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EXPERIMENTS ON THE SYNTHESIS OF VIRTUAL ACOUSTIC SOURCES IN AUTOMOTIVE INTERIORS

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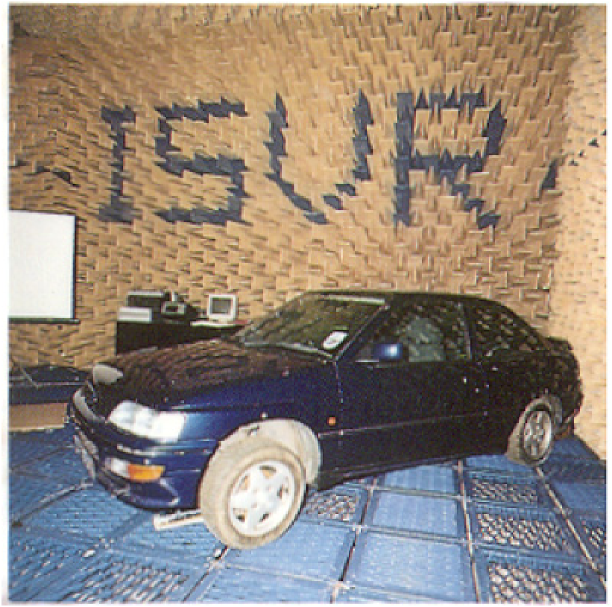

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CONTENTS

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VIRTUAL ACOUSTICS IN AUTOMOTIVE SPACES - INTRODUCTION

- **Disadvantages**
  - loudspeaker positions
  - small cavity
  - reflections due to windows
  - background noise
- **Advantages**
  - 'sweet-spot' and geometry are known
  - acoustic characteristics of the compartment are known
  - loudspeakers can be equalised
- **Methods**
  - time alignment, centre channel, Ambisonics
  - cross-talk cancellation, HRTF, convolution

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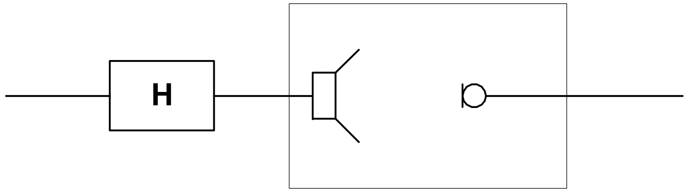
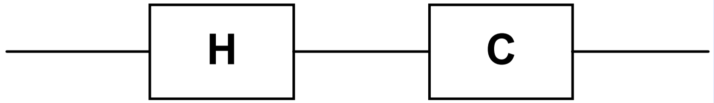
INVERSION STRATEGIES FOR A SINGLE CHANNEL ROOM ACOUSTIC RESPONSE

$$C(z) = \frac{z^{-k} B_c(z)}{A_c(z)}$$

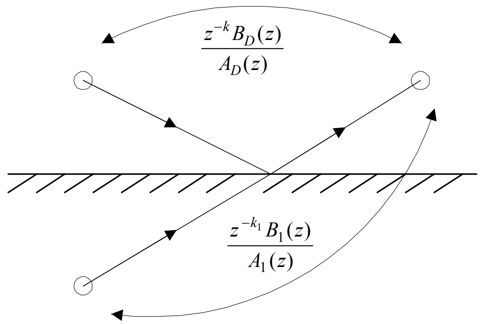


$$C(z) = \frac{z^{-k} B_D(z)}{A_D(z)} + \frac{z^{-k_1} B_1(z)}{A_1(z)} + \frac{z^{-k_2} B_2(z)}{A_2(z)} + \dots + \frac{z^{-k_n} B_n(z)}{A_n(z)}$$



and in compact form

$$C(z) = \frac{z^{-k} B_D(z)}{A_D(z)} + \sum_{i=1}^{I} \frac{z^{-k_i} B_i(z)}{A_i(z)} = C_D(z) + C_R(z)$$



