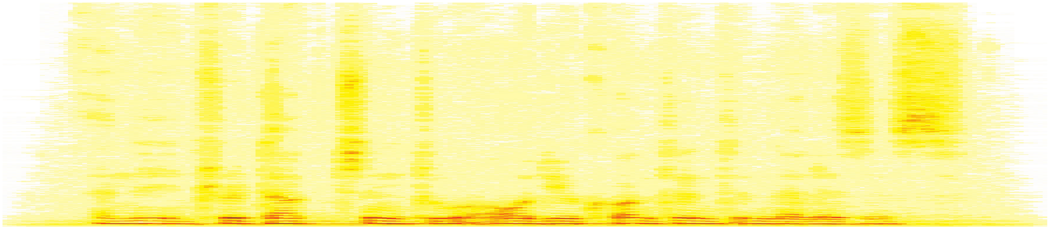
Introduction to Audio Content Analysis

Module 5.2: Fundamental Frequency Detection in Monophonic Signals

alexander lerch



Georgia Tech Center for Music Technology
College of Design

introduction
overview

corresponding textbook section

Chapter 5 — Tonal Analysis: pp. 91–103

- **lecture content**
  - established approaches to monophonic pitch tracking in
    - time domain
    - frequency domain

- **learning objectives**
  - define the task of monophonic pitch tracking
  - summarize the principles of time-domain f_0-trackers and describe one approach in detail
  - summarize the principles of frequency-domain f_0-trackers and describe one approach in detail

introduction
overview

corresponding textbook section

Chapter 5 — Tonal Analysis: pp. 91–103

- **lecture content**
  - established approaches to monophonic pitch tracking in
    - time domain
    - frequency domain

- **learning objectives**
  - define the task of monophonic pitch tracking
  - summarize the principles of time-domain f_0-trackers and describe one approach in detail
  - summarize the principles of frequency-domain f_0-trackers and describe one approach in detail

fundamental frequency
introduction

remember

Fourier series: every (quasi-)periodic sound is a combination of sinusoidals with integer frequency ratios

$$x(t) \approx x(t + T_0)$$

$$x(t) \approx \sum_{k=-\infty}^{\infty} a(k) e^{\mathrm{j}\omega_0 kt}$$

f_0: musically, perceptually most "relevant" frequency

fundamental frequency
introduction

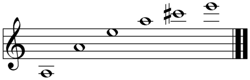
remember

Fourier series: every (quasi-)periodic sound is a combination of sinusoidals with integer frequency ratios

$$x(t) \approx x(t + T_0)$$

$$x(t) \approx \sum_{k=-\infty}^{\infty} a(k) e^{j\omega_0 kt}$$

f_0: musically, perceptually most “relevant” frequency



pitch detection
task definition

- detect the fundamental frequency f_0
- there is only one fundamental frequency at a time

- related subtasks:
    - detect when there is no fundamental frequency
    - segment into notes
        - start time and stop time
        - average note frequency
        - vibrato detection
    - map to pitch scale

monophonic fundamental frequency detection

zero crossing rate

- **number of zero crossings per block** (inaccurate)

$$T_0(n) = \frac{2 \cdot \big(i_\mathrm{e}(n) - i_\mathrm{s}(n)\big)}{f_\mathrm{S} \cdot \sum\limits_{i=i_\mathrm{s}(n)}^{i_\mathrm{e}(n)} \left|\mathrm{sign}\left[x(i)\right] - \mathrm{sign}\left[x(i-1)\right]\right|}$$

- **average period length**

$$T_0(n) = \frac{2}{\mathcal{Z}-1}\sum\limits_{j=0}^{\mathcal{Z}-2} \Delta t_\mathrm{ZC}(j).$$

- **variants**:
  - create histogram with distances and choose maximum
  - use not (only) ZC but distance between local extrema

monophonic fundamental frequency detection
zero crossing rate

- **number of zero crossings per block** (inaccurate)

$$T_0(n) = \frac{2 \cdot \left(i_\mathrm{e}(n) - i_\mathrm{s}(n)\right)}{f_\mathrm{S} \cdot \sum\limits_{i=i_\mathrm{s}(n)}^{i_\mathrm{e}(n)} \left|\mathrm{sign}\left[x(i)\right] - \mathrm{sign}\left[x(i-1)\right]\right|}$$

- **average period length**

$$T_0(n) = \frac{2}{\mathcal{Z}-1} \sum_{j=0}^{\mathcal{Z}-2} \Delta t_\mathrm{ZC}(j).$$

