Frequency compression – its past, present, and future

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Overview

EFFECTS OF HIGH-FREQUENCY HEARING IMPAIRMENT

SOME EARLY FREQUENCY-LOWERING SCHEMES

EXISTING COMMERCIAL FREQUENCY-LOWERING HEARING INSTRUMENTS

THE FUTURE
Normal hearing
Cochlear mechanics

[Diagram showing the cochlear duct and basilar membrane with frequency labels (1,500 Hz, 2,000 Hz, 3,000 Hz, 400 Hz, 600 Hz, 800 Hz, 200 Hz, 4,000 Hz, 7,000 Hz, 5,000 Hz, and 20,000 Hz).]
Why lower high frequencies?

• Hearing impairment is usually worse at high frequencies
• Many important sounds contain mostly high frequencies
• Some examples:
  • Birdsong
  • Speech: unvoiced fricatives /s/ and /sh/
Spectrogram of /a-s-a-sh-a/ (female speaker)
Why not amplify high frequencies more?

• Feedback whistling is more likely
• High-frequency sounds may be uncomfortable for some people with hearing loss
• There may be dead regions in the cochlea
Effect of dead region

“off-frequency listening”
Is high-frequency amplification always beneficial?

from Hogan & Turner, JASA 1998
The solution: frequency shifting

• For many people with hearing impairment that is severe-to-profound in the high frequencies, frequency lowering can improve signal audibility.
• Numerous different frequency-lowering schemes have been developed and evaluated.
• Some previous schemes have been shown to improve speech understanding for certain hearing-aid users.
One early frequency-lowering hearing aid (described in 1959)

A New Coding Amplifier System for the Severely Hard of Hearing

B. JOHANSSON

The Royal Institute of Technology, Stockholm (Sweden)

Proceedings of the 3rd International Congress on Acoustics, Stuttgart
Spectra of fricative noise for /s/ and /z/ from Stelmachowicz et al., Ear & Hearing 2002

Boothroyd (1992) and others suggest that the frequency response of hearing aids should extend to at least 10 kHz

from Stelmachowicz et al., Ear & Hearing 2002
Johansson's 'transposer'

- Only high-frequency sounds were processed separately
- Sidebands were created by mixing them with a high-frequency tone
- The low-frequency sideband (below 1500 Hz) was filtered and mixed with the original sound

from Johansson, 1966
Advantages and disadvantages

• Some speech-perception benefits were observed
• Could be implemented in a wearable hearing instrument
• Disadvantages:
  – processing caused sound distortion
  – unnatural spectral shape
  – masking of original low-frequency sounds by lowered high-frequency sounds
Practical frequency-shifting techniques

- Downward frequency shift
  — All frequencies or selected frequencies?
  — All of the time or some of the time?
## Frequency shifting alternatives

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<thead>
<tr>
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<th>Only when certain phonemes detected</th>
<th>All the time</th>
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<tr>
<td>All frequencies</td>
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Shifting all frequencies all of the time

First reported in the 1960s, implemented with variable-speed tape recorders

- Original speech
- Speech lowered by one octave
- It is not acceptable to lower the pitch of the speech!
...but it can improve speech recognition

from Turner & Hurtig, JASA 1998
Today's frequency-shifting alternatives

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AVR Sonovation

(*TranSonic, ImpaCt, Nano Xp*)

- Shifts frequencies *only* when the input spectrum is dominated by signals above 2.5 kHz
- Uses time-domain record-and-replay technique
- Boosts output level while transposing
Advantages and disadvantages of the AVR scheme

• Small speech-perception benefits reported in several studies
• Available in a wearable hearing instrument
• **Disadvantages:**
  – difficult to detect phonemes such as /s/ reliably using a simple algorithm, especially in noisy conditions, or with competing speakers
  – switching the transposition on and off at the phoneme boundaries can produce audible artefacts
  – the record/replay technique can run out of memory, discarding some information
## Today's frequency-shifting alternatives

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Experimental transposition scheme

• Described by Robinson et al. in the International Journal of Audiology, 2007
• Active only when high-frequency energy dominates the signal
• When active, a high-frequency band is shifted down and mixed with signals in a lower band
• Benefits found for some subjects:
  — better perception of affricates
  — better detection of word-final /s/ and /z/
## Today's frequency-shifting alternatives

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**PHONAK**
Widex *Inteo* 'Audibility Extender'

**SOURCE OCTAVE**

**TARGET OCTAVE**

SHIFT AND OVERLAP (MIX)
Widex AE – continued

FILTER OUTPUT
SIGNAL ‘TO LIMIT MASKING EFFECT’

OUTPUT SPECTRUM:

INPUT SPECTRUM:
Input-to-output frequency conversion

<table>
<thead>
<tr>
<th>Input frequency (kHz)</th>
<th>Output frequency (kHz)</th>
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<tr>
<td>0.1</td>
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<tr>
<td>0.2</td>
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<td>0.5</td>
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- **NORMAL AMPLIFICATION**
- **TRANSPOSITION**
- **SOURCE OCTAVE**

