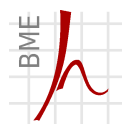
Acoustical evaluation of a novel flute head construction

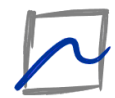
Péter Rucz

rucz@hit.bme.hu

DAGA 2018
44. Jahrestagung für Akustik
Paper ID: 485



Department of Networked Systems and Services

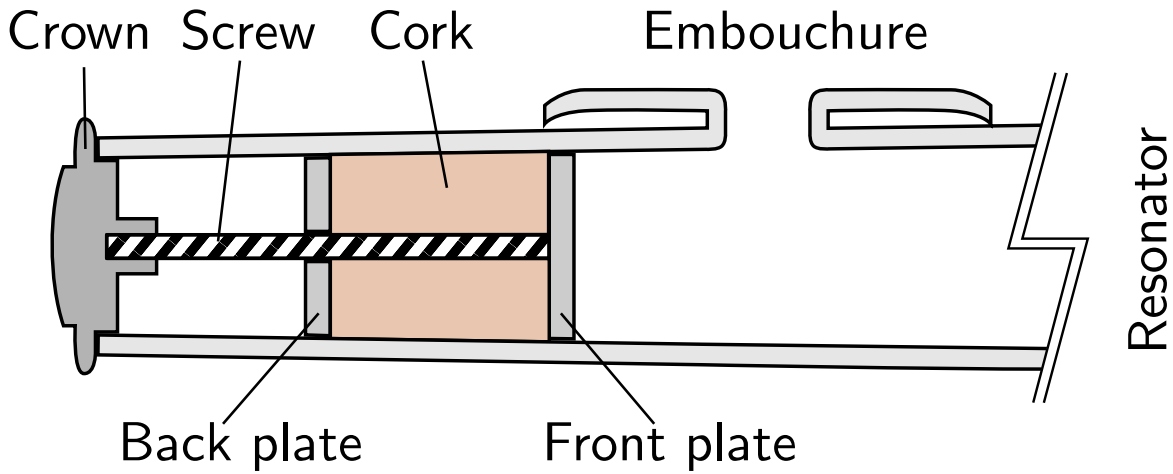


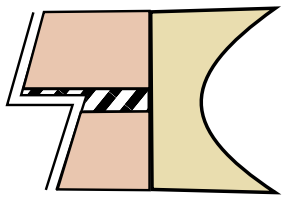
Laboratory of Acoustics

Introduction

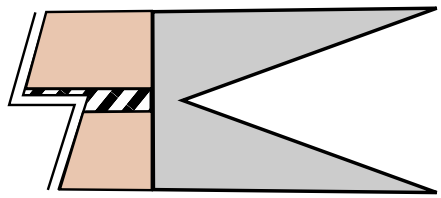
- Modern western flute design
  - Based on Theobald Boehm's design from the mid-19th century
  - Minor improvements by different instrument makers
- Novel flute head
  - Patented by an expert flutist
  - Revised geometry of the tuning plug
  - New materials: bone, wood, metals
  - Observation: both material and shape significantly affect the timbre
- Acoustical analysis
  - Recordings in semi-anechoic chamber
  - Objective evaluation of recordings
  - Acoustical model

The new tuning plug and flute head





Novel design #1
Cocobolo, bone



Novel design #2
Silver, steel, titanium

- Front plate of tuning plug is curved or conical
- Various materials: bone, cocobolo wood, metals and alloys
- Numerous tuning plug and crown plug combinations

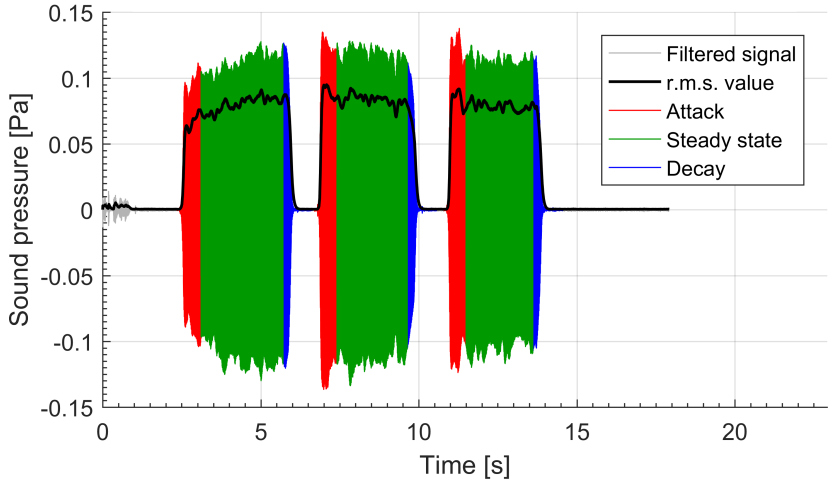
Measurements

- Trevor James Cantabile silver plated concert flute
- 6 flute heads, 37 notes held steady, *piano* & *forte* dynamics
- 2 nearfield and 2 farfield $1/4''$ microphones
- $\sum 444$ recordings, each containing 3 samples of the same note