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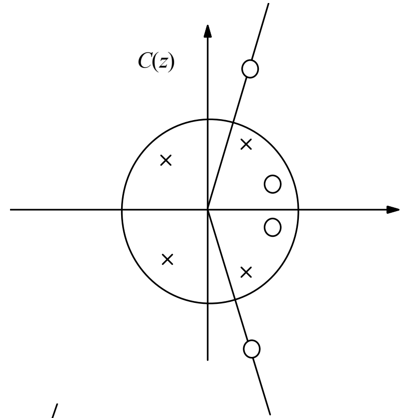
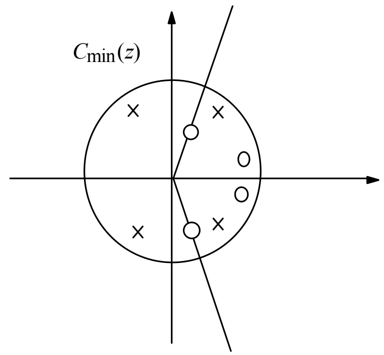
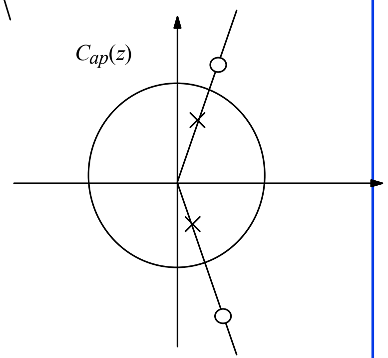
INVERSION STRATEGIES FOR A SINGLE CHANNEL ROOM ACOUSTIC RESPONSE (cont.)

$$C(z) = \frac{z^{-k} B_c^+(z) B_c^-(z)}{A_c(z)}$$



$$C(z) = z^{-k} \cdot \frac{B_c^+(c) z^{-N} B_c^-(z^{-1})}{A_c(z)} \cdot \frac{B_c^-(z)}{z^{-N} B_c^-(z^{-1})}$$



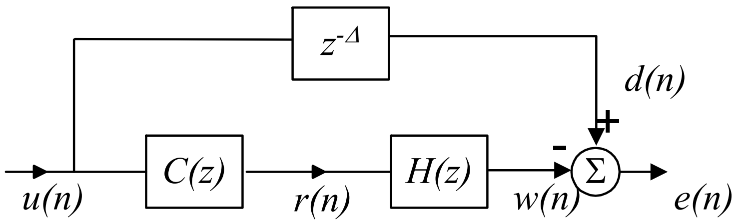


$$C_{min}(z) = \frac{B_c^+(z) z^{-N} B_c^-(z^{-1})}{A_c(z)}$$

$$C_{ap}(z) = \frac{B_c^-(z)}{z^{-N} B_c^-(z^{-1})}$$

SOLUTION FOR THE WIENER FILTER

The transfer function $H(z)$ that minimises the time averaged squared error $E[e^2(n)]$ is given by



$$H(z) = \frac{1}{S(z)} \left\{ \frac{S_{rd}(z)}{S(z^{-1})} \right\}_+$$

Where $\{\ \}_+$ denotes "the causal part of"

$S_{rd}(z)$ is the cross power spectral density between the received and desired signals

$$S_{rd}(z) = S_{dr}(z^{-1}) = \frac{z^{k-\Delta} B(z^{-1})}{A(z^{-1})}$$

$S(z)$, $S(z^{-1})$ are the spectral factors given by $S_{rr}(z) = S(z)\, S(z^{-1})$

$$S_{rr}(z) = C_{min}(z) C_{min}(z^{-1})$$

$S_{rr}(z)$ is the power spectral density of the received signal

$$H(z) = \frac{1}{C_{min}(z)} \left\{ \frac{z^{k-\Delta}}{C_{ap}(z)} \right\}_+$$

INVERSION STRATEGIES

- **Inversion strategy #1: inverse of minimum phase part**

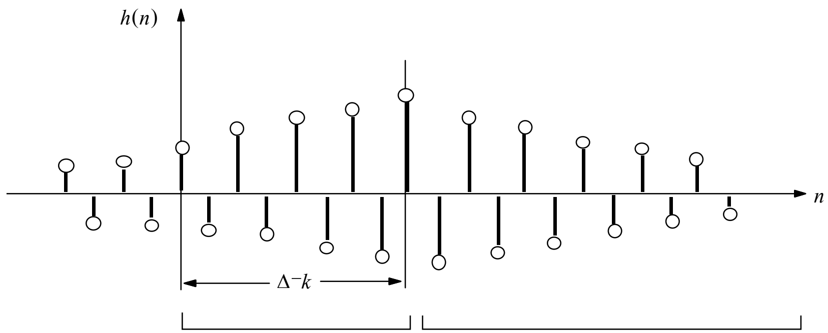
$$H(z) = \frac{C_{min}(z)}{1} \quad \Longrightarrow \quad H(z)\,C(z) = z^{-k} C_{ap}(z)$$

•loudspeaker, HRTF, room (?)

