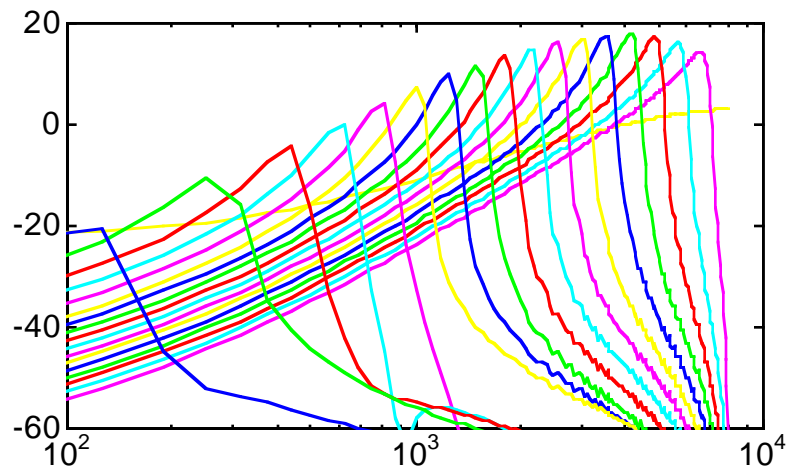


Auditory Toolbox

Version 2

Malcolm Slaney

Technical Report #1998-010
Interval Research Corporation
malcolm@interval.com



Auditory Toolbox:

A M ATLAB Toolbox for Auditory Modeling Work

Version 2

Malcolm Slaney

Interval Research Corporation

malcolm@interval.com

© 1993-1994 Apple Computer, Inc.

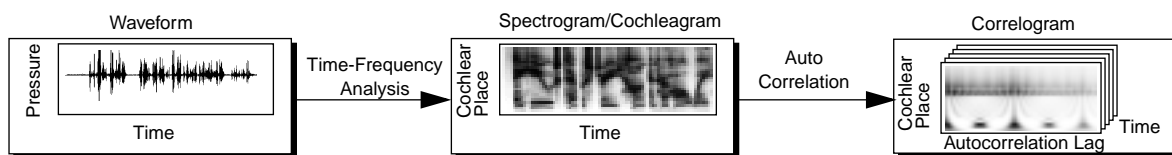
©1994-1998 Interval Research Corporation

All Rights Reserved

This report describes a collection of tools that implement several popular auditory models for a numerical programming environment called MATLAB. This toolbox will be useful to researchers that are interested in how the auditory periphery works and want to compare and test their theories. This toolbox will also be useful to speech and auditory engineers who want to see how the human auditory system represents sounds.

This version of the toolbox fixes several bugs, especially in the Gammatone and MFCC implementations, and adds several new functions. This report was previously published as Apple Computer Technical Report #45. We appreciate receiving permission from Apple Computer to republish their code and to update this package.

There are many ways to describe and represent sounds. The figure below shows one taxonomy based on signal dimensionality. A simple waveform is a one-dimensional representation of sound. The two-dimensional representation describes the acoustic signal as a time-frequency image. This is the typical approach for sound and speech analysis. This toolbox includes conventional tools such as the short-time-Fourier-Transform (STFT or Spectrogram) and several cochlear models that estimate auditory nerve firing “probabilities” as a function of time. Finally, the next level of abstraction is to summarize the periodicities of the cochlear output with the correlogram. The correlogram provides a powerful representation that makes it easier to understand multiple sounds and to perform auditory scene analysis.



Six types of auditory time-frequency representations are implemented in this toolbox:

- 1) Richard F. Lyon has described an auditory model based on a transmission line model of the basilar membrane and followed by several stages of adaptation. This model can represent sound at either a fine time scale (probabilities of an auditory nerve firing) or at the longer time scales characteristic of the spectrogram or MFCC analysis. The *LyonPassiveEar* command implements this particular ear model.
- 2) Roy Patterson has proposed a model of psychoacoustic filtering based on critical bands. This auditory front-end combines a Gammatone filter bank with a model of hair cell dynamics proposed by Ray Meddis. This auditory model is implemented using the *MakeERBFilters*, *ERBFilterBank*, and *MeddisHairCell* commands.
- 3) Stephanie Seneff has described a cochlear model that combines a critical band filterbank with models of detection and automatic gain control. This toolbox implements stages I and II of her model.
- 4) Conventional FFT analysis is represented using the spectrogram. Both narrow band and wide band spectrograms are possible. See the *spectrogram* command for more information.
- 5) A common front-end for many speech recognition systems consists of Mel-frequency cepstral coefficients (MFCC). This technique combines an auditory filter-bank with a cosine transform to give a rate representation roughly similar to the auditory system. See the *mfcc* command for more information. In addition, a common technique known as *rasta* is included to filter the coefficients, simulating the effects of masking and providing speech recognition system a measure of environmental adaptation.
- 6) Conventional speech-recognition systems often use linear-predictive analysis to model a speech signal. The forward transform, *proclpc*, and its inverse, *synlpc* are included.

My work has concentrated on how to capture and represent the information in our auditory environment. Towards this

goal, we have been investigating the correlogram. The primary goal of the correlogram is to summarize the temporal activity at the output of the cochlea. With most sounds, and especially with voiced speech, much of the information in the waveform and cochlear output is repetitive. The correlogram is an easy way to capture the periodicities and make them visible. This toolbox includes several routines to compute and display correlograms, and to compute pitch estimate from correlograms.

This toolbox has a very simple view of data. Sound waveforms are stored as one-dimensional arrays. The output from cochlear models is stored as a two-dimensional array, each row representing one neuron's firing probability, and columns of the matrix representing firing probabilities on the auditory nerves at one time. Correlograms can be stored as either movies or as an array. Filter coefficients are either stored as lists, like the MATLAB filter function, or second-order-sections are stored as a list of five coefficients.

Many of the auditory routines in this toolbox are demonstrated using the same speech signal. This test sound is supplied as the file "tapestry.wav" and can be imported into MATLAB using the wavread function. This signal is a female speaking saying "A huge tapestry hung in her hallway" and is from the TIMIT speech database (TRAIN/DR5/FCDRI/SX106/SX106.ADC).

This report is not a detailed description of each auditory model. Most function descriptions include references to more detailed descriptions of each model.

This software has been tested on Macintosh and Windows95 computers running MATLAB 5.2 and on SGI and Sun workstations. All of this code is portable so we don't expect any problems when running on any other machine that runs MATLAB.

There are several other packages of auditory models. They have slightly different philosophies and coding styles. Roy Patterson and his colleagues in Cambridge UK have a package called the Auditory Image Model (AIM). Written in C, this package allows many different models of auditory perception to be linked together. More information about the AIM model is available at

<http://www.mrc-cbu.cam.ac.uk/personal/roy.patterson/aim/>

A similar package has been written by Ray Meddis and Lowel O'Mard. More information about LUTEAR is available at

<http://www.essex.ac.uk/psychology/hearinglab/lutear/home.html>

Finally, a word from our lawyers:

Warranty Information: Even though Interval has reviewed this software, Interval makes no warranty or representation, either express or implied, with respect to this software, its quality, accuracy, merchantability, or fitness for a particular purpose. As a result, this software is provided "as is," and you, its user, are assuming the entire risk as to its quality and accuracy.

A flowchart showing how all the commands in this toolbox fit together is shown in the next section.

Installation

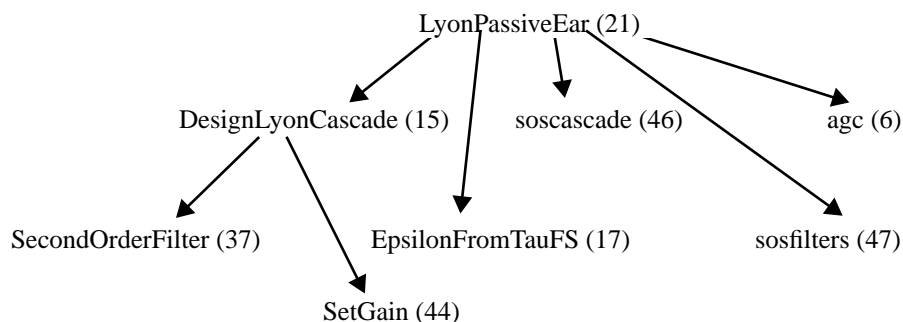
This toolbox is supplied as a collection of MATLAB m-functions and three MEX functions written in C. The three MEX functions, *agc*, *soscascade*, and *sosfilters*, are precompiled for the Macintosh. You will need to compile them yourself for other machines using the Mathworks mex function. Use the example code, included with this documentation, to test each function.

A m-function called *test_auditory* is provided to quickly run through all the examples provided in this documentation. Use this function to test whether all functions are performing according to the documentation.

Flow Charts

This section shows which routines are used by each function in this toolbox. This will help readers understand the structure of the cochlear models. Page numbers are shown in parenthesis.

Lyons Passive Long Wave Cochlear Model



Patterson-Holdsworth ERB Filter Bank

MakeERBFilters (24) ERBFilterBank (18) MeddisHairCell (27)

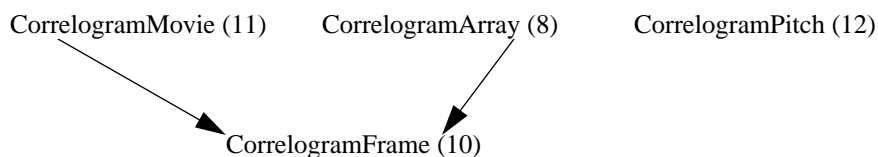
Seneff Auditory Model



Alternate Analysis Techniques

mfcc (29) spectrogram (49)
 proclpc (33) synlpc (50) rasta (35)

Correlogram Processing



Demonstrations

MakeVowel (26) FMPoints (19)
 WhiteVowel (52)

Purpose

Adaptation process for Lyon's passive longwave cochlear model

Synopsis

[output, state] = agc(input, coeffs, state)

Description

This function implements multiple stages of the multiplicative adaptive gain used by Lyon's passive longwave cochlear model. The input is a number of channels from a filter bank. An optional array of state filters, one per channel and per stage, measure a running average of the energy in the channel. These state variables are then used to drive a single multiplicative gain per stage per channel.

The coeffs array is used to parameterize the AGC system. Two parameters must be supplied for each stage, a target output value and an epsilon. The AGC tries to keep the output below the target value. The gain is changed gradually based on the value of epsilon. Smaller values of epsilon allow the AGC process to take longer to adjust the output. Values of epsilon should be between 0 and 1. See the routine *EpsilonFromTauFS* (17) for more information.

The state argument is optional. If the input has N samples then the parameters have the following sizes:

input is C x N
Coeffs is 2 x S (targets;epsilons)
output is C x N
state is C x S

Note, the implementation of the *agc* function in this toolbox includes an additional limiting term to prevent the system gain from getting too close to zero. This is done as described on page 19 of "Lyon's Cochlear Model," by not letting the state variable exceed 0.9.

Examples

```
»agc(ones(1,20),[.5;.5])

ans =

Columns 1 through 7

    1.0000    0.1000    0.4500    0.2750    0.3625    0.3187    0.3406

Columns 8 through 14

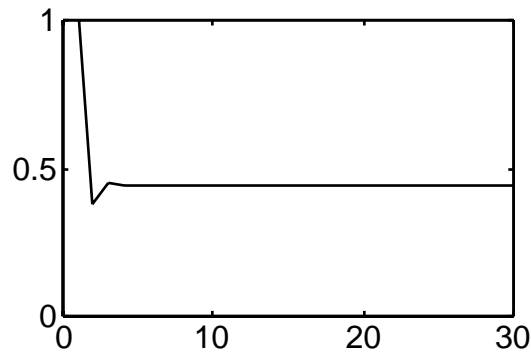
    0.3297    0.3352    0.3324    0.3338    0.3331    0.3334    0.3333

Columns 15 through 20

    0.3334    0.3333    0.3333    0.3333    0.3333    0.3333
```

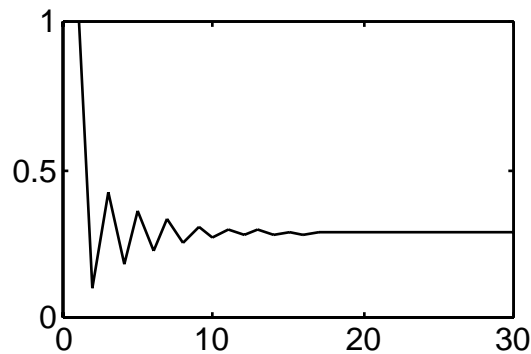
Here are some more examples. First use a target of 0.8 and a relatively short time constant (large value of epsilon or 0.5). Note the final output value will be dependent on both the input value and the AGC target. The oscillatory behaviour is normal when the input signal gets larger than the target faster than the AGC can cut the gain.

```
»plot(agc(ones(1,30), [.8;.5]))
```



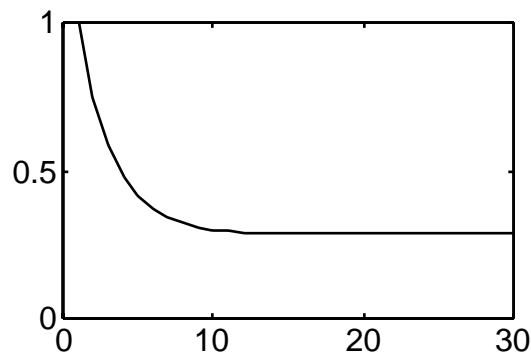
Now switch to a much smaller target value.

```
»plot(agc(ones(1,30), [.4;.5]))
```



Finally, we switch to a much longer time constant (smaller value of epsilon.) This makes the response much less likely to oscillate, but now the AGC takes longer to cut the signal level to the target.

```
»plot(agc(ones(1,30), [.4;.1]))
```



See Also

Malcolm Slaney, *Lyon's Cochlear Model*, Apple Computer Technical Report #13, 1988. Currently available at
<http://web.interval.com/~malcolm/pubs.html#LyonCochlear>

CorrelogramArray

Purpose

Compute a sequence of correlogram frames and store in one large array

Synopsis

```
movie = CorrelogramArray(input, sr, frameRate, width)
```

Description

This routine computes multiple frames of a correlogram, storing each frame as one row in a large array. The *input* data can be from any of the cochlear models in this toolbox.