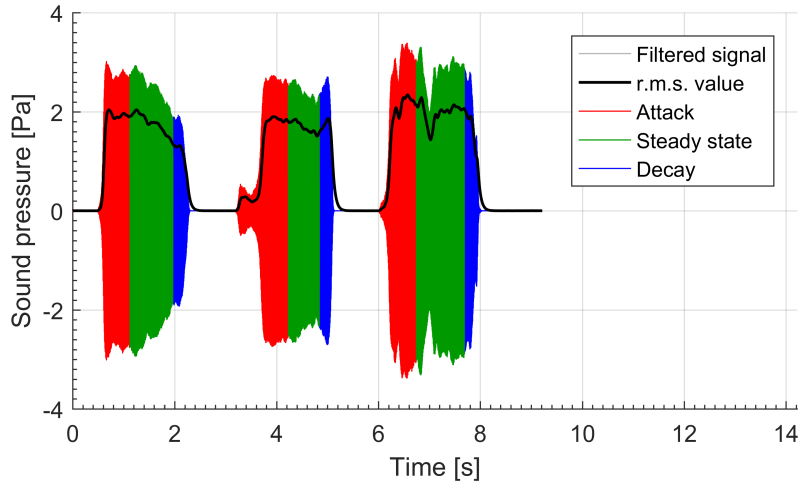
Signal processing

1. Automatic segmentation
   - Using r.m.s. of signal
   - Segments differ significantly along the chromatic scale
2. Pitch analysis
   - Mean fundamental f_1
   - Small fluctuations
   - Temporal statistics
3. Resampling
4. Steady state evaluation
   - Loudness
   - Spectrum
   - Spectral centroid
5. Attack analysis
   - Order of harmonics
   - Attack speed

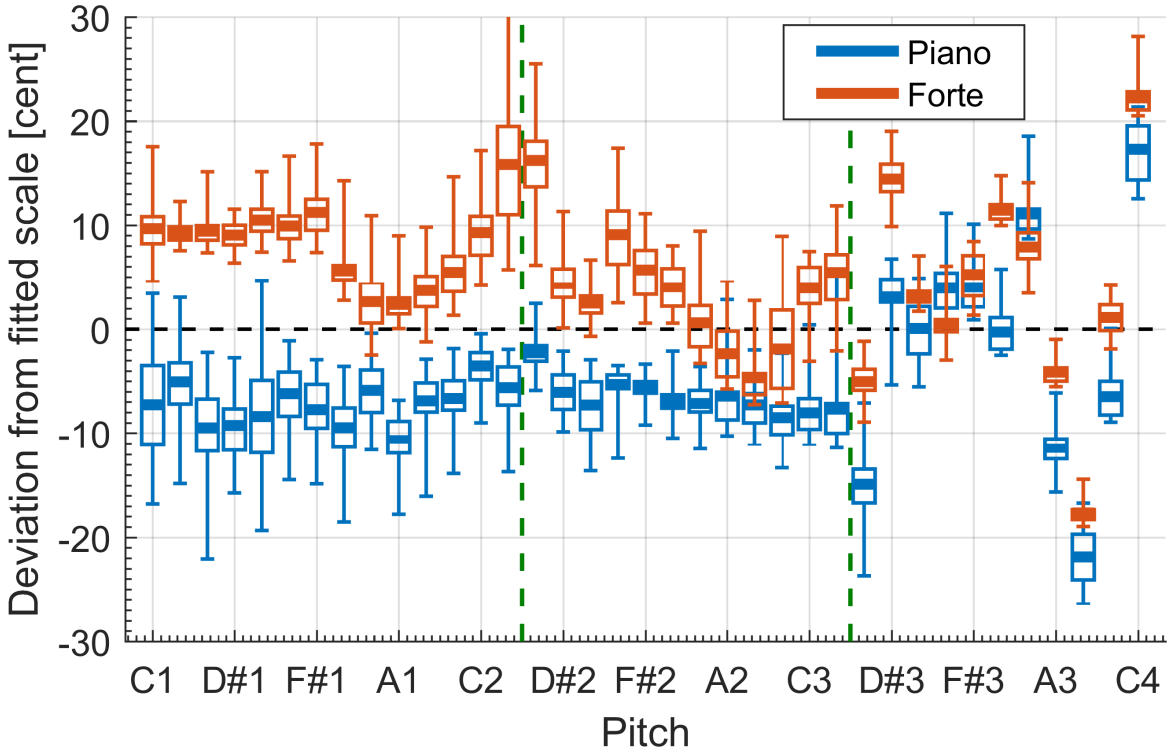
Segmentation of A1 *piano* (steel plug)