- **variants**:
  - create histogram with distances and choose maximum
  - use not (only) ZC but distance between local extrema

monophonic fundamental frequency detection

zero crossing rate

- **number of zero crossings per block** (inaccurate)

$$T_0(n) = \frac{2 \cdot \left(i_\mathrm{e}(n) - i_\mathrm{s}(n)\right)}{f_\mathrm{S} \cdot \sum\limits_{i=i_\mathrm{s}(n)}^{i_\mathrm{e}(n)} \left|\mathrm{sign}\left[x(i)\right] - \mathrm{sign}\left[x(i-1)\right]\right|}$$

- **average period length**

$$T_0(n) = \frac{2}{\mathcal{Z} - 1} \sum_{j=0}^{\mathcal{Z}-2} \Delta t_\mathrm{ZC}(j).$$

- **variants**:
  - create histogram with distances and choose maximum
  - use not (only) ZC but distance between local extrema

monophonic fundamental frequency detection

auto correlation function

- find **lag of ACF maximum**

$$r_{xx}(\eta, n) = \sum_{i=i_s(n)}^{i_e(n)-\eta} x(i) \cdot x(i+\eta)$$

- **variants**:
  - center clipping

monophonic fundamental frequency detection
auto correlation function

- find **lag of ACF maximum**

$$r_{xx}(\eta, n) = \sum_{i=i_s(n)}^{i_e(n)-\eta} x(i) \cdot x(i+\eta)$$

- **variants**:
  - center clipping

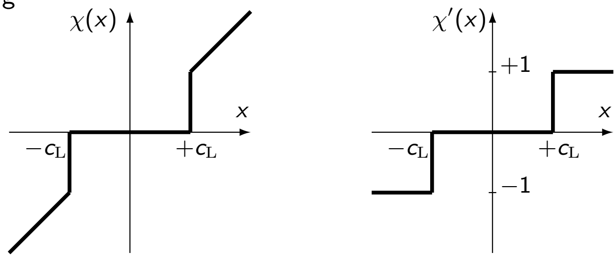
monophonic fundamental frequency detection

auto correlation function

- find **lag of ACF maximum**

$$r_{xx}(\eta, n) = \sum_{i=i_s(n)}^{i_e(n)-\eta} x(i) \cdot x(i+\eta)$$

- **variants**:
  - center clipping



monophonic fundamental frequency detection

average magnitude difference function

Georgia Tech Center for Music Technology College of Design

- find **lag of AMDF minimum**

$$\mathrm{AMDF}_{xx}(\eta, n) = \frac{1}{i_\mathrm{e}(n) - i_\mathrm{s}(n) + 1} \sum_{i=i_\mathrm{s}(n)}^{i_\mathrm{e}(n)-\eta} |x(i) - x(i+\eta)|$$

- **variants**:
  - AMDF-weighted ACF

$$r'_{xx}(\eta, n) = \frac{r_{xx}(\eta, n)}{\mathrm{AMDF}_{xx}(\eta, n) + 1}$$

monophonic fundamental frequency detection

average magnitude difference function

- find **lag of AMDF minimum**

$$\mathrm{AMDF}_{xx}(\eta, n) = \frac{1}{i_\mathrm{e}(n) - i_\mathrm{s}(n) + 1} \sum_{i=i_\mathrm{s}(n)}^{i_\mathrm{e}(n)-\eta} |x(i) - x(i+\eta)|$$

- **variants**:
    - AMDF-weighted ACF

$$r'_{xx}(\eta, n) = \frac{r_{xx}(\eta, n)}{\mathrm{AMDF}_{xx}(\eta, n) + 1}$$

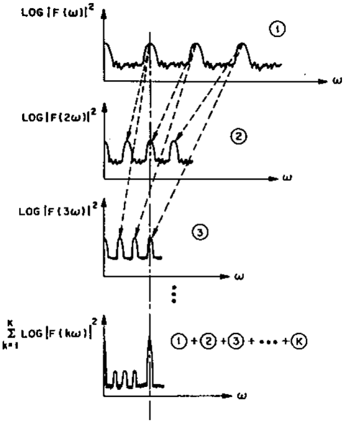
monophonic fundamental frequency detection

harmonic product spectrum 1/2

$$X_{\mathrm{HPS}}(k, n) = \prod_{j=1}^{\mathcal{O}} |X(j \cdot k, n)|^2$$

first published in the 1960s by Noll (graph from that paper)