The *input* array should be of size $N \times L$ where N is the number of cochlear channels, and each channel has L time steps, each sample representing an auditory fiber firing probability. The *input* is sampled at a frequency of *sr*.

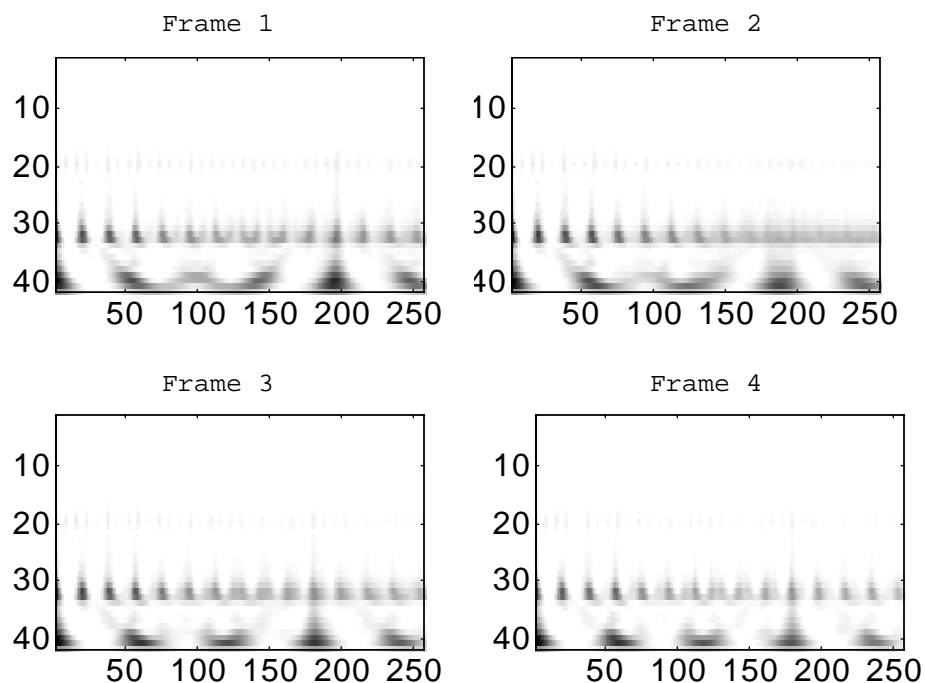
The resulting correlogram array has one frame stored in each row. These frames are computed *frameRate* times per second. Each image in the correlogram is $N \times \text{width}$ in size. The rows in the output array each have $N \times \text{width}$ elements.

Examples

The correlogram of a vowel with vibrato can be calculated, played, and displayed using the following code.

```
»u=MakeVowel(4000,FMPoints(4000,120),16000,'u');
»soundsc(u,16000)
»coch=LyonPassiveEar(u,16000,1,4,.25);
»width = 256;
»cor=CorrelogramArray(coch,16000,16,width);
Correlogram spacing is 1000 samples per frame.
CorrelogramFrame fftSize is 8192
CorrelogramFrame fftSize is 8192
CorrelogramFrame fftSize is 8192
CorrelogramFrame fftSize is 8192
»[pixels frames] = size(cor);
»colormap(1-gray);
»for j=1:frames
    imagesc(reshape(cor(:,j),pixels/width,width));
    drawnow;
end
```


This produces the following images. Note how the pitch line moves.



See Also

CorrelogramFrame, CorrelogramMovie

Malcolm Slaney and R. F. Lyon, “On the importance of time—A temporal representation of sound,” in *Visual Representations of Speech Signals*, M. Cooke, S. Beete, and M. Crawford, eds., J. Wiley and Sons, Sussex, England, 1993. Also available at <http://web.interval.com/~malcolm/pubs.html#ImportanceOfTime>

CorrelogramFrame

Purpose

Compute one frame of a correlogram

Synopsis

```
picture = CorrelogramFrame(data, picWidth, start, winLen)
```

Description

This routine computes one frame of a correlogram. The *input* data is a two-dimensional array of cochlear data, each row representing firing probabilities from one cochlear channel. The output picture is a two dimensional array with one row for each row of cochlear input data and *picWidth* pixels wide.

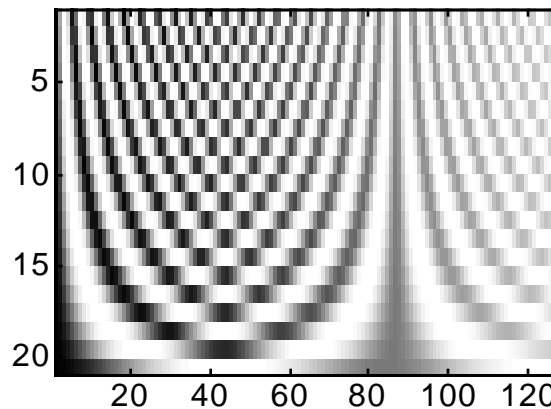
The correlogram is computed with autocorrelation using data from the input array. For each channel, the data from is extracted starting at column *start* and extending for *winLength* time steps.

Examples

A simple correlogram can be calculated from synthetic data using the following code. We use 20 harmonic sinusoids as input (with high frequencies at the top to simulate the cochlea).

```
»for j=20:-1:1
    c(j,:) = max(0,sin((1:256)/256*(21-j)*3*2*pi));
end
»picture=CorrelogramFrame(c,128,1,256);
»image(picture/4*length(colormap))
»colormap(1-gray)
```

Which produces the following image:



See Also

This routine is used by the *CorrelogramArray* and *CorrelogramMovie* routines.

Malcolm Slaney and R. F. Lyon, “On the importance of time—A temporal representation of sound,” in *Visual Representations of Speech Signals*, M. Cooke, S. Beete, and M. Crawford, eds., J. Wiley and Sons, Sussex, England, 1993. Also available at <http://web.interval.com/~malcolm/pubs.html#ImportanceOfTime>

CorrelogramMovie

Purpose

Compute a correlogram movie

Synopsis

```
movie = CorrelogramMovie(data, sr, frameRate, width)
```

Description

This routine computes multiple frames of a correlogram, storing each image as one frame in a MATLAB movie object. The *input* data can be from any of the cochlear models in this toolbox.

The *input* array should be of size $N \times L$ where N is the number of cochlear channels, and each channel has L firing probabilities. The *input* is sampled at a frequency of *sr*.

The resulting correlogram array has one frame stored in each row. These frames are computed *frameRate* times per second. Each image in the correlogram is $N \times \text{width}$ in size. The rows in the output array each have $N \times \text{width}$ elements. Use the MATLAB movie command to play the resulting movie on the screen.

Examples

A correlogram movie can be calculated using the following code. See the *CorrelogramArray* (8) documentation for images of the movie frames.

```
»u=MakeVowel(4000,FMPoints(4000,120),16000,'u');
»soundsc(u,16000)
»coch=LyonPassiveEar(u,16000,1,4,.25);
»mov=CorrelogramMovie(coch,16000,16,256);
»movie(mov,-10,16)
```

See Also

CorrelogramFrame, *CorrelogramArray*

Malcolm Slaney and R. F. Lyon, "On the importance of time—A temporal representation of sound," in *Visual Representations of Speech Signals*, M. Cooke, S. Beete, and M. Crawford, eds., J. Wiley and Sons, Sussex, England, 1993. Also available at <http://web.interval.com/~malcolm/pubs.html#ImportanceOfTime>

CorrelogramPitch

Purpose

Compute the pitch of a sound using the correlogram

Synopsis

```
[pitch salience]=CorrelogramPitch(correlogram, ...
                                   width, sr [, lowPitch, highPitch]);
```

Description

This routine calculates the pitch of a sound using a correlogram model of human pitch perception. Given a correlogram, as computed by *CorrelogramArray*, this routine performs the following operations on each frame of the correlogram.

- 1) Reshape the data in one row of the correlogram array into a correlogram image. The second function argument, *width*, is needed to reshape the correlogram to the proper size.
- 2) Summarize the correlogram frame by adding the energy at each time lag across all channels.
- 3) Remove the peak in the summary correlogram at zero lag by removing all points in the summary correlogram up to the first positive inflection.
- 4) Remove all points from the summary correlogram outside the valid pitch range.
- 5) Find the position of the largest peak that remains. This is an estimate of the pitch. The sample rate (sr) argument is used to convert from autocorrelation lag index to pitch frequency.
- 6) Pitch salience is calculated by dividing the value of the summary correlogram at the pitch peak into the value of the summary correlogram at zero lag. Highly periodic sounds with an easily perceivable pitch will have a salience close to 1, aperiodic sounds will have a salience closer to zero.

The result is a single pitch estimate and a crude estimate of pitch salience at every frame.

Note, this routine uses a very simple, but powerful, algorithm to model human pitch perception. The paper by Slaney and Lyon describes additional algorithmic enhancements that allow more robust pitch estimates.

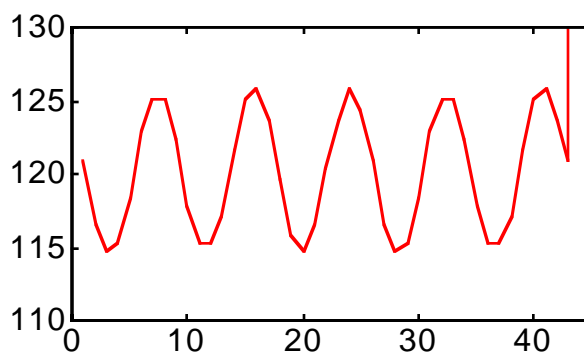
The *CorrelogramPitch* function uses optional *lowPitch* and *highPitch* arguments to limit the range of legal pitch values. It is important to note that neither *CorrelogramPitch* or the papers referenced below include any other higher-level knowledge about pitch. Notably, this work does not enforce any frame-to-frame continuity in the pitch. Each pitch estimate is independent and there is no restriction preventing the estimate to change instantaneously from frame to frame.

Examples

The simplest possible pitch detector is computed using auto-correlation of the original waveform. This can be done by computing the correlogram of the original waveform (pretending that it is the output of a cochlear model with just one channel). The input is a vowel with its pitch centered at 120Hz and a 5Hz vibrato.

```
»u=MakeVowel(20000,FMPoints(20000,120),22254,'u');
»cor=CorrelogramArray(u,22254,50,256);
»p=CorrelogramPitch(cor,256,22254);
»plot(p)
»axis([0 45 110 130])
```

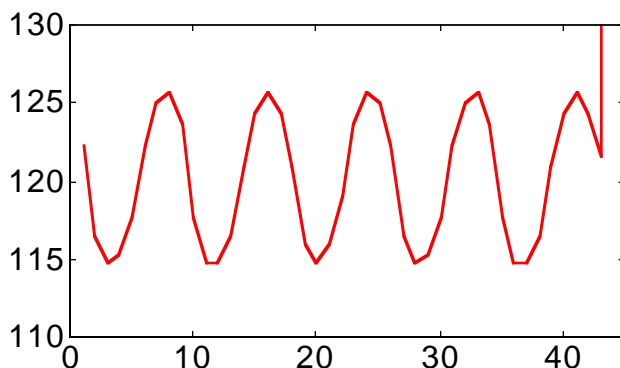
The resulting pitch is shown below. The final pitch value is an artifact of the computation at the end of the signal.



A more robust result is possible if the correlogram is computed on the output of a cochlear model. The example below computes the cochlear output and then the correlogram of the /u/ vowel.

```
» coch=LyonPassiveEar(u,22254,1,4,.5);
» cor=CorrelogramArray(coch,22254,50,256);
» p=CorrelogramPitch(cor,256,22254);
» plot(p)
» axis([0 45 110 130])
```

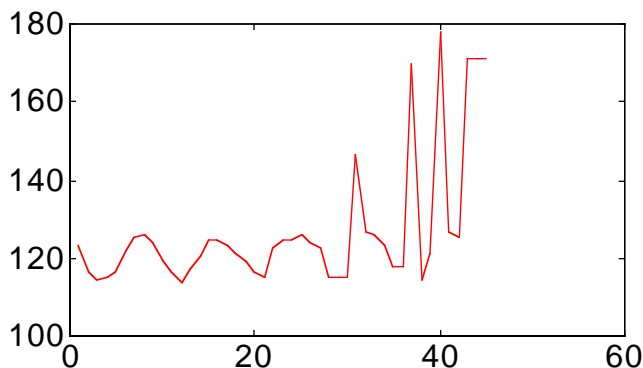
The resulting pitch estimate is



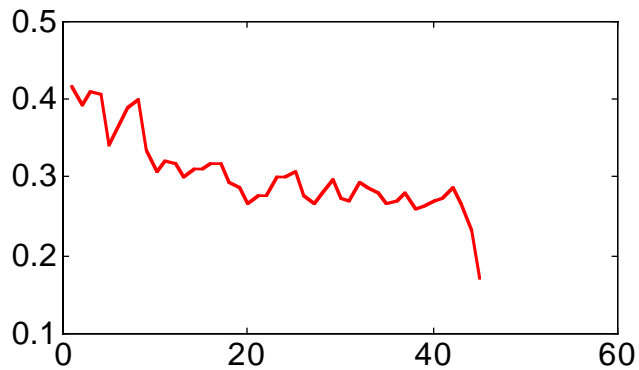
The *lowPitch* and *highPitch* arguments can be used to limit the pitch estimates to a known range. This is a simple way to make the pitch estimate use high-order bodies of knowledge. The example below shows adding steadily increasing gaussian-white noise to the /u/ vowel and then estimating the pitch.

```
» u=MakeVowel(20000,FMPoints(20000,120),22254,'u');
» n=randn([1 20000]).*(1:20000)/20000;
» un=u+n/4;
» coch=LyonPassiveEar(un,22254,1,4,.5);
» cor=CorrelogramArray(coch,22254,50,256);
» [pitch sal]=CorrelogramPitch(cor,256,22254,100,200);
» plot(pitch)
```

The pitch is limited to values between 100 and 200Hz and the resulting estimate is



The salience of this pitch estimate declines as the signal to noise ratio goes down.