Segmentation of H3 *piano* (steel plug)



Pitch analysis



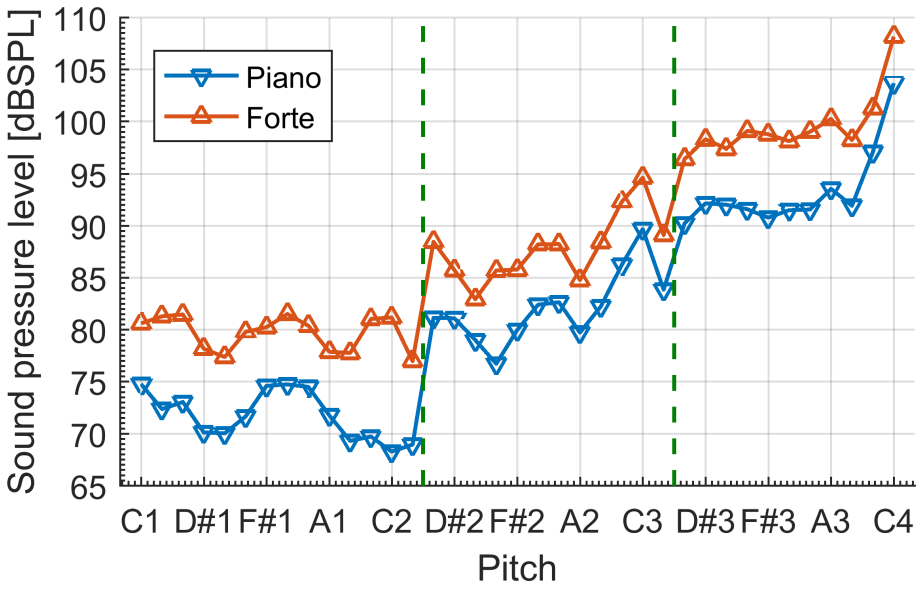
Typical result of the steady state pitch analysis

Box plot

- Thick: mean
- Boxes: quartiles
- Thin: min & max

- Comparison with a fitted tempered scale
- *piano*: below, *forte*: above the fitted scale
- The 3rd register is hard to play, notes are hard to hold steady