- **Inversion strategy #2: least squares inversion**

$$H(z) = \frac{1}{C_{min}(z)} \left\{ \frac{z^{k-\Delta}}{C_{ap}(z)} \right\}_+$$

$$H(z)\,C(z) = z^{-k} C_{ap}(z) \left\{ \frac{z^{k-\Delta}}{C_{ap}(z)} \right\}_+$$



$$\left\{ \frac{z^{k-\Delta}}{C_{ap}(z)} \right\}_+ \qquad \frac{1}{C_{min}(z)}$$

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INVERSION STRATEGIES (cont.)

- **Inversion strategy #3: inverse of minimum phase part (direct path)**

$$\frac{z^{-k}B_D(z)}{A_D(z)} = z^{-k}C_{Dmin}(z)C_{Dap}(z)$$

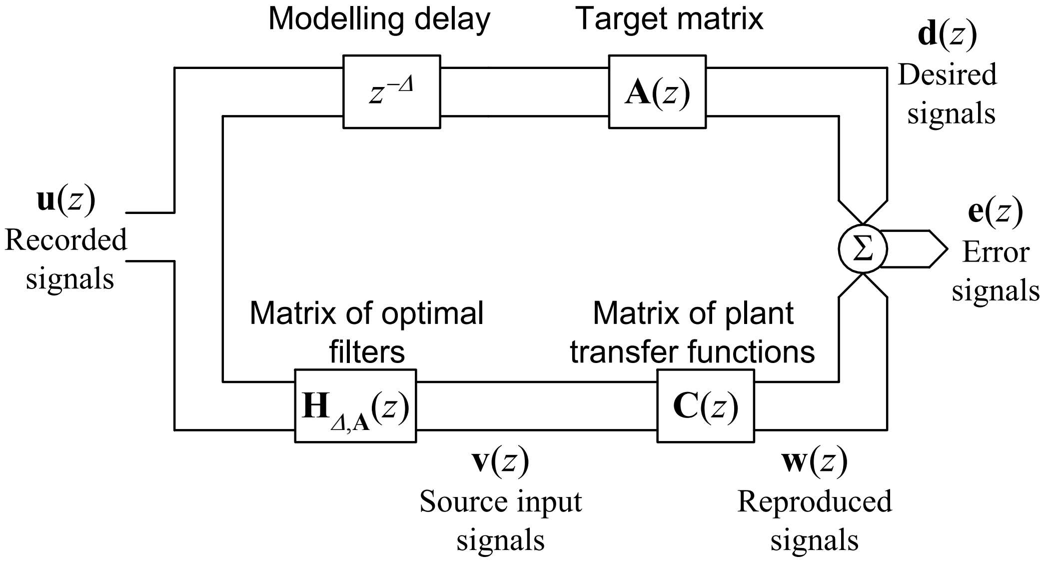
$$H(z) = \frac{1}{C_{Dmin}(z)} \Longrightarrow H(z)\,C(z) = z^{-k}C_{Dap}(z) + \frac{C_R(z)}{C_{Dmin}(z)}$$

- **Inversion strategy #4: least squares inversion**

$$H(z) = \frac{1}{C_{Dmin}(z)}\left\{\frac{z^{k-\Delta}}{C_{Dap}(z)}\right\}_+$$

$$H(z)\,C(z) = z^{-k}C_{Dap}(z)\left\{\frac{z^{k-\Delta}}{C_{Dap}}\right\}_+ + \frac{C_R(z)}{C_{Dmin}(z)}\left\{\frac{z^{k-\Delta}}{C_{Dap}(z)}\right\}_+$$