See Also

The basic idea behind this model of pitch is described in three papers. The first paper extends the functionality implemented by this function using several techniques to more reliably pick the most robust peak.

Malcolm Slaney and Richard F. Lyon, "A perceptual pitch detector," in the *Proceedings of the 1990 International Conference on Acoustics, Speech, and Signal Processing*, Albuquerque, NM, IEEE, pp 357-360, 1990. Also available at <http://web.interval.com/~malcolm/pubs.html#perceptualpitch>

An extensive comparison of the performance of a correlogram model of pitch and human performance is described in:

Ray Meddis and Michael J. Hewitt, "Virtual pitch and phase sensitivity of a computer model of the auditory periphery, I. Pitch identification," *J. Acoustical Society of America*, 89 (6), pp. 2866-2682, 1991.

Ray Meddis and Michael J. Hewitt, "Virtual pitch and phase sensitivity of a computer model of the auditory periphery, II. Phase sensitivity," *J. Acoustical Society of America*, 89 (6), pp. 2683-2894, 1991.

DesignLyonFilters

Purpose

Design the filters needed to implement Lyon's passive cochlear model

Synopsis

```
[filters, freqs] = DesignLyonFilters(fs, EarQ, StepFactor)
```

Description

Design the cascade of second order filters and the front filters (outer/middle and compensator) needed for Lyon's Passive Short Wave (Second Order Sections) cochlear model. The variables used here come from Apple ATG Technical Report #13 titled *Lyon's Cochlear Model*.

Most of the parameters are hardwired into this m-function. The user settable parameters are the digital sampling rate (*fs*), the basic Q of the each stage (*EarQ*, usually 8 or 4), and the *StepFactor* between channels (usually .25 and .125, respectively.) The *EarQ* and *Stepfactor* parameters default to 8 and 32/*EarQ* respectively.

The result is returned as rows of second order filters; three coefficients for the numerator and two for the denominator. Using the same convention as the MATLAB filter function, the coefficients are [B0 B1 B2 A1 A2].

This function is called automatically by LyonPassiveEar to design the appropriate filterbank.

Examples

The first five channels of a typical filter bank design are shown below. Note, the first two channels implement the model's outer and middle ear filters.

```
» filts = DesignLyonFilters(16000);
» size(filts)

ans =

      88      5

» filts(1:5, :)

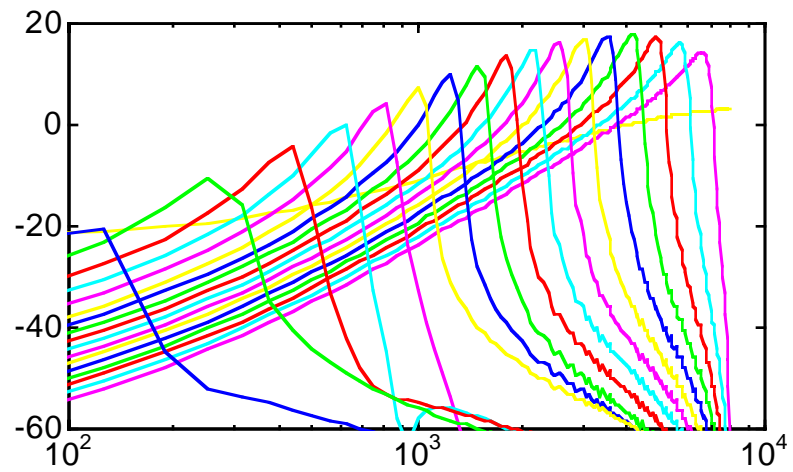
ans =

         0    0.7474   -0.6644         0         0
    0.8373         0   -0.8373    1.6433    0.6772
    0.8899    1.7137    0.8251    1.6369    0.6854
    0.8877    1.7027    0.8250    1.6160    0.6934
    0.8859    1.6774    0.8252    1.5821    0.7011
```

The frequency response of this filter bank can be calculated using `soscascade`.

```
» resp = soscascade([1 zeros(1,255)], filts);
» freqResp = 20*log10(abs(fft(resp(1:5:88, :)))));
» freqScale = (0:255)/256*16000;
» semilogx(freqScale(1:128), freqResp(1:128, :))
» axis([100 10000 -60 20])
```

The resulting response for every fifth channel is shown below.



See Also

Malcolm Slaney, *Lyon's Cochlear Model*, Apple Computer Technical Report #13, 1988. Also available at

<http://web.interval.com/~malcolm/pubs.html#LyonsCochlear>

EpsilonFromTauFS

Purpose

Calculate first order decay coefficient (τ)

Synopsis

`epsilon = EpsilonFromTauFS(tau, fs)`

Description

Find first order filter coefficient as a function of time constant and sample rate

Examples

The following example shows the design of a first order filter with a sampling interval of 1 and a time constant of 5 (samples). A simple digital filter is formed by adding at each time the current input value and (1-epsilon) times the last output value. The resulting impulse response decays exponentially, reaching 37% of it's original value in one time constant, τ .

You can verify the relationship between the time constant and the impulse response using the following example code.

```
»eps=EpsilonFromTauFS(5,1)

eps =

    0.1813

»filter(1, [1 eps-1],[1 zeros(1,9)])

ans =

Columns 1 through 7

    1.0000    0.8187    0.6703    0.5488    0.4493    0.3679    0.3012

Columns 8 through 10

    0.2466    0.2019    0.1653

»sosfilters([1 zeros(1,9)],[1 0 0 eps-1 0])

ans =

Columns 1 through 7

    1.0000    0.8187    0.6703    0.5488    0.4493    0.3679    0.3012

Columns 8 through 10

    0.2466    0.2019    0.1653
```

ERBFilterBank

Purpose

Filter an audio signal with a bank of Gammatone filters

Synopsis

```
output = ERBFilterBank(x, fcoefs)
```

Description

Process an audio waveform with a gammatone filter bank. Use the *MakeERBFilters* function to design the *fcoefs* parameter, which completely specifies the Gammatone filterbank.

This function takes a single sound vector, and returns an array of filter outputs, one output per column. The filter coefficients are computed for you if you do not specify them. The default Gammatone filter bank has a 22050Hz sampling rate, and provides 64 filters down to 100Hz.

Examples

See the examples shown in the *MakeERBFilters* on page 24.

FMPoints

Purpose

Compute glottal pulses for voice with vibrato

Synopsis

```
points=FMPoints(len, freq, fmFreq, fmAmp, fs)
```

Description

This routine generates (fractional) sample locations for frequency-modulated impulses.

len	number of samples
freq	pitch frequency (Hz)
fmFreq	vibrato frequency (Hz) (defaults to 6 Hz)
fmAmp	max change in pitch (defaults to 5% of freq)
fs	sample frequency (defaults to 22254.545454 samples/s)

The basic formula for the phase angle is

$$\theta = 2\pi \cdot \text{freq} \cdot t + \text{fmAmp}/\text{fmFreq} \cdot \sin(2\pi \text{fmFreq} \cdot t)$$

The output of this routine is a list of glottal pulse locations that can be used by the *MakeVowel* routine.

Examples

The *MakeVowel* routine is used to synthesize simple vowels. More realistic sounding vowels are possible with a bit of vibrato added to them using the *FMPoints* routine.

```
»u=MakeVowel(20000,FMPoints(20000,120), 22050,'u');
»soundsc(u/max(u), 22050)
```

Acknowledgments

This routine was written by Richard O. Duda of San Jose State University.

FreqResp

Purpose

Evaluate frequency response of a second order filter

Synopsis

```
mag = FreqResp(filter, f, fs)
```

Description

Find the frequency response (in dB) of a filter (1x5 vector) at frequency *f* assuming a sampling rate *fs*. A vector of frequencies can be used as input.

The filter is a biquadratic section with a transfer function equal to

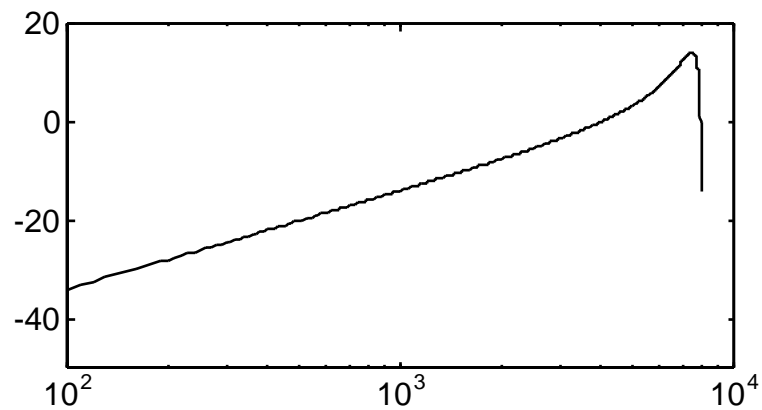
$$\frac{B_0 + B_1 z^{-1} + B_2 z^{-2}}{1 + A_1 z^{-1} + A_2 z^{-2}}.$$

The filter is described by a five element row vector with the filter's coefficients equal to [B0 B1 B2 A1 A2].

Examples

The *FreqResp* function can be used to evaluate the second filter in the default filter bank shown in the *DesignLyonFilters* example.

```
»f=10:10:7990;
»resp=FreqResp([0.8373 0 -0.8373 1.6433 .6772], ...
               f, 16000);
»semilogx(f, resp);
```



LyonPassiveEar

Purpose

Calculate auditory nerve responses using Lyon's passive cochlear model

Synopsis

`y=LyonPassiveEar(x,sr,df,earQ,stepfactor,diff,agcf,taufactor)`

Description

This m-function calculates the probability of firing along the auditory nerve due to a input sound, *x*, with a sample rate, *sr*. The remaining arguments are optional parameters of the cochlear model implementation and are described below. The default value for each parameter is shown in parenthesis.

- | | |
|---------------|--|
| df (1) | Decimation Factor - How much to decimate the model's output. Normally the cochlear model produces one output per channel at each sample time. This parameters allows the output to be decimated in time (using a filter to reduce aliasing. See the <i>taufactor</i> parameter.) |
| earQ (8) | Quality Factor - The quality factor of a filter is a measure of its bandwidth. In this case it measures the ratio of the width of each band-pass filter at a point 3dB down from the maximum. Normally, critical band filters have a Q of about 8. Smaller values of <i>earQ</i> mean broader cochlear filters. |
| stepfactor | Filter stepping factor - Each filter in a filter bank is overlapped by a fixed fraction given by this parameter. The default value is given by <i>earQ</i> /32. Thus normal filters (q=8) are overlapped by 25%. |
| differ (1) | Channel Difference Flag - Adjacent filter channels can be subtracted to further improve the model's frequency response. This parameter is a flag; non-zero values indicate the channel differences should be computed. |
| agcf (1) | Automatic Gain Control Flag - An automatic gain control is used to model neural adaptation. This flag turns the adaptation mechanism on and off. |
| taufactor (3) | Filter Decimation Tau Factor - When the output of the cochlear model is decimated, a low pass filter is applied to each channel to reduce the high frequency content and minimize aliasing. The filter's time constant (tau) is set to the decimation factor multiplied by this argument. Larger values for the <i>taufactor</i> mean less high frequency information is passed. |

Note this function resets the filter state each time it is run. The default state of the AGC filters is zero, so the cochlear model is very sensitive to initial sounds.