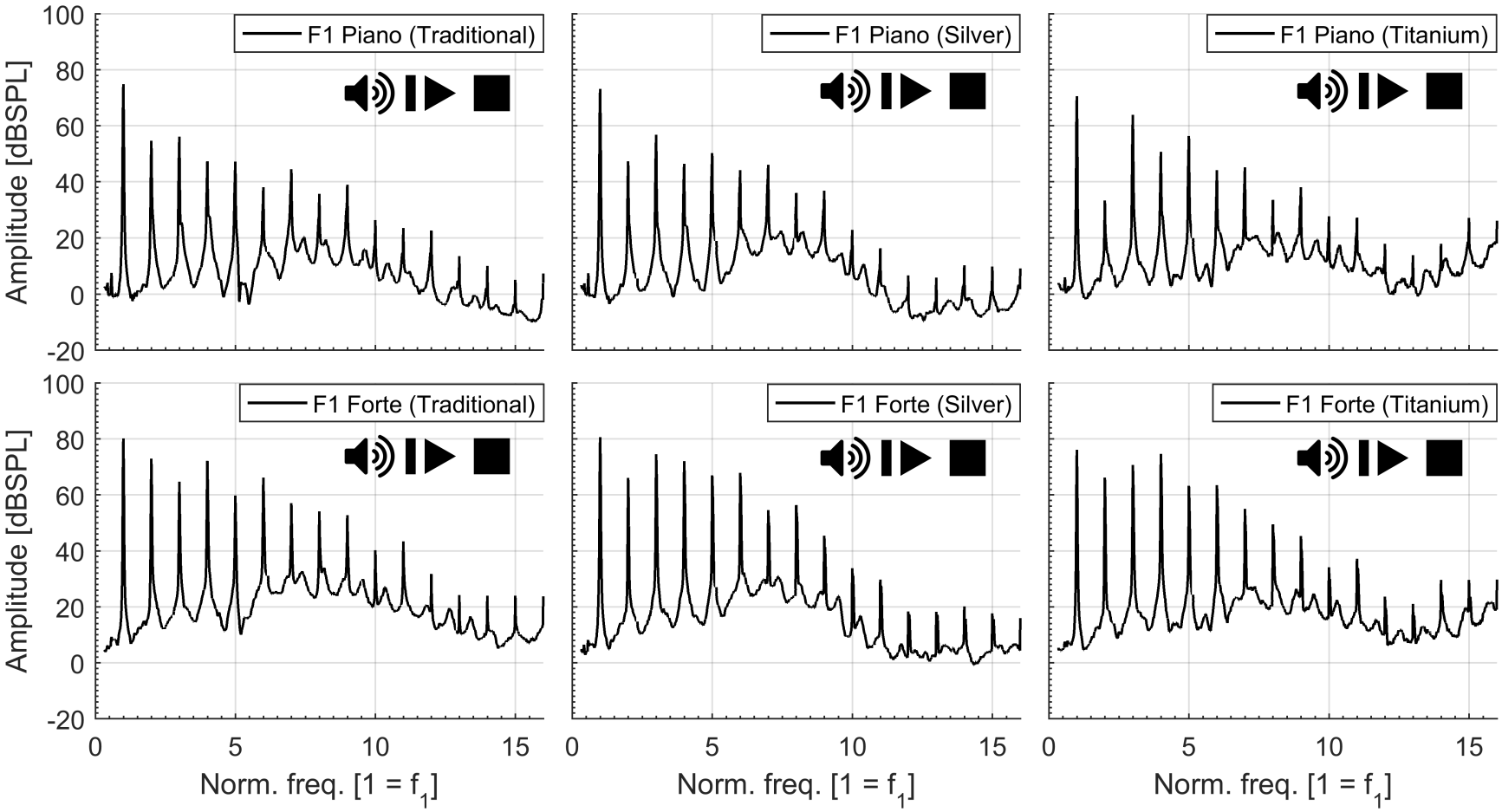
Equivalent loudness



Dynamics	f/p [dB]		
Register	1st	2nd	3rd
Steel	9.3	6.2	6.6
Cocobolo	7.8	5.8	7.0
Bone	6.8	5.3	4.8
Silver	9.7	5.4	5.2
Titanium	7.8	5.7	5.9
Traditional	8.5	5.7	5.7

- General observations
  - Level jumps between consecutive registers
  - Due to differences in blowing strength (overblowing)
- Novel flute head
  - The achieved *forte* to *piano* ratio is slightly increased (steel or silver plugs) or decreased (bone plug)