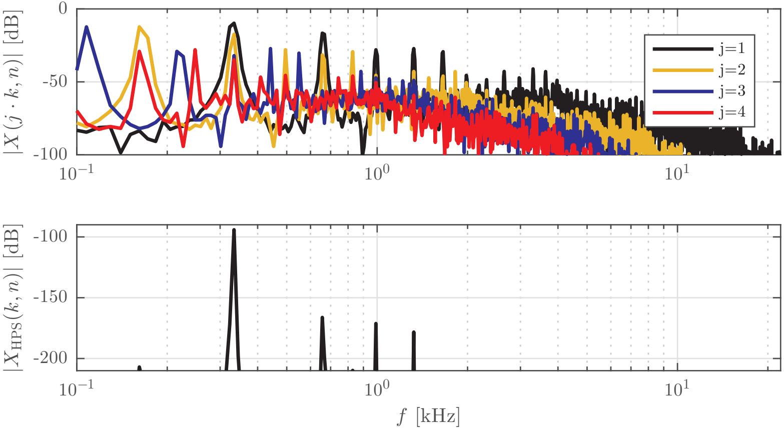
1



[1] A. M. Noll, "Pitch Determination of Human Speech by the Harmonic Product Spectrum, the Harmonic Sum Spectrum, and a Maximum Likelihood Estimate," in *Proceedings of the Symposium on Computer Processing in Communications*, vol. 19, Brooklyn: Polytechnic Press of the University of Brooklyn, 1969, pp. 779–797.

monophonic fundamental frequency detection

harmonic product spectrum 2/2



matlab source: matlab/displayHarmonicProductSpectrum.m

monophonic fundamental frequency detection

harmonic sum spectrum

Georgia Tech Center for Music Technology
College of Design

- sum instead product sum

$$X_{\mathrm{HSS}}(k,n) = \sum_{j=1}^{\mathcal{O}} |X(j \cdot k, n)|^2$$

- **advantage**
  - robust against missing harmonics
- **disadvantage**
  - less pronounced peak

monophonic fundamental frequency detection

ACF of magnitude spectrum

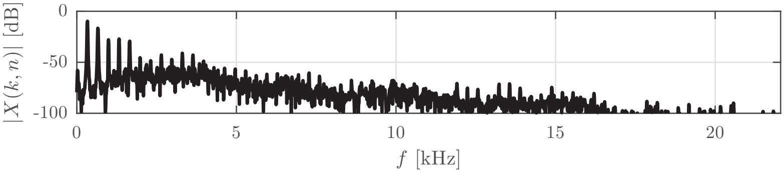
$$r_{XX}(\eta, n) = \sum_{k=-\mathcal{K}/2}^{\mathcal{K}/2-1} |X(k, n)| \cdot |X(k+\eta, n)|$$

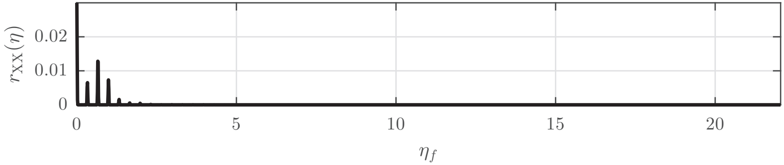
$\Rightarrow$ **detect maximum location**

monophonic fundamental frequency detection
ACF of magnitude spectrum

$$r_{XX}(\eta, n) = \sum_{k=-\mathcal{K}/2}^{\mathcal{K}/2-1} |X(k,n)| \cdot |X(k+\eta, n)|$$

$\Rightarrow$ **detect maximum location**





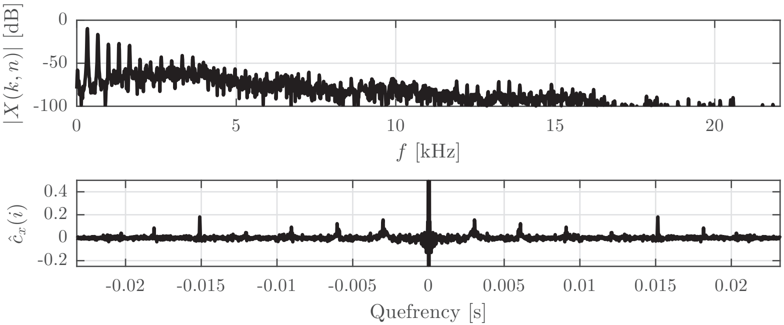
matlab source: matlab/displayAcfOfFft.m

monophonic fundamental frequency detection

cepstral pitch detection

Georgia Tech Center for Music Technology College of Design

1. compute cepstrum
2. detect periodicities



matlab source: matlab/displayCepstrum.m

monophonic fundamental frequency detection

spectral maximum likelihood

- create **template matrix** with (smoothed) delta pulses for all possible frequencies
- compute the **cross correlation** ($lag = 0$) between spectrum and all templates
- pick the result with the **highest correlation** $\Rightarrow$ frequency estimate (graph see[2])

[2] P. de la Cuadra, *Pitch detection methods review*, [Online]. Available: https://ccrma.stanford.edu/~pdelac/154/m154paper.htm (visited on 08/04/2015).