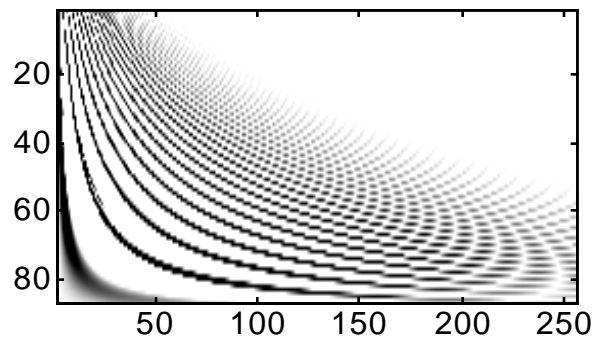
Examples

Calculate the impulse response with

```
»is=LyonPassiveEar([1 zeros(1,255)],16000,1);
»imagesc(min(is, 0.0004))
```

The image is clipped so it shows an output range between 0 and 0.0004, which is the maximum target range of the last AGC stage. This is necessary because the impulse has such a fast attack that the AGC can't limit the output fast enough. The response

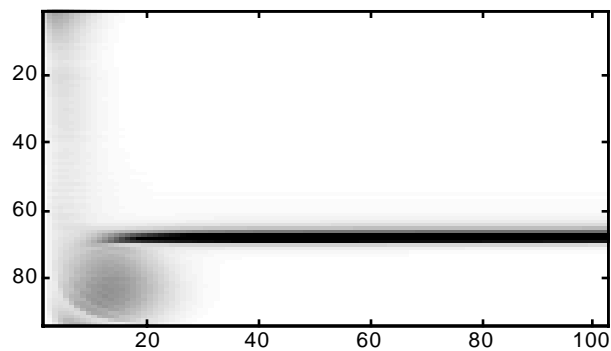
looks like



A sine wave (1kHz) is generated and run through the standard cochlear model using the following code.

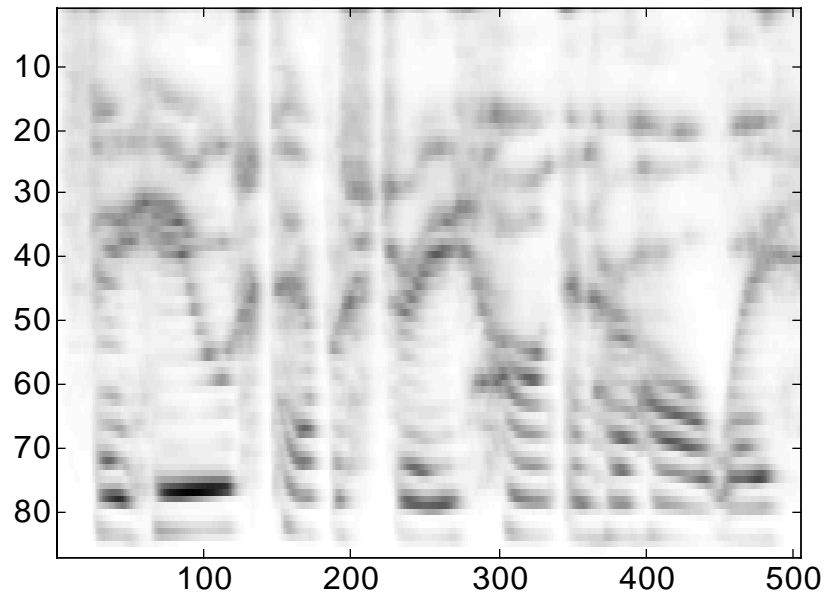
```
»s=sin((0:2041)/20000*2*pi*1000);
»ys=LyonPassiveEar(s,20000,20);
»imagesc(ys);
```

The resulting image looks like this:



Finally, a cochleagram of the 'A huge tapestry hung in her hallway' utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC) is shown below. It was computed using the following command line.

```
»coch=LyonPassiveEar(tap,16000,100);
»imagesc(coch);
```



See Also

“Lyon’s Cochlear Model”, by Malcolm Slaney and published as Apple Technical Report #13 (1988) describes the implementation of this particular cochlear model. This report is also available at
<http://web.interval.com/~malcolm/pubs.html#LyonCochlear>

DesignLyonFilters, soscascade, agc

MakeERBFilters

Purpose

Design the filters needed to implement an ERB cochlear model.

Synopsis

```
fcoefs = MakeERBFilters(fs,numChannels,lowFreq)
```

Description

This function computes the filter coefficients for a bank of Gammatone filters. These filters were defined by Patterson and Holdworth for simulating the cochlea.

The result is returned as an array of filter coefficients. Each row of the filter arrays contains the coefficients for four second order filters. The transfer function for these four filters share the same denominator (poles) but have different numerators (zeros). All of these coefficients are assembled into one vector that the *ERBFilterBank* function can take apart to implement the filter.

The filter bank contains *numChannels* channels that extend from half the sampling rate (*fs*) to *lowFreq*.

Note this implementation fixes a problem in the original code. The original version calculated a single eighth-order polynomial representing the entire filter function. This new version computes four separate second order filters. This avoids a problem with round off errors in cases with very small characteristic frequencies (<100Hz) and large sample rates (>44kHz). The problem is caused by roundoff error when a number of poles are combined, all very close to the unit circle. Small errors in the eighth-order coefficient, are magnified when the eighth root is taken to give the pole location. These small errors lead to poles outside the unit circle and instability. Thanks to Julius Smith for pointer me to the proper explanation.

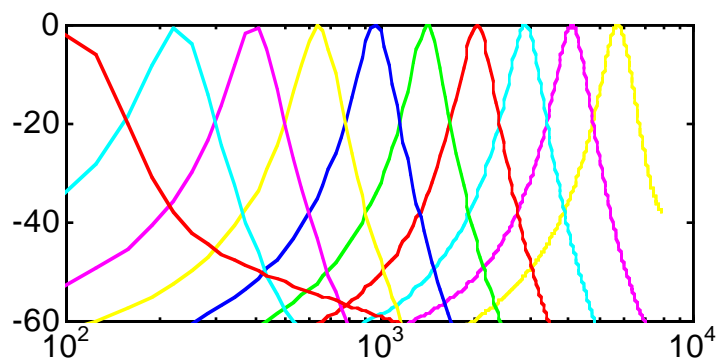
Examples

The ten ERB filters between 100 and 8000Hz are computed using

```
»fcoefs = MakeERBFilters(16000,10,100);
```

The resulting frequency response is given by

```
»y = ERBFilterBank([1 zeros(1,511)], fcoefs);
»resp = 20*log10(abs(fft(y')));
»freqScale = (0:511)/512*16000;
»semilogx(freqScale(1:255),resp(1:255,:));
»axis([100 16000 -60 0])
»xlabel('Frequency (Hz)');
»ylabel('Filter Response (dB)');
```

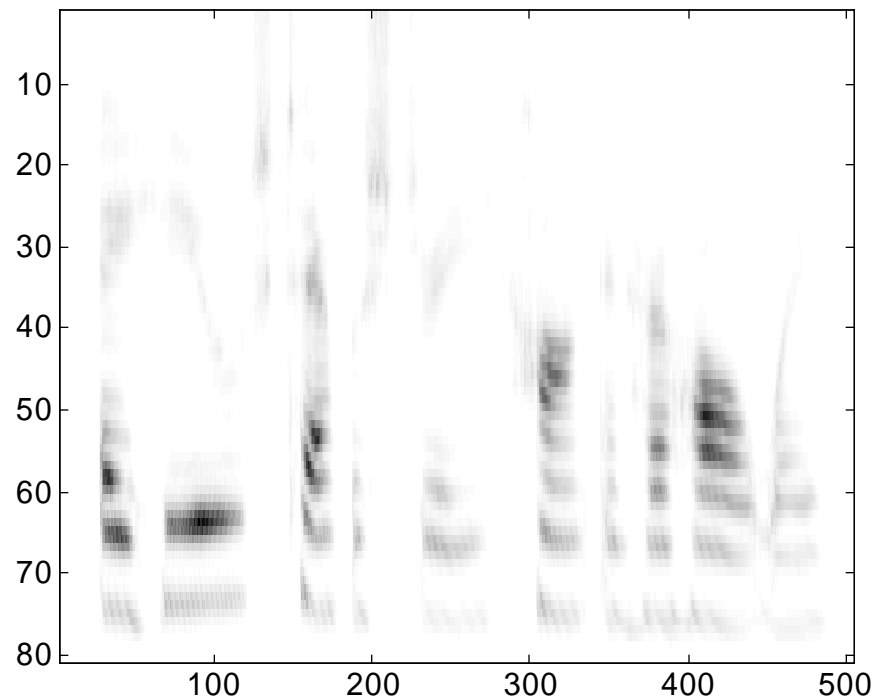


A simple cochlear model can be formed by filtering an utterance with these filters. To convert this data into an image we pass each row of the cochleagram through a half-wave-rectifier, a low-pass filter, and then decimate by a factor of 100. A cochleagram of the 'A huge tapestry hung in her hallway' utterance from the TIMIT database

(TRAIN/DR5/FCDR1/SX106/SX106.ADC) is shown below. It was computed using the following commands.

```
»fcoefs=MakeERBFilters(16000,40,100);
»coch=ERBFilterBank(tap, fcoefs);
»for j=1:size(coch,1)
    c=max(coch(j,:),0);
    c=filter([1],[1 -.99],c);
    coch(j,:)=c;
end
»imagesc(coch);
```

Unlike the other cochlear models in this report, there is no adaptation or automatic gain control to equalize the formant frequencies and enhance the onsets. The *MeddisHairCell* (27) function can be used to do this.



See Also

Malcolm Slaney, *An Efficient Implementation of the Patterson-Holdsworth Auditory Filter Bank*, Apple Computer Technical Report #35, 1993. This report is also available at

<http://web.interval.com/~malcolm/pubs.html#Gammatone>

MakeVowel

Purpose

Simple vowel synthesis

Synopsis

```
y = MakeVowel(len, pitch, sampleRate, f1, f2, f3)
```

Description

Make a vowel with *length* samples and the given *pitch*. The vowel's sample rate is given by *sampleRate*. The formant frequencies are *f1*, *f2* & *f3*. The formant frequencies for these English vowels are given by:

Vowel	<i>f1</i>	<i>f2</i>	<i>f3</i>
/a/	730	1090	2440
/i/	270	2290	3010
/u/	300	870	2240

The *pitch* variable can either be a scalar indicating the actual pitch frequency, or an array of impulse locations. Using an array of impulses allows this routine to compute vowels with varying pitch.

Alternatively, *f1* can be replaced with one of the following strings 'a', 'i', 'u' and the appropriate formant frequencies are automatically selected.

Examples

A sequence of three vowels can be computed using

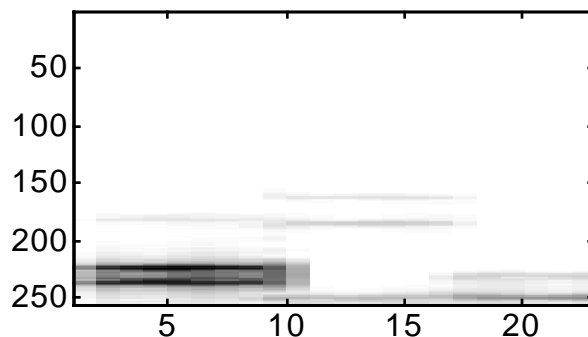
```
»vowels = [ MakeVowel(10000, 100, 16000, 'a') ...
            MakeVowel(10000, 100, 16000, 'i') ...
            MakeVowel(10000, 100, 16000, 'u') ];
```

and then played with

```
»soundsc(vowels, 16000);
```

Similarly, a shorter sequence of vowels can be displayed as a spectrogram.

```
»vowels = [ MakeVowel(1000,100,16000, 'a') ...
            MakeVowel(1000,100,16000, 'i') ...
            MakeVowel(1000,100,16000, 'u') ];
»s=spectrogram(vowels,256,2,2);
»imagesc(s)
```



Acknowledgments

The first version of this routine was written by Richard O. Duda (San Jose State University). Additional debugging was provided by Professor. Duda.

MeddisHairCell

Purpose

Implement Meddis' Inner Hair Cell Model

Synopsis

`y = MeddisHairCell(data,sampleRate[,subtractSpont])`

Description

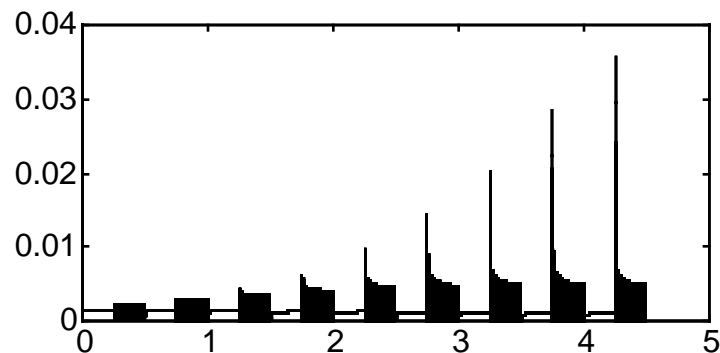
This function calculates the output of Ray Meddis' hair cell model for a number of channels. Data is arrayed as one auditory channel per row. All channels are done in parallel (but each time step is sequential) so it is much more efficient to process lots of channels at once.

The *subtractSpont* argument is optional. If this argument is positive then the hair cell's spontaneous rate is subtracted before the result is returned.