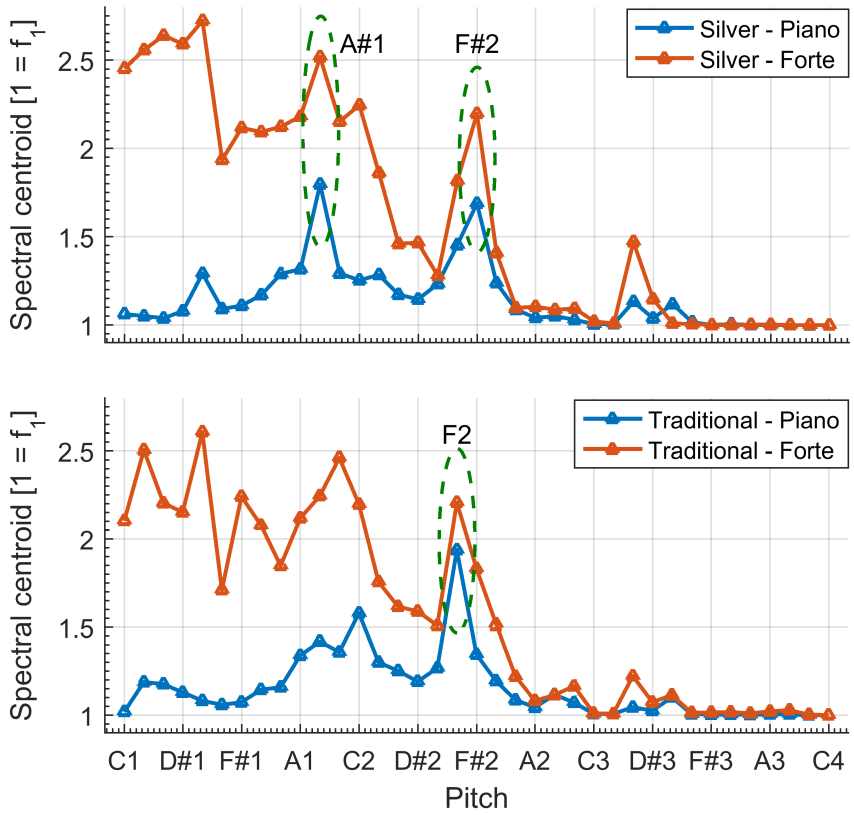
Stationary spectra – examples



- Significant differences of spectral envelopes and harmonic content
- Greatest observable deviations in the 1st register

Spectral centroid

Dynamics	Piano		Forte	
Register	1st	2nd	1st	2nd
Steel	1.42	1.20	2.38	1.33
Cocobolo	1.36	1.22	2.26	1.38
Bone	1.33	1.17	2.12	1.28
Silver	1.22	1.18	2.30	1.34
Titanium	1.39	1.18	2.31	1.28
Traditional	1.22	1.21	2.16	1.41



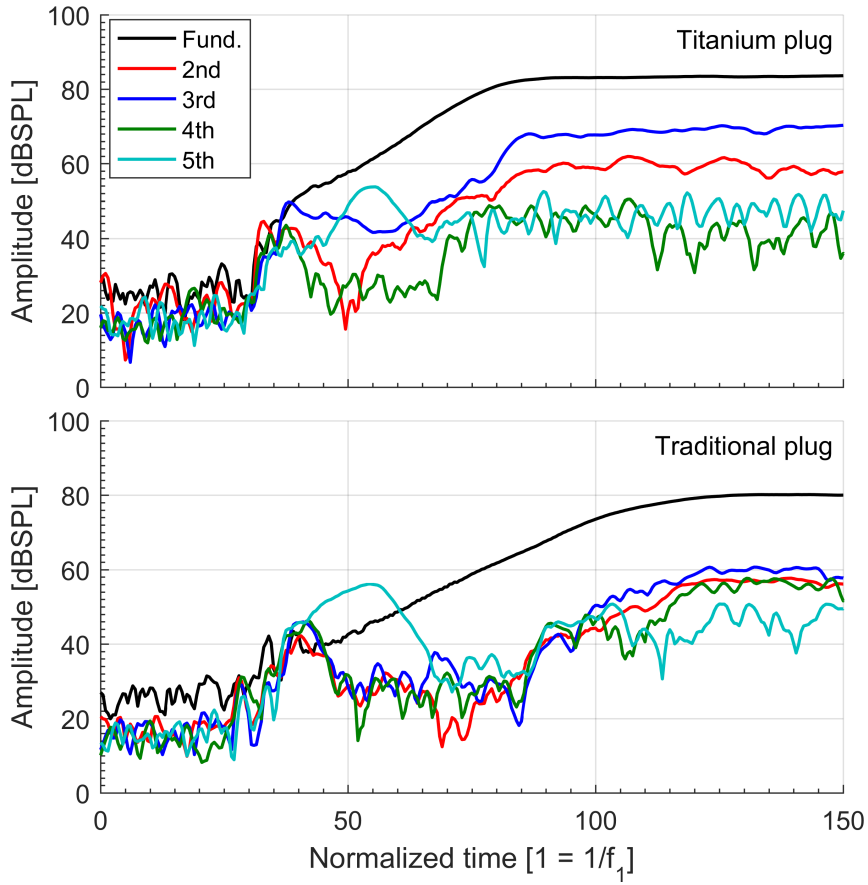
- Enhanced harmonic content: steel, cocobolo, titanium plugs
- Less harmonics: bone plug

- Large variation of centroid along the scale
- Certain notes have remarkably different centroids than neighbors
  - Silver plug: A#1, F#2, other plugs: F2

