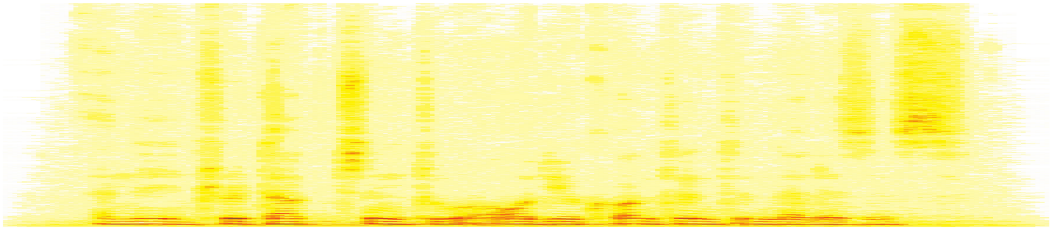
Introduction to Audio Content Analysis

Module 5.6: Tuning Frequency Estimation

alexander lerch



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introduction

overview

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corresponding textbook section

Chapter 5 — Tonal Analysis: pp. 94–96
Chapter 5 — Tonal Analysis: pp. 114–116

- **lecture content**
  - definition of tuning frequency
  - approaches to tuning frequency estimation

- **learning objectives**
  - explain the term tuning frequency
  - discuss when automatic tuning frequency estimation might be necessary
  - compare different general approaches to tuning frequency estimation

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tuning frequency

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tuning frequency

frequency of the concert pitch $A4$

- used to tune groups of instruments
- standardized:[1] 440 Hz

[1] I. 16:1975, "Acoustics Standard tuning frequency (Standard musical pitch)," ISO, Standard, 1975.

tuning frequency

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tuning frequency

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tuning frequency

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- tuning frequency range *in history*

Year	Lower Deviation	Upper Deviation
1750	$-50\,\mathrm{Hz}$	$+30\,\mathrm{Hz}$
1850	$-20\,\mathrm{Hz}$	$+20\,\mathrm{Hz}$
1950	$-5\,\mathrm{Hz}$	$+10\,\mathrm{Hz}$

[1] I. 16:1975, "Acoustics Standard tuning frequency (Standard musical pitch)," ISO, Standard, 1975.

tuning frequency

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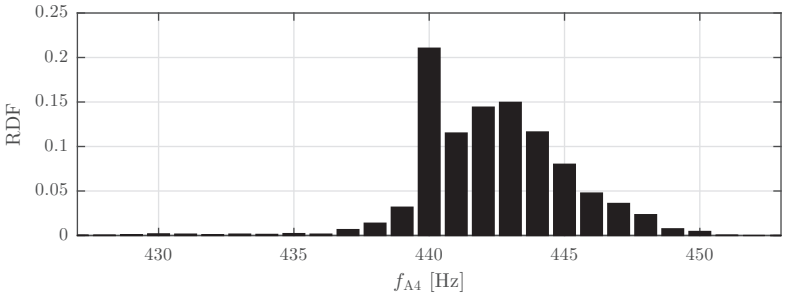

- tuning frequencies *today*
  - electronic music: often exactly 440 Hz
  - "classical" music:[2]
    - Chicago Symphony, New York Philharmonic: 442 Hz
    - Berlin Philharmonic, Vienna Philharmonic: 443 Hz

[2] A. Lerch, "On the Requirement of Automatic Tuning Frequency Estimation," in *Proceedings of the 7th International Conference on Music Information Retrieval (ISMIR)*, Victoria, 2006.

matlab source: matlab/displayTuningFreqDistribution.m

tuning frequency estimation

problem statement

- any pitch-based analysis system relies on tuning frequency (pre-defined or adaptive)

  recall MIDI pitch: $\mathfrak{p}(f) = 69 + 12 \cdot \log_2\left(\frac{f}{f_{\mathrm{A4}}}\right)$

- tuning frequency might deviate significantly from 440 Hz
- key & temperament are unknown
- expressive intonation is unknown

$\Rightarrow$ a wrong tuning frequency assumption may impact the pitch reliability

tuning frequency estimation

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tuning frequency estimation

assumptions and limits

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1. **key is unknown** $\Rightarrow$ deviations larger than half a semitone will be mapped back to semitone range
2. **temperament/intonation is unknown** $\Rightarrow$ assuming equidistant spaced pitch (equally tempered)
3. piece **may be polyphonic**
4. piece **may not contain the pitch A4**
5. if tuning frequency changes over time, it will **change slowly**

tuning frequency estimation

overview

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- **typical processing steps**
  1. estimate fundamental frequencies
  2. calculate deviation ΔC from the nearest (equally tempered) pitch frequency in Cents
  3. average all deviations: $\rightarrow \Delta \bar{C}$
  4. compute the tuning frequency from the average distance:

$$\hat{f}_{A4} = 440\,\mathrm{Hz} \cdot 2^{\frac{\Delta \bar{C}}{1200}}$$

tuning frequency estimation

score-based

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1. analyze score and **identify important pitches**
2. define a set of narrow **band pass filters** per pitch
3. **sweep band pass** filter's mid frequency over selected audio segments
4. identify most likely **mid frequency** maximizing the filter's output energy
5. compute its **deviation** ΔC from the (equally tempered) pitch frequency in Cent
6. **average** all results
7. compute overall result in Hertz