Examples

This MEX function can be checked by comparing the results to those published in Ray Meddis' 1986 JASA paper. The first two statements generate a sequence of tone pips, each 250 ms long, ranging in amplitude from 40dB to 80 dB in 5dB steps. Note the amplitude scale is arbitrary. In this case it was chosen to agree with the examples shown in his 1990 paper.

```
»tone=sin((0:4999)/20000*2*pi*1000);
»s=[zeros(1,5000) ...
    tone*10^(40/20-1.35) zeros(1,5000) ...
    tone*10^(45/20-1.35) zeros(1,5000) ...
    tone*10^(50/20-1.35) zeros(1,5000) ...
    tone*10^(55/20-1.35) zeros(1,5000) ...
    tone*10^(60/20-1.35) zeros(1,5000) ...
    tone*10^(65/20-1.35) zeros(1,5000) ...
    tone*10^(70/20-1.35) zeros(1,5000) ...
    tone*10^(75/20-1.35) zeros(1,5000) ...
    tone*10^(80/20-1.35)];
»y=MeddisHairCell(s,20000);
»plot((1:90000)/20000,y(1:90000))
```

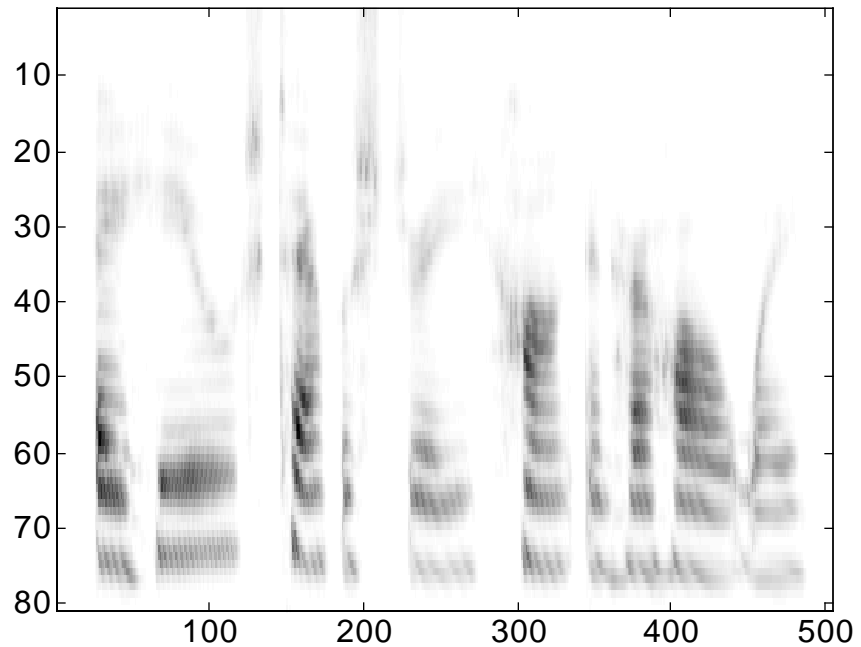


This hair cell model can be added to the back-end of a Gammatone filter bank to form a “complete” auditory model. A cochleagram of the ‘A huge tapestry hung in her hallway’ utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC) is shown below. The output of the filter-bank is scaled by a factor of 80 to put this particular result in the correct range for the hair cell model. The filtering operation in the loop and the decimation are performed to reduce the amount of data to display. The cochleagram was computed using the following commands.

```

»[frwd,fdbk]=MakeERBFilters(16000,80,100);
»coch=ERBFilterBank(frwd,fdbk,tap);
»hc=MeddisHairCell(coch/max(max(coch))*80,16000,1);
»for j=1:80
    c=hc(j,:);
    c=filter([1],[1, -.99],c);
    h(j,:)=c(1:100:50381);
end
»imagesc(h);

```



See Also

R. Meddis, "Simulation of mechanical to neural transduction in the auditory receptor," *Journal of the Acoustical Society of America*, vol.79, no.3, p. 702-711, March 1986.

M. J. Hewitt, R. Meddis, "Implementation details of a computation model of the inner hair-cell/auditory-nerve synapse," *Journal of the Acoustical Society of America*, vol.87, no.4, p. 1813-1816, April 1990.

mfcc

Purpose

Mel-frequency cepstral coefficient transform of an audio signal

Synopsis

```
[ceps, freqresp, fb, fbrecon, freqrecon] = ...  
    mfcc2(input, samplingRate, [frameRate])
```

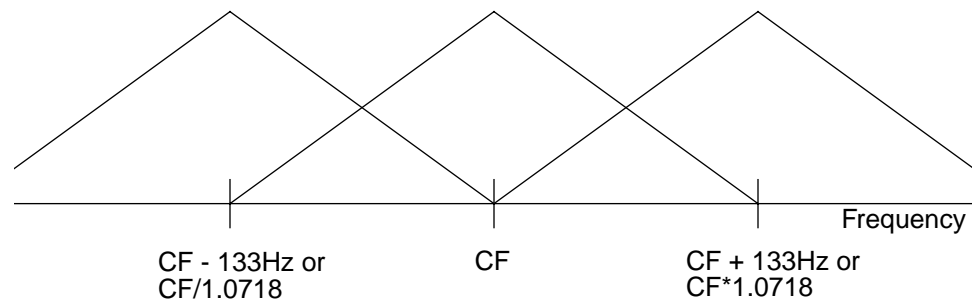
Description

Find the mel-frequency cepstral coefficients (*ceps*) corresponding to the input. Three other quantities are optionally returned that represent the detailed FFT magnitude (*freqresp*), the \log_{10} mel-scale filter bank output (*fb*), and the reconstruction of the filter bank output by inverting the cosine transform.

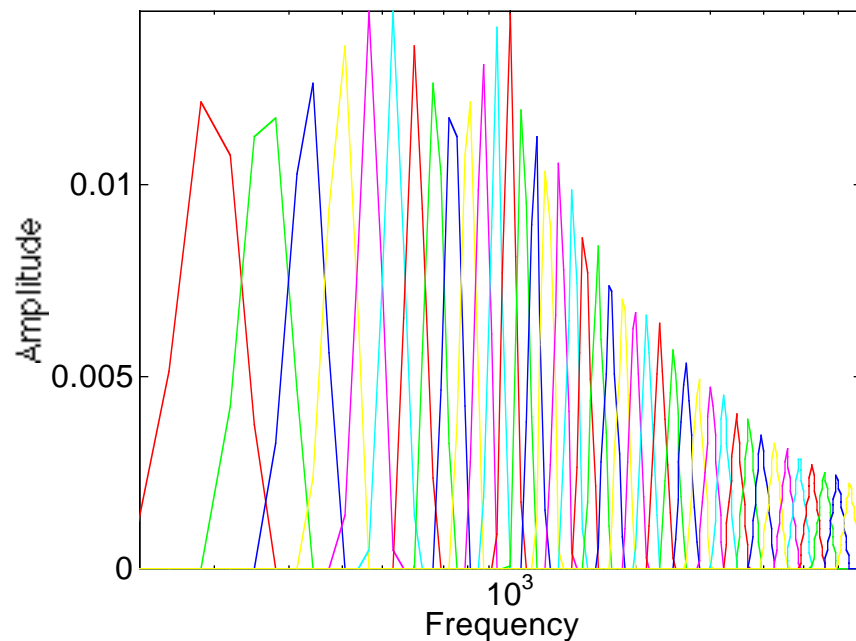
The sequence of processing includes for each chunk of data:

- Window the data with a hamming window,
- Shift it into FFT order,
- Find the magnitude of the FFT,
- Convert the FFT data into filter bank outputs,
- Find the log base 10,
- Find the cosine transform to reduce dimensionality.

The filter bank is constructed using 13 linearly-spaced filters (133.33Hz between center frequencies,) followed by 27 log-spaced filters (separated by a factor of 1.0711703 in frequency.) Each filter is constructed by combining the amplitude of FFT bin as shown in the figure below.



The forty filters have this frequency response.



The outputs from this routine are the MFCC coefficients and several optional intermediate results and inverse results.

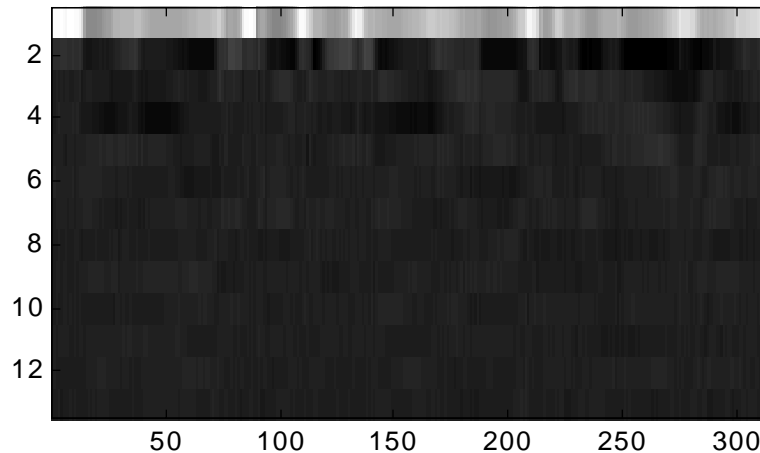
`freqresp` the detailed fft magnitude used in MFCC calculation, 256 rows.
`fb` the mel-scale filter bank output, 40 rows.
`fbrecon` the filter bank output found by inverting the cepstrals with a cosine transform, 40 rows.
`freqrecon` the smooth frequency response by interpolating the `fb` reconstruction, 256 channels to match the original `freqresp`.

This version is improved over the version in Release 1 in a number of ways. The discrete-cosine transform was fixed and the reconstructions have been added.

Examples

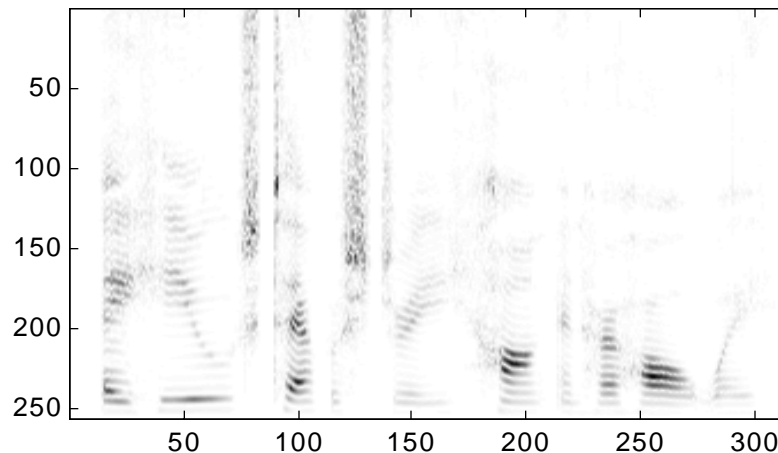
Here is the result of calculating the cepstral coefficients of the 'A huge tapestry hung in her hallway' utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC). The utterance is 50189 samples long at 16kHz, and all pictures are sampled at 100Hz and there are 312 frames. Note, the top row of the mfcc-cepstrum, `ceps(1,:)`, is known as C_0 and is a function of the power in the signal. Since the waveform in our work is normalized to be between -1 and 1, the C_0 coefficients are all negative. The other coefficients, C_1 - C_{12} , are generally zero-mean.

```
»tap = wavread('tapestry.wav');
»[ceps,freqresp,fb,fbrecon,freqrecon]= ...
    mfcc(tap,16000,100);
»imagesc(ceps); colormap(1-gray);
```



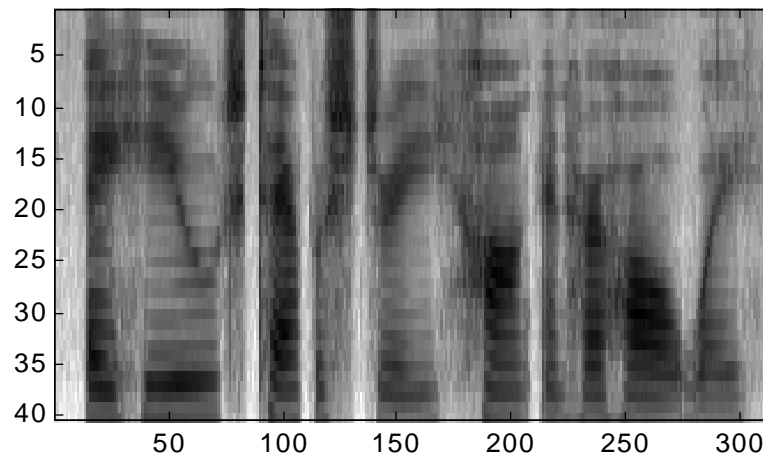
Several intermediate results are also generated that can be used to investigate the performance of the algorithm. The uncompressed FFT spectrogram (`freqresp`) is shown below (it's been flipped so that high frequencies are at the top.)

```
»imagesc(flipud(freqresp));
```



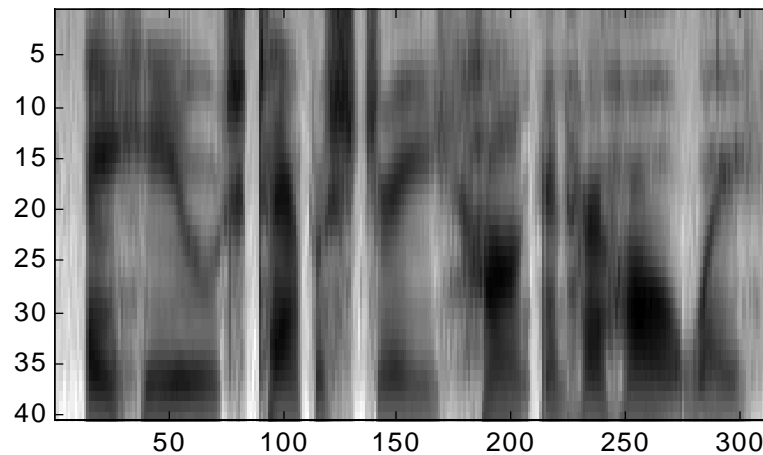
After combining several FFT channels into a single mel-scale channel, the result is the filter bank output. This is shown below (the `fb` output of the `mfcc` command includes the \log_{10} calculation.)

```
imagesc(flipud(fb));
```



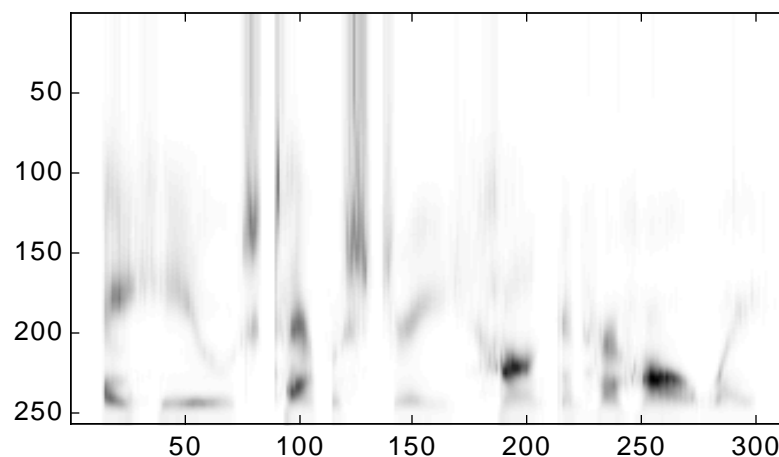
Finally, the conversion into the cepstral domain uses the discrete cosine transform to reduce the dimensionality of the output. We can invert the cosine transform to get back into the filter bank domain and see how much information we have lost. The *recon* output is shown below (flipped again so that the high frequency channel is at the top). Note the result is much smoother than the original filter bank output.

```
»imagesc(flipud(fbrecon));
```



The original spectrogram is reproduced by resampling the result above. Note the fine lines indicating the pitch have been lost by the MFCC process. This is a useful feature for speech-recognition systems since they want a representation that is blind to pitch changes.

```
»imagesc(flipud(fregrecon));
```



See Also

An MFCC-like algorithm was proposed by M. J. Hunt, M. Lennig, and P. Mermelstein, “Experiments in syllable-based recognition of continuous speech,” *Proceedings of the 1980 ICASSP*, Denver, CO, pp. 880-883, 1980.