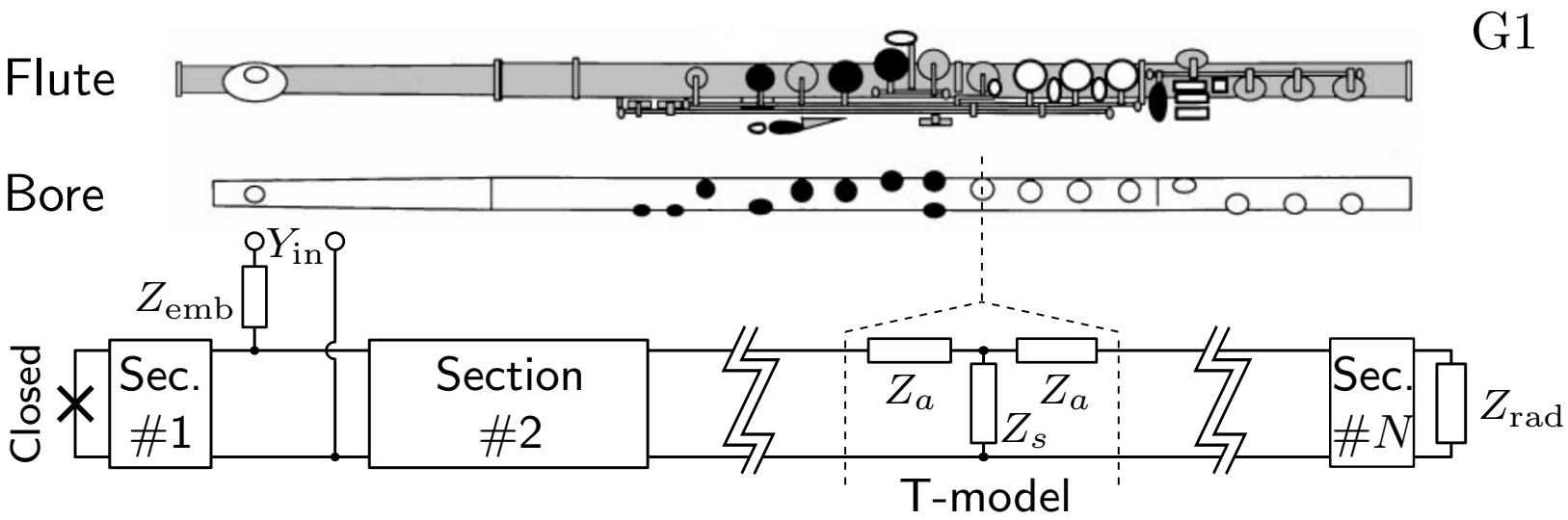
Attack transient

- Resampled signal
  - Allows coherent sampling
  - Resolution in t and f
  - Spectral leakage avoided
- Time history of harmonics
- Difficulties
  - Consecutive attacks can be remarkably different
  - Fastest attack evaluted
- Observations
  - Greatest differences for $\mathrm{F}\#1$
  - Attack very slow with traditional plug, strong 5th harmonic appears

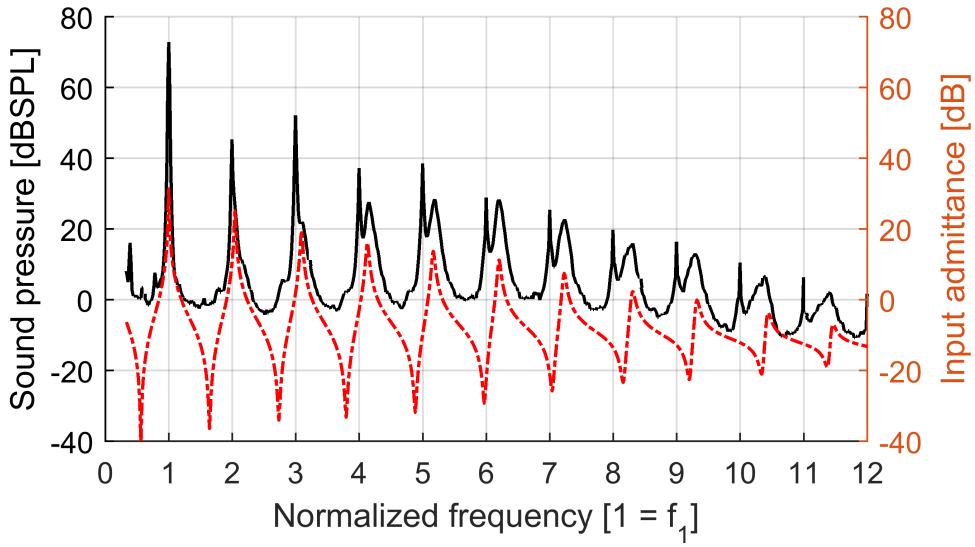
Attack of the $\mathrm{F}\#1$ *piano* note