**Legend:**
- Green: Frequency conversion range
- Black: Input frequency range

**Note:** This graph illustrates the relationship between input and output frequencies for a device or system, indicating how it processes sound through amplification and transposition stages.
Some technical details of the AE scheme

- The mixing of the signals originally in the source band with signals already present in the lower band may be undesirable.
- The extent of frequency shifting varies from instant to instant based on the frequency of the selected peak in the source octave.
- Although the selected peak is lowered by one octave, the surrounding frequencies are lowered by a constant number of Hertz.
Alternative input-to-output conversion

Output frequency (kHz) vs. Input frequency (kHz)

- **Cut-Off Frequency**
- **Slope**
Non-linear frequency compression

Input frequency (kHz)

Output frequency (kHz)

Cut-Off Frequency

PROGRESSIVE FREQUENCY LOWERING
Technical advantages of non-linear frequency compression (SoundRecover)

- It's simple!
- No mixing of the frequency-lowered signal with other signals already present
- Frequency compression is active all the time
- No need to detect phonemes or other features of the input signal
- The amount of lowering is constant over time
- Frequency lowering is applied progressively at high frequencies
- It increases the effective bandwidth of the HI
Effect of frequency compression parameters

- Low cut-off, Steep slope
- High cut-off, Shallow slope
Effect of parameters when processing /aSa/

- **Frequency**
- **Time**

Original

- **Frequency**
- **Time**

4000

- 1.5:1

2000

- 2:1

1500

- 4:1

Lower cut-off frequencies = stronger frequency compression
What does it sound like?

• *Speech processed through experimental aid, without frequency compression*

• *Speech with frequency compression (1600 Hz, 2:1)*
Initial experimental studies in Melbourne

(under contract to Phonak)
Subjects' average audiogram

N = 17

Hearing Level (dB HL) vs. Frequency (Hz)
Experimental gain selection

Average speech spectrum

Cut-off frequency

Level (dB SPL)

Frequency (kHz)

Adjusted for equal loudness
Overall results

CONVENTIONAL HEARING AID  FREQUENCY COMPRESSION

N=17

Percent correct

Phonemes  Vowels  Consonants  Consonants with frication

p < 0.001 for each comparison
Results – /f, s, sh, v, z, th, dj, ch/

from Simpson, Hersbach, & McDermott, 2005
Further development by Phonak

- Phonak *Naida* hearing instrument

- The frequency compression processing, *SoundRecover*, is functionally the same as in the original experimental scheme
Fitting of *SoundRecover* parameters

- The fitting of *SoundRecover* is automatic (although it can be adjusted if required)
  - based on the degree of hearing impairment, and the slope of the audiogram
  - gain remains the same with frequency compression
- Cut-off frequency and frequency-compression ratio are set together according to a single strength parameter
Candidacy for frequency compression

- People with *or without* cochlear 'dead regions' may benefit
- Many people with *less-severe impairment*, and/or less-steeply sloping audiograms seem to prefer it
- A trial with frequency compression before cochlear implantation may be worthwhile
- Benefits are often seen in hearing-impaired children as well as adults
The future

Use with less-severe hearing impairment
Perceptual bandwidth extension

- Effective bandwidth may be limited by hearing instrument (receiver) or listener's impairment
- Perceptual benefits may include better spatial hearing
When would a cochlear implant be most appropriate?

- **Cochlear implants** provide auditory information about high frequencies, but
  - at present, candidates generally have **minimal** high-frequency hearing
  - cochlear implants are expensive
  - implantation is effectively permanent
  - not every candidate wants to have an operation, or is suitable
  - the electric stimuli do not sound natural
**Bimodal** hearing can be highly beneficial
Conclusions

• For the people with hearing impairment who have participated in the (many) listening trials so far:
  — most obtain some benefit
  — some obtain little measurable benefit, but are not averse to the processing
  — a few may dislike the sound quality and/or obtain no benefit
• Children in particular may improve their speech production
• Frequency compression may also be beneficial for people with less-severe hearing impairment
• Cochlear implants can be used effectively in combination with acoustic hearing instruments in cases of minimal high-frequency hearing
Acknowledgments

- Phonak AG, including Stef Launer, Silvia Allegro, Peter Derleth, Michael Boretzki, Ora Bürkli, Myriel Nyffeler, Andrea Kegel, Nicola Schmitt, Rene Buergin, and numerous colleagues in Switzerland
- Peter Wohlfahrt, Phonak Australia
- Adam Hersbach, Andrea Simpson, Katherine Henshall, and many collaborators at The University of Melbourne, The Bionic Ear Institute, and other research centres
- The Garnett Passe and Rodney Williams Memorial Foundation
- The CRC for Cochlear Implant and Hearing Aid Innovation