Purpose

Perform LPC analysis on a speech signal

Synopsis

```
[aCoeff,resid,pitch,G,parcor,stream] = proclpc(data,sr,L,fr,fs,preemp)
```

Description

This function computes the LPC (linear-predictive coding) coefficients that describe a speech signal. The LPC coefficients are a short-time measure of the speech signal which describe the signal as the output of an all-pole filter. This all-pole filter provides a good description of the speech articulators; thus LPC analysis is often used in speech recognition and speech coding systems. The LPC parameters are recalculated, by default in this implementation, every 20ms.

The results of LPC analysis are a new representation of the signal

$$s(n) = G e(n) - \sum_{i=1}^L a(i)s(n-i)$$

where $s(n)$ is the original data. $a(i)$ and $e(n)$ are the outputs of the LPC analysis with $a(i)$ representing the LPC model. The $e(n)$ term represents either the speech source's excitation, or the residual: the details of the signal that are not captured by the LPC coefficients. The G factor is a gain term.

LPC analysis is performed on a monaural sound vector (*data*) which has been sampled at a sampling rate of *sr*. The following optional parameters modify the behaviour of this algorithm.

<i>L</i>	The order of the analysis. There are $L+1$ LPC coefficients in the output array <i>aCoeff</i> for each frame of data. <i>L</i> defaults to 13.
<i>fr</i>	Frame time increment, in ms. The LPC analysis is done starting every <i>fr</i> ms in time. Defaults to 20ms (50 LPC vectors a second)
<i>fs</i>	Frame size in ms. The LPC analysis is done using a rectangular window that is <i>fs</i> ms long. Defaults to 30ms
<i>preemp</i>	This variable is the epsilon in a digital one-zero filter which serves to preemphasize the speech signal and compensate for the 6dB per octave rolloff in the radiation function. Defaults to .9378.

The output variables from this function are

<i>aCoeff</i>	The LPC analysis results, $a(i)$. One column of L numbers for each frame of data
<i>resid</i>	The LPC residual, $e(n)$. One column of $sr*fs$ samples representing the excitation or residual of the LPC filter.
<i>pitch</i>	A frame-by-frame estimate of the pitch of the signal, calculated by finding the peak in the residual's autocorrelation for each frame.
<i>G</i>	The LPC gain for each frame.
<i>parcor</i>	The parcor coefficients. The parcor coefficients give the ratio between adjacent sections in a tubular model of the speech articulators. There are L parcor coefficients for each frame of speech.
<i>stream</i>	The LPC analysis' residual or excitation signal as one long vector. Overlapping frames of the <i>resid</i> output combined into a new one-dimensional signal and post-filtered.

The *synlpc* routine inverts this transform and returns the original speech signal.

Examples

We illustrate LPC analysis with the 'A huge tapestry hung in her hallway' utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC). The utterance is 50189 samples long at 16kHz.

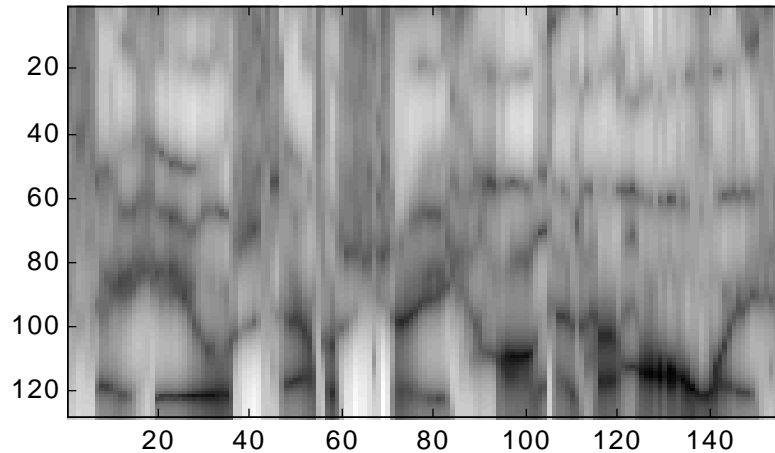
We can evaluate the LPC transfer function around the unit circle to find the transfer function's frequency response. The code to do this looks like this.

```

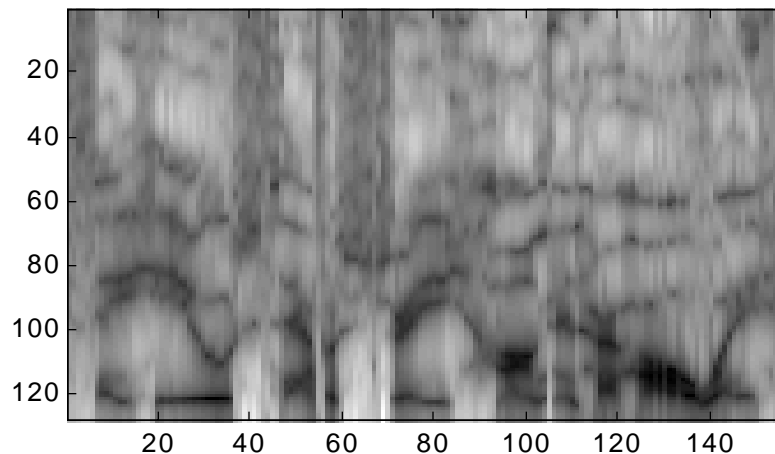
»[aCoeff,resid,pitch,G] = proclpc(tap,sr,L);
»cft=0:(1/255):1;
»for nframe=1:size(aCoeff,2)
»    gain=20*log10(G(nframe)) * 0;
»    for index=1:size(aCoeff,1)
»        gain = gain + aCoeff(index,nframe)* ...
»            exp(-i*2*pi*cft).^index;
»    end
»    gain = abs(1./gain);
»    spec(:,nframe) = 20*log10(gain(1:128))';
»end
»imagesc(flipud(spec));

```

The spectrogram for LPC with an 13th order analysis polynomial is shown below.



The spectrogram for LPC with a 26th order polynomial is shown below. Note how there is more detail in the spectrogram, because a 26th order polynomial can capture more details in the spectrum within each frame.



See Also

This code was graciously provided by Delores Etter (University of Colorado, Boulder) and Professor Geoffrey Orsak (Southern Methodist University). It was first published in

Orsak, G.C. et al. "Collaborative SP education using the Internet and MATLAB," *IEEE SIGNAL PROCESSING MAGAZINE*, Nov. 1995. vol.12, no.6, pp. 23-32.

Modified and debugging plots added by Kate Nguyen and Malcolm Slaney

A more complete set of routines for LPC analysis can be found at
<http://www.ee.ic.ac.uk/hp/staff/dmb/voicebox/voicebox.html>

Purpose

Implement the RASTA algorithm for environmental adaptation and simulating auditory masking

Synopsis

`y=rasta(x,fs)`

Description

This function implements the RASTA (RelAtive SpecTrAl) algorithm. The RASTA algorithm is a common piece of a speech-recognition system's front-end processing. It originally was designed to model adaptation processes in the auditory system, and to correct for environmental effects. Broadly speaking, it filters out the very low-frequency temporal components (below 1Hz) which are often due to a changing auditory environment or microphone. High frequency temporal components, above 13 Hz, are also removed since they represent changes that are faster than the speech articulators can move.

The first input to this routine is an array of spectral data, as produced by the LPC or MFCC routines. Each row contains one "channel" of data, each column is one time slice. The *fs* parameter specifies the sampling rate, 100Hz in many speech recognition systems.

The original RASTA filter is defined only for a frame rate of 100Hz. This code is equal to the original at 100Hz, but scales to other frame rates. Here the RASTA filter is approximated by a simple fourth order Butterworth bandpass filter.

Examples

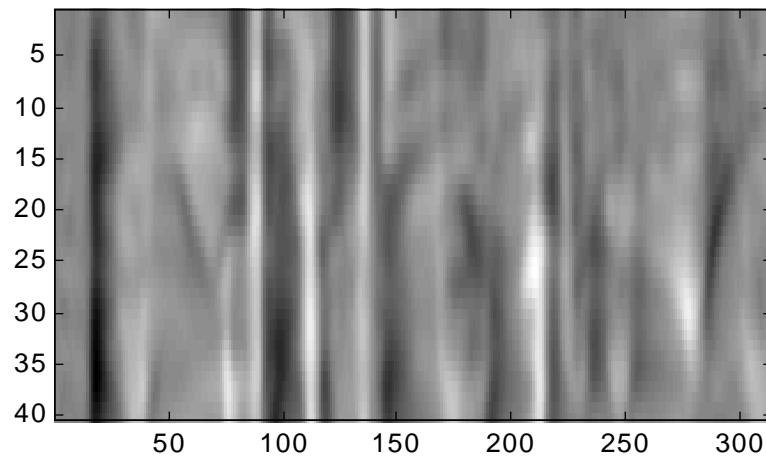
Both MFCC and LPC analysis have the property that they turn a row of a spectrogram into a small number of independent, random coefficients. This makes it difficult to view the results directly. RASTA then processes these coefficients in time. We show an example of RASTA analysis here by applying RASTA to the output of the MFCC routine and then reconstructing the original filterbank representation by inverting the discrete-cosine transform.

```
»tap = wavread('tapestry.wav');
»[ceps,freqresp,fb,fbrecon,freqrecon] = ...
    mfcc(tap,16000,100);
»rastaout = rasta(ceps,100);

»mfccDCTMatrix = 1/sqrt(40/2)*cos((0:(13-1))' * ...
    (2*(0:(40-1))+1) * pi/2/40);
»mfccDCTMatrix(1,:) = mfccDCTMatrix(1,:)*sqrt(2)/2;

»rastarecon = 0*fbrecon;
»for i=1:size(rastaout,2)
»    rastarecon(:,i) = mfccDCTMatrix' * ...
        rastaout(:,i);
»end
»imagesc(flipud(rastarecon));
```

The result below can be compared directly to the *fbrecon* result in the MFCC documentation on page 29. You should note that the transistions are sharper, and steady-state features have been removed.



See Also

Hynek Hermansky and N. Morgan, "RASTA Processing of Speech." *IEEE Transactions on Speech and Audio Processing*. vol. 2, no. 4, October 1994, pp. 578–589

Hynek Hermansky and Misha Pavel, "Rasta Model and Forward Masking." *Proceedings of the NATO Advanced Studies Institute on Computational Hearing*, Steven Greenberg and Malcolm Slaney, eds. Il Ciocco (Tuscany) Italy, 1-12 July 1998, pp. 107–110.

SecondOrderFilter

Purpose

Design a second order filter section

Synopsis

`filter = SecondOrderFilter(f, q, fs)`

Description

Design a second order digital filter with a center frequency of `f`, filter quality of `q`, and digital sampling rate of `fs` (Hz).

The filter is a biquadratic section with a transfer function equal to

$$\frac{B_0 + B_1 z^{-1} + B_2 z^{-2}}{1 + A_1 z^{-1} + A_2 z^{-2}}.$$

The filter is described by a five element row vector with the filter's coefficients equal to `[B0 B1 B2 A1 A2]`.