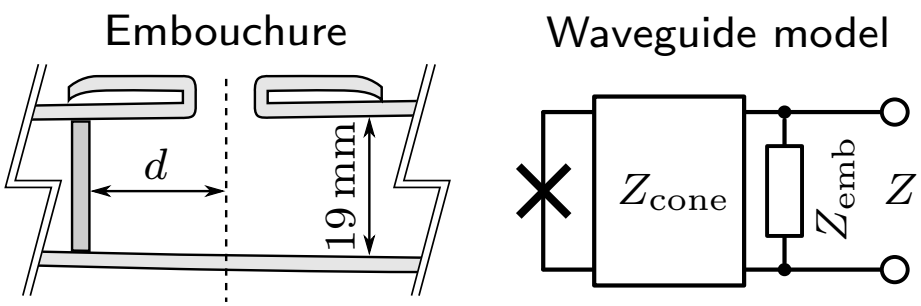
Acoustical waveguide model of the flute

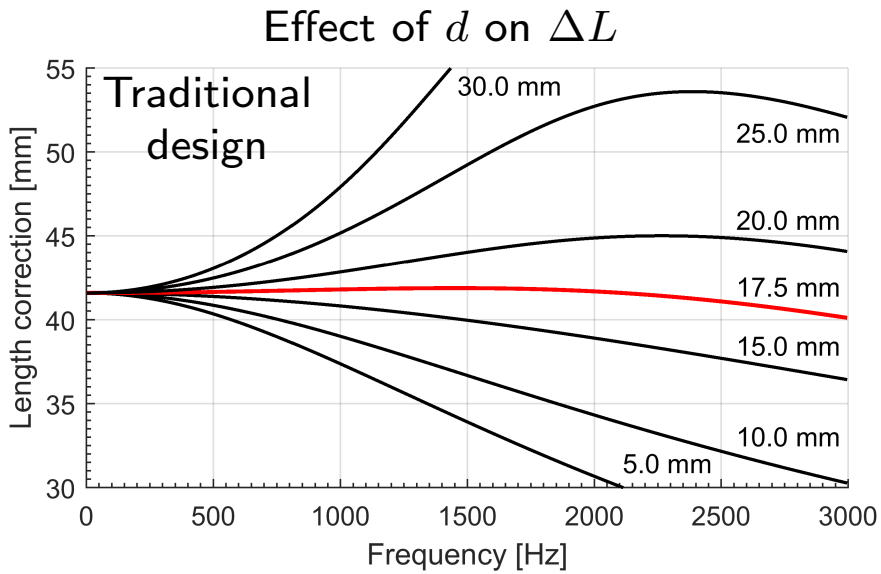


- Model components
  1. Bore sections
  2. Open / closed toneholes
  3. Radiation impedances (Length corrections)
- Input admittance $Y_{\text{in}}(f)$
  - Natural resonances
  - Harmonicity



Length correction at the embouchure

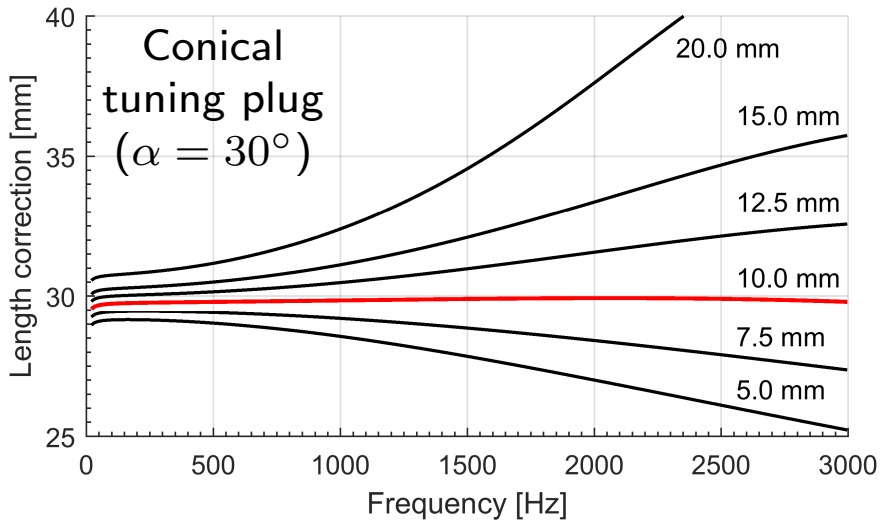




- Length correction calculation

$$R = \frac{Z - Z_0}{Z + Z_0} \qquad R = -|R|\,\mathrm{e}^{-2\mathrm{j}k\Delta L}$$

- Traditional design: $d \approx 17\,\mathrm{mm}$
  $\Delta L \approx \mathrm{const}$ $(f < 3\,\mathrm{kHz})$ [1]
- Can same be achieved with the novel design? $\rightarrow$ Yes.