tuning frequency estimation

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tuning frequency estimation

STFT-based

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1. identify **spectral peaks**
2. compute **instantaneous frequencies** $f_l(k)$
3. compute **distance** to nearest equally tempered semitone frequency $\hat{f}_{A4}(n-1)$ (in Cents)
4. iteratively **adjust tuning frequency** estimate to minimize distance

tuning frequency estimation

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tuning frequency estimation

histogram-based

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1. compute **CQT**: bin resolution 10 Cents
2. compute **distance** of peaks to nearest equally tempered semitone frequency @ $f_{A4} = 440\,\mathrm{Hz}$ (in Cents)
3. compute **histogram of deviations**
4. choose **position of histogram maximum** as tuning frequency deviation from f_{A4}

tuning frequency estimation

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tuning frequency estimation

filterbank-based 1/2

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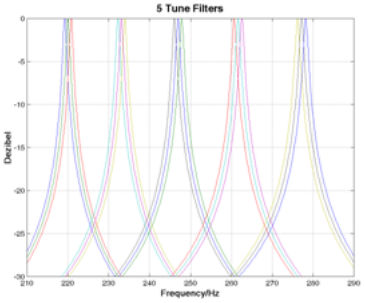
1. filterbank with 3 closely spaced filters per semi-tone
2. compute output energy for every triplet $E_j(0,n), E_j(1,n), E_j(2,n)$
3. compute overall triplet output energy

$$E(\cdot,n) = \sum_{\forall j} E_j(\cdot,n)$$



plots from[3],[4]

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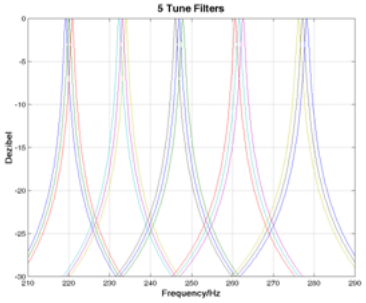

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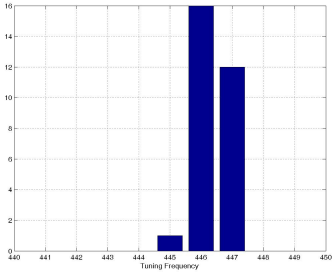

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tuning frequency estimation

filterbank-based 2/2

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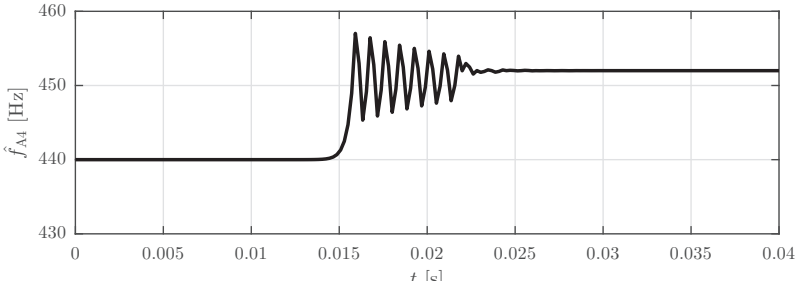
4. adapt current tuning frequency estimate

$$\begin{aligned} \hat{f}_{\mathrm{A4}}(n+1) &= \left(1 + \operatorname{sign}\left(E(2) - E(0)\right) \cdot \lambda(n)\right) \cdot \hat{f}_{\mathrm{A4}}(n) \\ \lambda(n+1) &= c \cdot \lambda(n) \end{aligned}$$

- $c > 1$ if constant direction/sign
- $c < 1$ if changed direction



matlab source: matlab/displayRprop.m

tuning frequency estimation

filterbank-based 2/2

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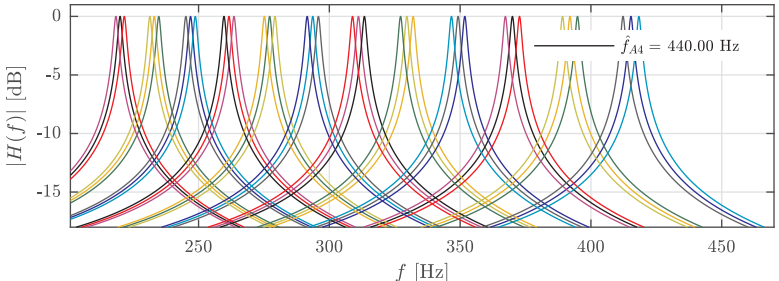

matlab source: matlab/animateFilterbankAdaptation.m

summary

lecture content

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- **tuning frequency**
  - important reference for all pitch-based algorithms
  - usually around 440 Hz
- **tuning frequency estimation**
  - can be online or offline, score-based or "blind"
  - typical processing steps
    1. estimate fundamental frequencies
    2. calculate deviation from the nearest (equally tempered) pitch frequency
    3. average deviations of all fundamental frequencies
    4. compute the tuning frequency from the average distance