Examples

A simple bandpass filter is formed by putting the filter's poles near the desired center frequency. This is shown below.

```
»f=10:10:7990;
»sos=SecondOrderFilter(3000,5,16000)

sos =

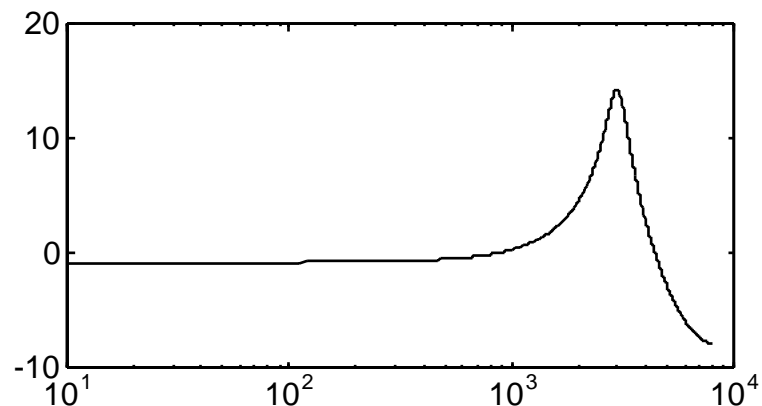
    1.0000    -0.6900     0.7901

»filt=[1 0 0 sos(2:3)]

filt =

    1.0000         0         0    -0.6900     0.7901

»semilogx(f,FreqResp(filt,f,16000))
```



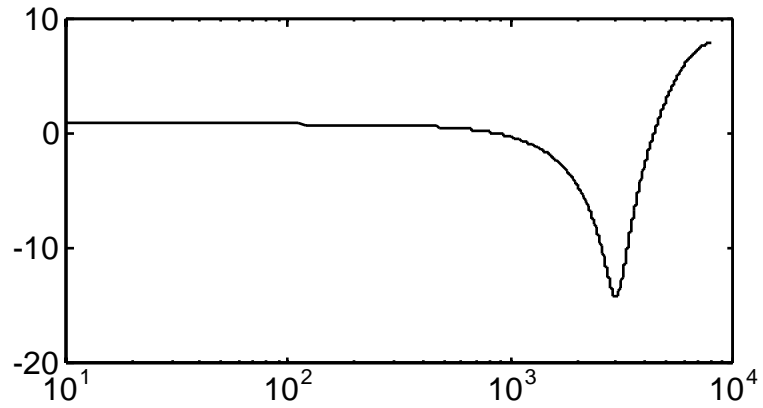
Likewise, a simple band-reject filter is formed by using a pair of zeros. The resulting filter looks like this.

```
»filt=[sos 0 0]

filt =

    1.0000    -0.6900     0.7901         0         0
```

```
»semilogx(f,FreqResp(filt,f,16000))
```



A broader filter is formed by using a lower q , in this case 2.

```
»sos=SecondOrderFilter(3000,2,16000)
```

```
sos =
```

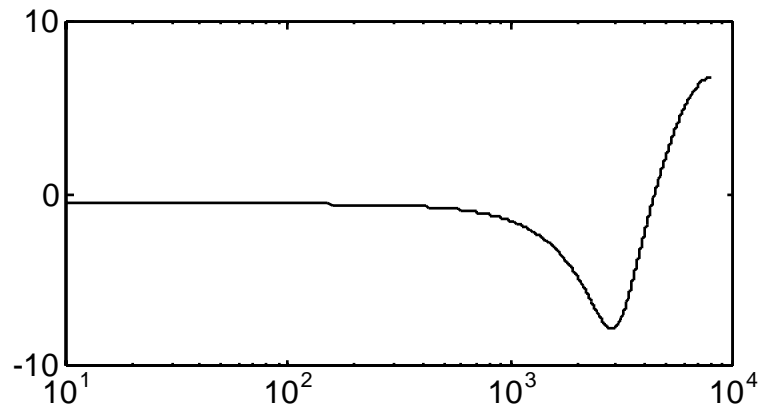
```
1.0000 -0.6212 0.5549
```

```
»filt=[sos 0 0]
```

```
filt =
```

```
1.0000 -0.6212 0.5549 0 0
```

```
»semilogx(f,FreqResp(filt,f,16000))
```



SeneffEar

Purpose

Implement Stages I and II of Seneff's Auditory Model

Synopsis

`y = SeneffEar(x, fs [, plotChannel])`

Description

This function implements Stage I (Critical Band Filter Bank) and Stage II (Hair Cell Synapse Model) of Seneff's Auditory model. This routine converts an input signal, x , into an array of

“detailed waveshapes of the probabilistic response to individual cycles of the input stimulus.”

This model is

“based on properties of the human auditory system. A bank of critical-band filters defines the initial spectral analysis. Filter outputs are processed by a model of the nonlinear transduction stages in the cochlea, which accounts for such features as saturation, adaptation and forward masking. The parameters of the model were adjusted to match existing experimental results of the physiology of the auditory periphery.”

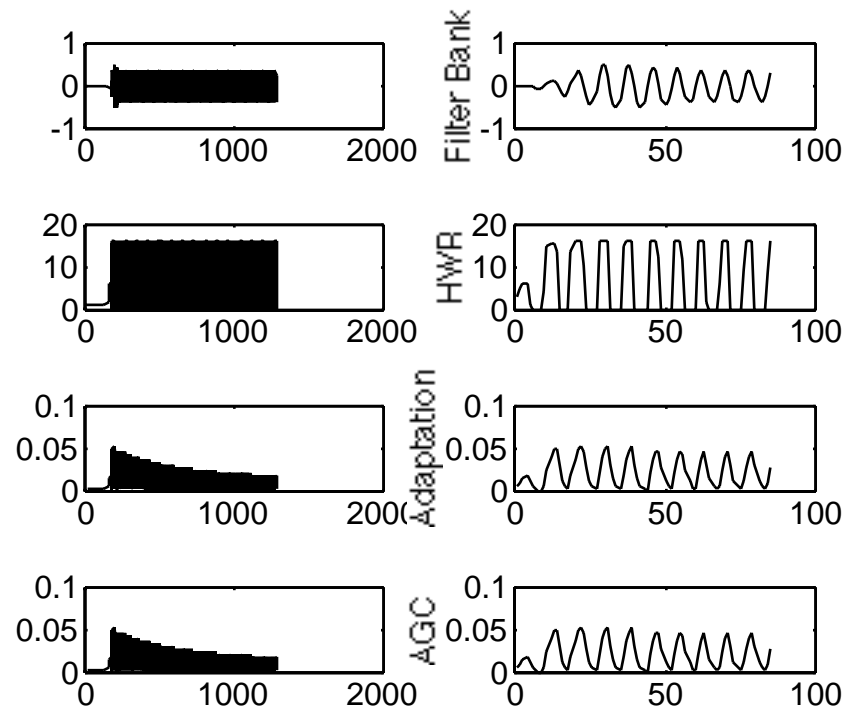
The input data (x) is a one-dimensional array with a sampling rate of fs . The optional parameter *plotChannel* is used to indicate a channel to plot for debugging (see example below.)

Examples

Figure 3 of Seneff's paper (1988) can be approximated with the following statements

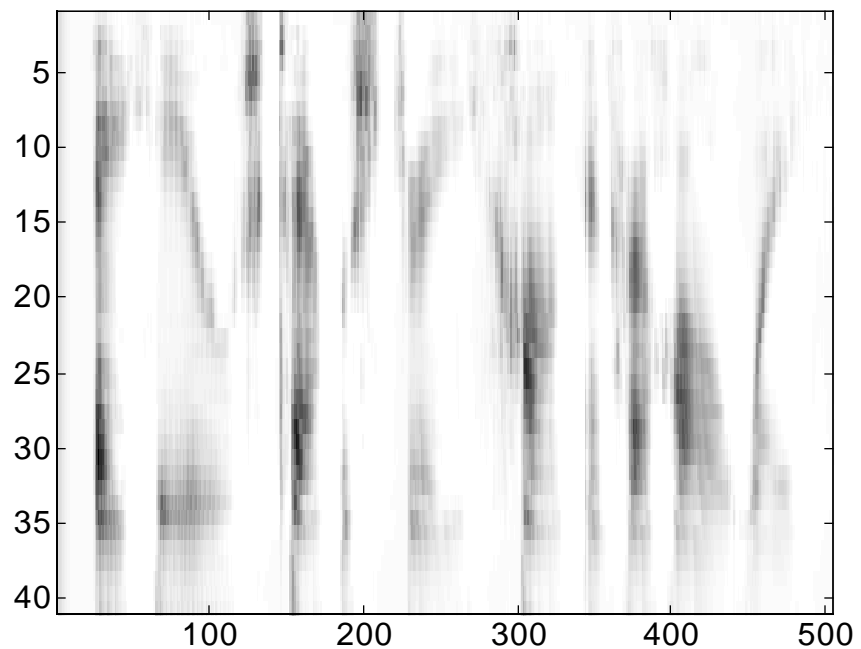
```
»s=[zeros(1,160) sin(2000*2*pi/16000*(1:1120))];
»y=SeneffEar(s,16000,15);
```

which produces the following plot. The results are not exactly equivalent for reasons I do not understand.



A cochleagram using Seneff's ear model of the 'A huge tapestry hung in her hall-way' utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC) is shown below. The filtering operation inside the loop and the decimation are performed to reduce the amount of data to display. The cochleagram was computed using the following commands.

```
»hc=SeneffEar(tap,16000);
»for j=1:40
    c=hc(j,:);
    c=filter([1],[1, -.99],c);
    h(j,:)=c(1:100:50381);
end
»imagesc(h);
```



Acknowledgments

This routine is based on work described by Benjamin D. Bryant and John D. Gowdy, “Simulation of Stages I and II of Seneff’s Auditory Model (SAM) Using Matlab,” and published in the *Proceedings of the 1993 Matlab User’s Group Conference*.

The detailed description of this model can be found in Stephanie Seneff, “A joint synchrony/mean-rate model of auditory speech processing,” *Journal of Phonetics*, Vol. 16, pp. 55-76, 1988.

SeneffEarSetup

Purpose

Design the filters for Seneff's Auditory Model

Synopsis

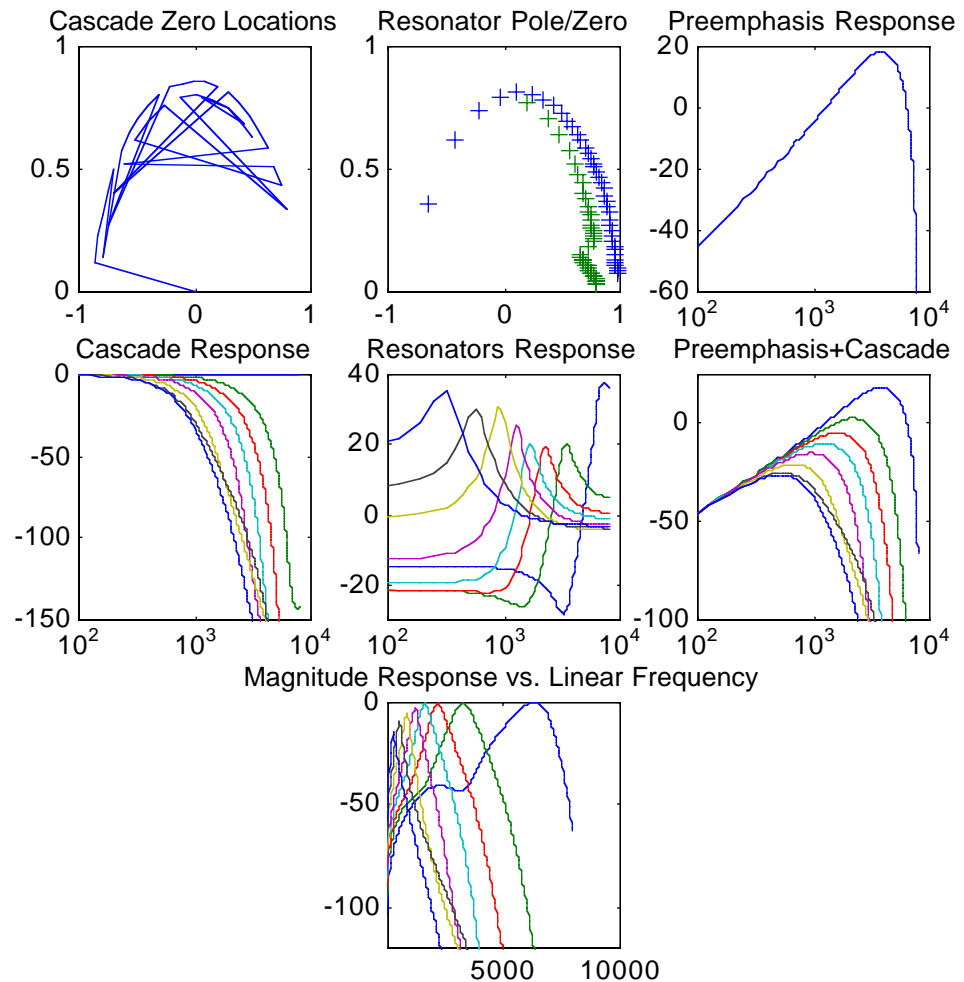
```
[SeneffPreemphasis, SeneffFilterBank, SeneffForward, SeneffBackward] ...
= SeneffEarSetup(fs)
```

Description

This function designs the preemphasis and filterbank filters for Seneff's Auditory Model. The only parameter to this function, fs , is the desired sampling rate of the digital system. See the *SeneffEar* command for more details.

Testing

This routine includes test code which can be turned on by setting the *plotTests* variable to a positive value. This produces the following plot showing the filter-bank's response.



Acknowledgments

This routine is based on work described by Benjamin D. Bryant and John D. Gowdy, "Simulation of Stages I and II of Seneff's Auditory Model (SAM) Using Matlab," and published in the *Proceedings of the 1993 Matlab User's Group Conference*.