monophonic fundamental frequency detection

spectral maximum likelihood

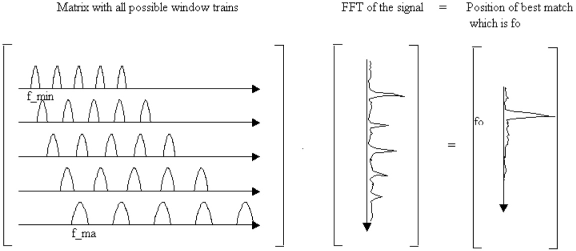
- create **template matrix** with (smoothed) delta pulses for all possible frequencies
- compute the **cross correlation** ($lag = 0$) between spectrum and all templates
- pick the result with the **highest correlation** $\Rightarrow$ frequency estimate (graph see[2])

[2] P. de la Cuadra, *Pitch detection methods review*, [Online]. Available: https://ccrma.stanford.edu/~pdelac/154/m154paper.htm (visited on 08/04/2015).

monophonic fundamental frequency detection

spectral maximum likelihood

- create **template matrix** with (smoothed) delta pulses for all possible frequencies
- compute the **cross correlation** ($lag = 0$) between spectrum and all templates
- pick the result with the **highest correlation** $\Rightarrow$ frequency estimate (graph see[2])



[2] P. de la Cuadra, *Pitch detection methods review*, [Online]. Available: https://ccrma.stanford.edu/~pdelac/154/m154paper.htm (visited on 08/04/2015).

monophonic fundamental frequency detection

auditory-motivated pitch tracking 1/2

1. **filterbank** of band pass filters (e.g., mel scale)
2. **HWR**
3. **smoothing**
4. within-band periodicity estimate (e.g. **ACF**)
5. **combination** of bands

monophonic fundamental frequency detection

auditory-motivated pitch tracking 1/2

Georgia Tech Center for Music Technology College of Design

1. **filterbank** of band pass filters (e.g., mel scale)
2. **HWR**
3. **smoothing**
4. within-band periodicity estimate (e.g. **ACF**)
5. **combination** of bands

monophonic fundamental frequency detection

auditory-motivated pitch tracking 1/2

1. **filterbank** of band pass filters (e.g., mel scale)
2. **HWR**
3. **smoothing**
4. within-band periodicity estimate (e.g. **ACF**)
5. **combination** of bands

monophonic fundamental frequency detection

auditory-motivated pitch tracking 1/2

1. **filterbank** of band pass filters (e.g., mel scale)
2. **HWR**
3. **smoothing**
4. within-band periodicity estimate (e.g. **ACF**)
5. **combination** of bands

monophonic fundamental frequency detection

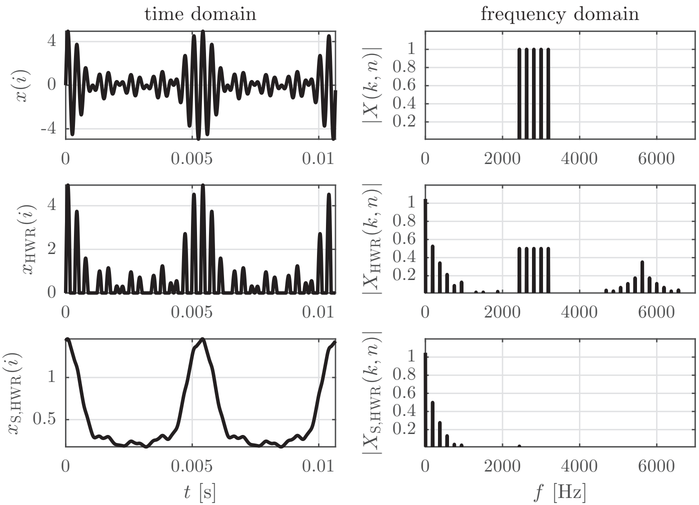
auditory-motivated pitch tracking 1/2

1. **filterbank** of band pass filters (e.g., mel scale)
2. **HWR**
3. **smoothing**
4. within-band periodicity estimate (e.g. **ACF**)
5. **combination** of bands

monophonic fundamental frequency detection

auditory-motivated pitch tracking 2/2

1. filterbank output
2. half wave rectification
3. smoothed output



matlab source: matlab/displayAuditoryPitchTracking.m

summary
lecture content

- **basic approach**
  - all approaches look for **periodicity**
    - waveform similarity in time domain
    - equidistant harmonics/peaks in freq domain
- **state-of-the-art**
  - despite the age of the presented methods, tweaked versions of the presented approaches are still often considered state-of-the-art
  - especially combinations of different approaches can be very successful