effects of input variables on the sound descriptors. Different maps must be elaborated (using data analysis methods e.g. PCA) to represent these relationships and help the instrument design,

- to consider new descriptors of the behavior of instruments, related to the timbre of the instrument (e.g. spectral centroid), or the attack time, not considered in the previous internships, and to fit ML models on the simulated data,
- to confirm that the predictions, made on virtual prototypes, are valid when real prototypes are considered. For this, prototypes of a part of a resonator (typically the leadpipe of a trumpet) could be manufactured using rapid prototyping techniques, and tested with musicians, in collaboration with Yamaha corporation, who will provide different case studies and a realistic industrial context,
- to improve the sound simulation techniques, by considering an improved model of the excitator (the lips of the virtual musician), and by the integration of non-linear propagations in the resonator.

Keywords: computer aided design, machine learning, musical acoustics, acoustics of brass instruments, sensitivity analysis, psychoacoustics

Description

For the development of new instruments or their optimization, it is important to be able to predict during the design phase how a future product will be perceived by the musician. In this context, sound simulations by physical models constitute a very interesting approach because they allow, by working on a virtual prototype, to explore the design space, creating a large number of virtual instruments. The main interest of these simulations is that the sound result is driven by the causes that create the sound, as for a real instrument: if the physical model used is detailed enough to generate simulations in agreement with the real behavior (such as it is perceived by the musician), then the simulations can constitute a predictive tool for the development of the instrument (virtual acoustics) [5]. The project focuses on the brass instruments (the trumpet), for which previous studies were conducted in 2023-2024 [1-2-3].

In the continuation of this previous study, the objective of the project is to model the relationships between the sound of an instrument (characterized by descriptors such as the intonation, the timbre, …) and the shape of the resonator (called the bore). Machine learning models will be fitted to a training set of virtual instruments, simulated with a classical physical model already developed in the teams of the supervisors [6-7].

The work will include the following stages:

1. **Generation of sounds**. Sound simulations by physical model are used to create a database of sounds, with the shape of the resonator as input and the sound signal as an output. This stage includes the calculation of the input impedance of the resonator. Different features will be considered to describe the sounds (spectral centroid, MFCC, inharmonicity, intonation, …). In this stage, implementations of temporal simulations, already available in the teams of the supervisors, will be used. Non-linear

propagation in the resonator might also be included.

2. **Supervised learning**. A model is fitted to the database, with the shape of the resonator (bore geometry) as an input and the different features as outputs. Different (classical) methods will be tested (regularized regression, Multilayer perceptron (MLP), neural networks, SVM, …) [58-9-10],
3. **Optimization**. An optimization of the bore geometry is carried out, for a given target of the features, using the previous model. Different gradient-free methods can be implemented (Genetic Algorithm, Nelder Mead simplex, Rosenbrock method, …) [11],
4. **Validation**. The objective of this last stage is to verify that the optimized bore, obtained in stage 3, produces sound features close to the target, using sound simulations,
5. **Validation with a prototype**. After the manufacturing of the shape of the resonator (rapid prototyping), tests with musicians can be carried out to test the optimized bore.

This work is a first step to be able to include simulations by physical model in the design process of musical instruments. According to the interest of the student, perceptual tests could be carried out to assess the ability of sound simulations to represent the functioning of real instruments with musicians.

Short Bibliography:

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[2] Gaspard HAMELIN. Brass instrument bore optimization via machine learning and physics-based sound simulations. Rapport de Stage Ingénieur, Ecole Centrale de Nantes, septembre 2024.
[3] J-F. Petiot, Misael ROATTA, Vincent Freour. “Contribution of Machine Learning and Physics-based Sound Simulations for the Characterization of Brass Instruments”. In: *Forum Acusticum 2023* Turin, september 2023.
[4] Bertrand Iooss, Paul Lemaitre. A review on global sensitivity analysis methods. C. Meloni and G. Dellino. Uncertainty management in Simulation-optimization of complex systems. Algorithms and Applications, Springer, 2015
[5] Petiot J-F., Gilbert J. Comparison of trumpets' sounds played by a musician or simulated by physical modeling. Acta Acustica united with Acustica. Vol. 99, (2013), 629-641. DOI 10.3813/AAA.918642
[6] Tournemenne Robin. Optimisation d’un instrument de musique de type cuivre basée sur des simulations sonores par modèle physique. Thèse de l’Ecole Centrale de Nantes, 2017.
[7] V. Fréour, L. Guillot, H. Masuda, S. Usa, E. Tominaga, Y. Tohgi. Numerical continuation of a physical model of brass instruments: Application to trumpet comparison, Journal of the Acoustical Society of America, 148 (2), 2020, pp 748-758
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characteristics in artificial neural networks, 2016. EndFragment.
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Short CV of the supervisors

A) Jean-François PETIOT (Professeur, Ecole Centrale de Nantes, LS2N (UMR CNRS 6004))

Research themes

Design science; user-centered design; musical acoustics

Publications (extract)

Jean-François PETIOT. A genetic approach for the interactive design of sounds: Application to electric vehicles. In Non Food Sensory Practices. Edited by Anne-Marie Pensé-Lhéritier, Irène Bacle, Julien Delarue. ELSEVIER, Woodhead publishing series in Food Science, Technology and Nutrition, 2021.
Félix Gontier, Vincent Lostanlen, Mathieu Lagrange, Nicolas Fortin, Catherine Lavandier, and Jean-François Petiot, "Polyphonic training set synthesis improves self-supervised urban sound classification", The Journal of the Acoustical Society of America 149, 4309 4326 (2021) https://doi.org/10.1121/10.0005277.
Tournemenne R., Petiot J.-F., Talgorn B., Gilbert J., Kokkolaras M. Sound simulation-based design optimization of brass wind instruments. J. Acoust. Soc. Am. 145(6), June 2019. DOI: 10.1121/1.5111346.
Lafay, G., Rossignol, M., Misdariis, N., Lagrange M., Petiot J-F. Investigating the perception of soundscapes through acoustic scene simulation. Behavior Research Methods, 2019, 51(2), 532-555. https://doi.org/10.3758/s13428-018-1138-0.
Gloaguen, Jean-Rémy ; Can, Arnaud ; Lagrange, Mathieu ; Petiot, Jean-François. Road traffic sound level estimation from realistic urban sound mixtures by Non-negative Matrix Factorization. Applied Acoustics, 143, (2019), 229-238, doi: 10.1016/j.apacoust.2018.08.018

B) Vincent FREOUR (Researcher, YAMAHA Research & Development division)

Research themes

Musical acoustics; nonlinear dynamical systems; biomechanics of music performance

Publications (extract)

Freour, V., Guillot, L., Masuda, H, Vergez, C. and Cochelin B. (2022). Parameter identification of a physical model of brass instruments by constrained continuation, Acta Acustica, 6, No. 9. https://doi.org/10.1051/aacus/2022004
Freour, V., Gautier, F., David, B. and Curtit, M. (2015). Extraction and analysis of body-induced partials of guitar tones, Journal of the Acoustical Society of America, 138, No. 6, pp. 3930-3940
Mansour, H., Freour, V., Saitis, C. and Scavone, G.P. (2015). Post-classication of nominally identical steel string guitars using bridge admittances, Acta Acustica united with Acustica, 101, No. 2, pp. 394 407.

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Cossette, I., Fabre, B., Freour, V., Montgermont, N., Monaco, P. (2010). From breath to sound: linking respiratory mechanics to aeroacoustic sound production in flutes. Acta Acustica united with Acustica, 96, No. 4, pp. 654-667.