The detailed description of this model can be found in Stephanie Seneff, “A joint synchrony/mean-rate model of auditory speech processing,” *Journal of Phonetics*, Vol. 16, pp. 55-76, 1988.

SetGain

Purpose

Set the gain of a second order section

Synopsis

```
filter = SetGain(filter, desired, f, fs)
```

Description

Set the gain of a second order biquadratic filter section to any desired gain at any desired frequency, f , assuming a sampling rate of fs . The filter section is a 1x5 element vector as produced by the *SecondOrderFilter* function.

Examples

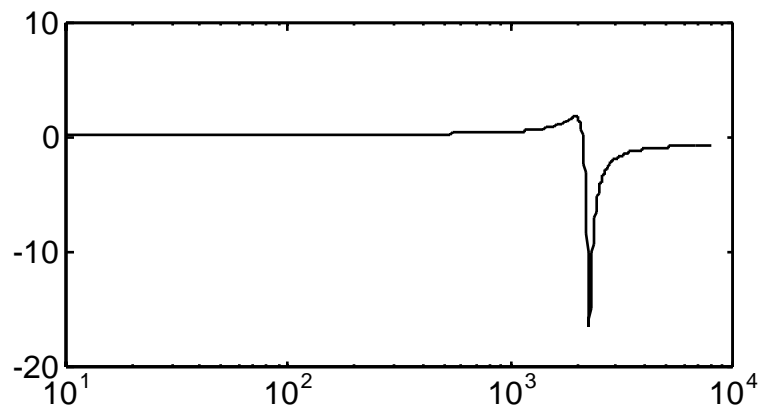
This example shows a second order section designed for Lyon's passive long-wave cochlear model. The frequency response is first plotted for the normal filter.

```
» filts = DesignSosFilters(16000);
» filt = filts(42, :)
```

```
filt =
```

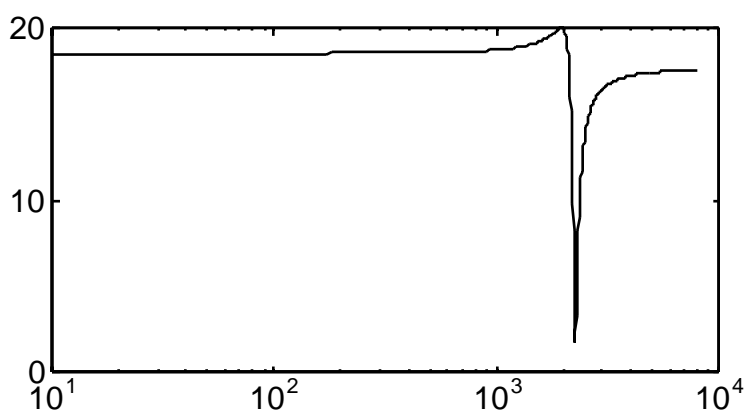
```
    0.8993   -1.1193    0.8786   -1.2535    0.8899
```

```
» f = 10:10:7990;
» semilogx(f, FreqResp(filt, f, 16000));
```



Then the gain of the filter section is set to 10 (20dB) near the filter's best frequency (1960 Hz). The new frequency response is plotted below.

```
» newFilt = SetGain(filt, 10, 1960, 16000);
» semilogx(f, FreqResp(newFilt, f, 16000));
```



soscascade

Purpose

Implement a cascade of second order filters.

Synopsis

[output state]= soscascade(input, coeffs, states)

Description

This routine implements a cascade of second order filters. A cascade of filters means that each filter's output is used as input to the next filter. The number of filters defines the number of channels in the filter bank and each channel of the filter bank has its own output waveform. This block is a basic building block for Lyon's passive long-wave cochlear model.

The filter implemented at each stage is a biquadratic section with a transfer function equal to

$$\frac{B_0 + B_1 z^{-1} + B_2 z^{-2}}{1 + A_1 z^{-1} + A_2 z^{-2}}$$

Each filter is described by a five element row vector. The number of filter channels is equal to the number of rows in the coeffs argument to soscascade. Within each row the filter's coefficients are equal to [B0 B1 B2 A1 A2].

The states argument is optional. If the input has N samples then:

coeffs is C x 5 where C is the number of channels

output is C x N

state is C x 2

Examples

Test this command by trying the following command. The correct results are shown below. The first filter is a simple exponential decay. The second filter sums the immediately preceeding outputs (in time) from the first filter.

```
>>soscascade([1 0 0 0 0],[1 0 0 -.9 0;1 1 0 0 0])
```

```
ans =
```

```
1.0000    0.9000    0.8100    0.7290    0.6561
1.0000    1.9000    1.7100    1.5390    1.3851
```

See Also

LyonPassiveEar

sosfilters

Purpose

Implement a bank of second order filters.

Synopsis

[output state] = sosfilters(input, coeffs, states)

Description

This routine implements a bank of second order filters. Each channel of the filter bank is independent of the other filters. The number of filters defines the number of channels in the filter bank and each channel of the filter bank has its own output waveform. This block is a basic building block for the Patterson-Holdsworth ERB cochlear model.

The filter implemented at each stage is a biquadratic section with a transfer function equal to

$$\frac{B_0 + B_1 z^{-1} + B_2 z^{-2}}{1 + A_1 z^{-1} + A_2 z^{-2}}$$

Each filter is described by a five element row vector. The number of filter channels is equal to the number of rows in the coeffs argument to soscascade. Within each row the filter's coefficients are equal to [B0 B1 B2 A1 A2].

The states argument is optional. If the input has N samples and there are C channels, then:

input is 1 x N or C x N
 coeffs is 1 x 5 or C x 5
 state is max(1,C) x 2
 output is max(1,C) x N

Examples

Test this command by trying the following commands. The correct results are shown below. The first example filters an impulse with two low pass filters.

```
»sosfilters([1 0 0 0 0 0],[1 0 0 -.9 0;1 0 0 -.8 0])
```

ans =

```
1.0000    0.9000    0.8100    0.7290    0.6561    0.5905
1.0000    0.8000    0.6400    0.5120    0.4096    0.3277
```

The next example shows a variant; multiple input arrays, one per filter channel.

```
»sosfilters([1 0 0 0 0 0;2 0 0 0 0 0], ...
            [1 0 0 -.9 0;1 0 0 -.8 0])
```

ans =

```
1.0000    0.9000    0.8100    0.7290    0.6561    0.5905
2.0000    1.6000    1.2800    1.0240    0.8192    0.6554
```

Finally, multiple input arrays can be filtered by a single filter.

```
»sosfilters([1 0 0 0 0 0;2 0 0 0 0 0],[1 0 0 -.9 0])
```

ans =

```
1.0000    0.9000    0.8100    0.7290    0.6561    0.5905
2.0000    1.8000    1.6200    1.4580    1.3122    1.1810
```

sosfilters

See Also

soscascade

spectrogram

Purpose

Compute the spectrogram of a signal

Synopsis

```
[spectrogram raw] = spectrogram(wave, segsize, nlap, ntrans)
```

Description

Compute a short-time Fourier transform (STFT) or spectrogram of a one-dimensional signal. The following optional arguments are used to control the window size, overlap, and thus the image quality.

`segsize(128)` Size of a segment of data used to calculate each frame. This determines the basic frequency resolution of the spectrogram. Smaller segment sizes give more detailed time resolution, but at the expense of frequency resolution.

`nlap(8)` Number of hamming windows overlapping a point. Larger overlaps give better resolution in the time domain.

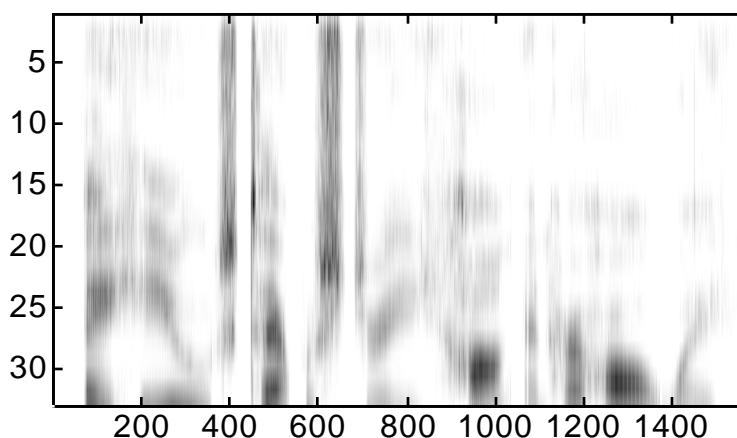
`ntrans(4)` Factor by which transform is bigger than segment, larger sizes magnify the frequency axis, but don't really give any better resolution.

This function returns a spectrogram *specgram* compressed with the square root of the maximum amplitude (fourth root of power). The optional *raw* output returns the unprocessed spectrogram data.

Example

A spectrogram of the 'A huge tapestry hung in her hallway' utterance from the TIMIT database (TRAIN/DR5/FCDR1/SX106/SX106.ADC) is shown below. It was computed using the following command line.

```
»spec=spectrogram(tap,64,2,1);
»imagesc(spec);
```



Author

Richard F. Lyon wrote the stabilization code and the smoothing algorithm.

Purpose

Synthesize a speech signal from its LPC coefficients

Synopsis

```
synWave = synlpc(aCoeff,source,sr,G,fr,fs,preemp)
```

Description

This function synthesizes a (speech) signal based on a LPC (linear- predictive coding) model of the signal. The LPC coefficients are a short-time measure of the speech signal which describe the signal as the output of an all-pole filter. This all-pole filter provides a good description of the speech articulators; thus LPC analysis is often used in speech recognition and speech coding systems. The LPC analysis is done using the `proclpc` routine. This routine can be used to verify that the LPC analysis produces the correct answer, or as a synthesis stage after first modifying the LPC model.

The results of LPC analysis are a new representation of the signal

$$s(n) = G e(n) - \sum_{i=1}^L a(i)s(n-i)$$

where $s(n)$ is the original data. $a(i)$ and $e(n)$ are the outputs of the LPC analysis with $a(i)$ representing the LPC model. The $e(n)$ term represents either the speech source's excitation, or the residual: the details of the signal that are not captured by the LPC coefficients. The G factor is a gain term.

LPC synthesis produces a monaural sound vector, *synWave*, which is sampled at a sampling rate of *sr*. The following parameters are mandatory

<i>aCoeff</i>	The LPC analysis results, $a(i)$. One column of $L+1$ numbers for each frame of data. The number of rows of <i>aCoeff</i> determines L .
<i>source</i>	The LPC residual, $e(n)$. One column of $sr \times fs$ samples representing the excitation or residual of the LPC filter.
<i>G</i>	The LPC gain for each frame.

The following parameters are optional and default to the indicated values.

<i>fr</i>	Frame time increment, in ms. The LPC analysis is done starting every <i>fr</i> ms in time. Defaults to 20ms (50 LPC vectors a second)
<i>fs</i>	Frame size in ms. The LPC analysis is done by windowing the speech data with a rectangular window that is <i>fs</i> ms long. Defaults to 30ms
<i>preemp</i>	This variable is the epsilon in a digital one-zero filter which serves to preemphasize the speech signal and compensate for the 6dB per octave rolloff in the radiation function. Defaults to .9378.

Examples

A simple analysis-resynthesis combination is easy to implement

```
»[aCoeff,resid,pitch,G,parcor,stream] = ...
    proclpc(tap,sr,13);
»syntap = synlpc(aCoeff, stream, sr, G);;
»soundsc(syntap,16000);
```

Like wise, a simple voice transformation is implemented by changing the residual to a pure noise signal. The resulting speech sounds whispered.

```
»[aCoeff,resid,pitch,G,parcor,stream] = ...
    proclpc(tap,sr,13);
»stream=randn(size(stream));
»syntap = synlpc(aCoeff, stream, sr, G);;
»soundsc(syntap,16000);
```

See Also

This code was graciously provided by Delores Etter (University of Colorado, Boulder) and Professor Geoffrey Orsak (Southern Methodist University). It was first published in

Orsak, G.C. et al. "Collaborative SP education using the Internet and MATLAB," *IEEE SIGNAL PROCESSING MAGAZINE*, Nov. 1995. vol.12, no.6, pp. 23-32.

Modified and debugging plots added by Kate Nguyen and Malcolm Slaney

A more complete set of routines for LPC analysis can be found at
<http://www.ee.ic.ac.uk/hp/staff/dmb/voicebox/voicebox.html>

WhiteVowel

Purpose

Demonstrate the effect of whitening one portion of a speech signal

Synopsis

```
[output,aCoeff] = WhiteVowel(data,sr,L,pos)
```

Description

Speech is often described as having spectral peaks or formants which identify the phonetic signal. An interesting experiment filters a speech signal to remove all the formant information at one time during the speech. If there are no formant peaks, how can the speech be understood? It turns out that processing, much like RASTA, means that relative changes in spectrum are the most important, thus the speech signal is understood because the formant transitions carry the information. This gives speech an important transparency due

This function takes a speech signal (*data*) with a given sampling rate (*sr*). It then finds the *L*-order LPC filter that describes the speech at the given position (*pos* ms). The entire speech signal is then filtered with the inverse of the LPC filter, effectively turning the speech spectrum at the given time white (flat).

Examples

The tapestry utterance can be filtered so that the 50th frame is white. The computation is shown below.

```
»whitetap = WhiteVowel(tap,16000,13,1000);  
»soundsc(whitetap, 16000);
```

A debugging plot shows the spectrogram before and after whitening. Note that the overall variation of the spectral slide is much reduced after filtering.