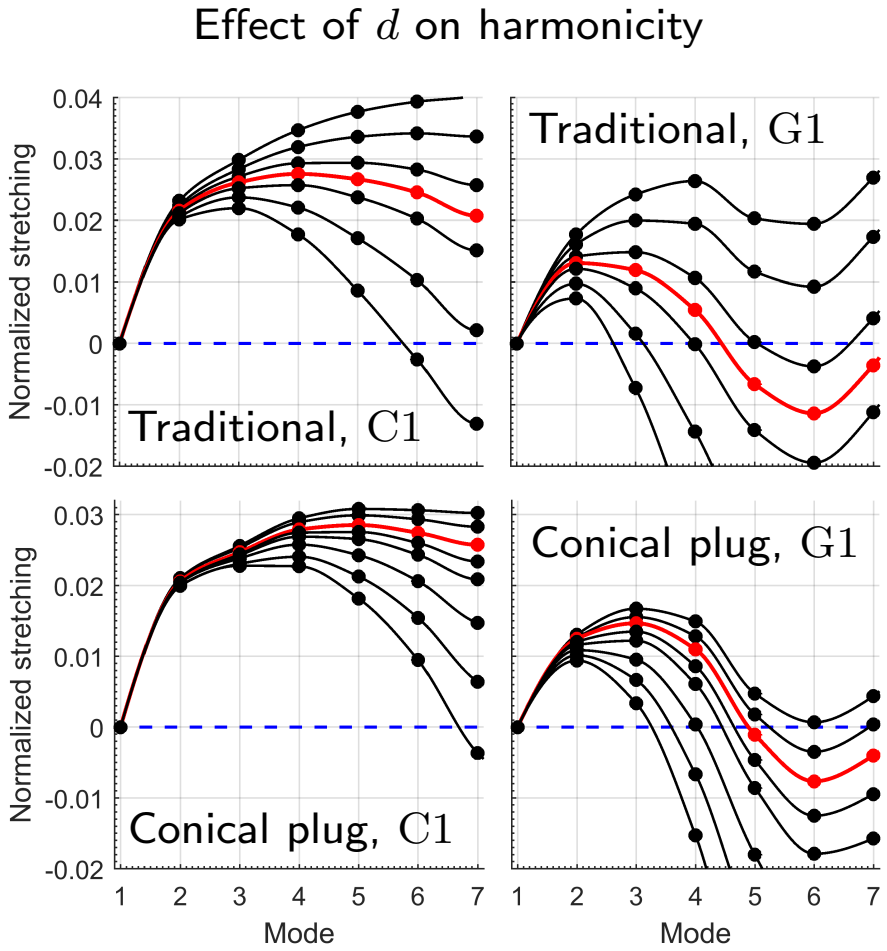


Effect of tuning plug on harmonicity

- Harmonic content of sound $\sim$ harmonicity of resonator [2]
  - Modes are stretched (C1)
  - Or compressed (G1)
- Normalized stretching

$$\mathrm{Str}(n) = \frac{f_n}{n f_1} - 1$$

- Does $\Delta L = \mathrm{const}$ lead to the best harmonicity?
- Novel design gives similar harmonicity, less sensitive
- Embouchure impedance [3]
  - Affected by player
  - Varies along the scale [4]
  - Limiting factor



Summary

- Novel flute head
  - New shape of tuning plug, combined with various crowns
  - Various materials used: wood, metals, alloys
- Measurement results
  - Significant differences in steady state spectra
  - Analyzed: loudness, spectral centroid, attack transient
  - Perceived sound quality affected by novel tuning plugs
- Acoustical waveguide model
  - Length corrections and harmonicity of novel and traditional designs
  - Limiting factor: embouchure impedance model

- Music sample – main theme from Ravel's Bolero
  Played on traditional and three different novel flute heads

Acknowledgments

Zoltán Lakat
(Expert flutist, patent holder of construction)

Thank you for your kind attention!

References

[1] N.H. Fletcher, T.D. Rossing. *The physics of musical instruments.* Springer, New York. Chapter 16. (1991)

[2] P. Rucz *et al. Sound design of chimney pipes by optimization of their resonators.* JASA **133** pp. 529–537 (2013)

[3] J. Wolfe *et al. Acoustic impedance spectra of classical and modern flutes.* JSV **243** pp. 127–144 (2001)

[4] P.A. Dickens. *Flute acoustics: measurement, modelling and design* Ph.D. thesis, University of New South Wales (2007)