MULTI-CHANNEL LEAST SQUARES INVERSION



$$J(\mathrm{e}^{\mathrm{j}\omega}) = \mathbf{e}^{\mathrm{H}}(\mathrm{e}^{\mathrm{j}\omega})\mathbf{e}(\mathrm{e}^{\mathrm{j}\omega}) + \beta\mathbf{v}^{\mathrm{H}}(\mathrm{e}^{\mathrm{j}\omega})\mathbf{v}(\mathrm{e}^{\mathrm{j}\omega})$$

$$\mathbf{H}_{0,\mathbf{A}}(z) = [\mathbf{C}^{\mathrm{T}}(z^{-1})\mathbf{C}(z) + \beta\mathbf{I}]^{-1}\mathbf{C}^{\mathrm{T}}(z^{-1})\mathbf{A}(z).$$

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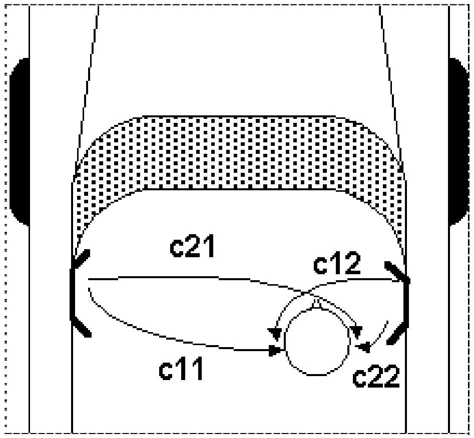
FILTER DESIGN AND MEASUREMENTS UNDER ANECHOIC CONDITIONS

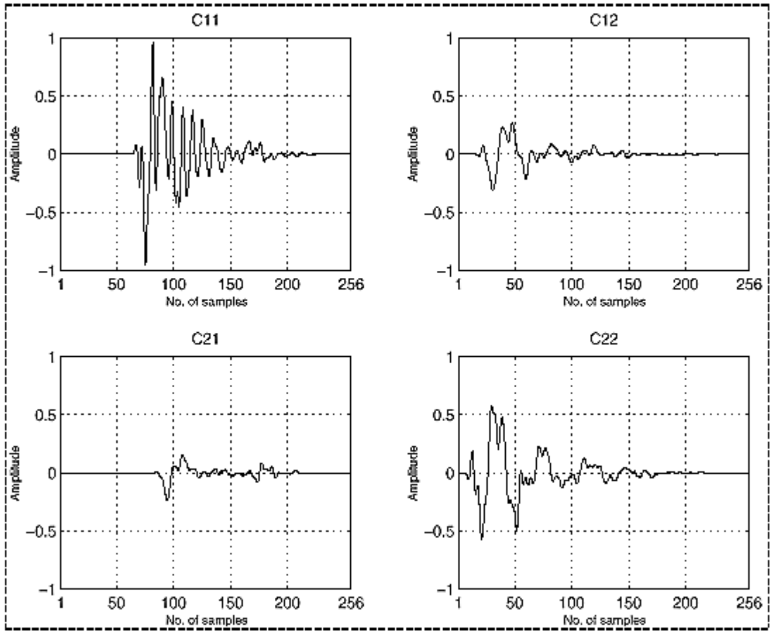
•'Free-field' direct path in the car:

Doors, speakers, car-seat, KEMAR

• Non-minimum phase matrix

• Dynamic range





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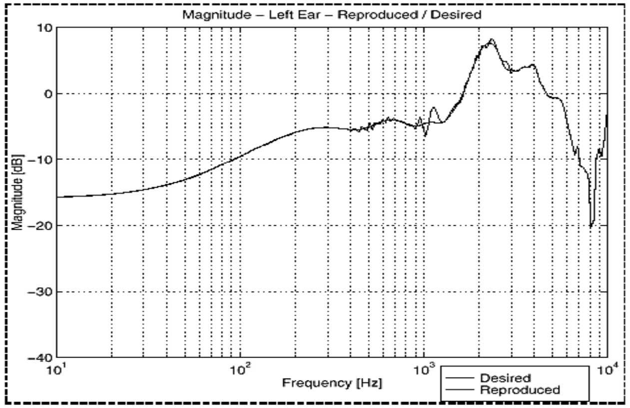
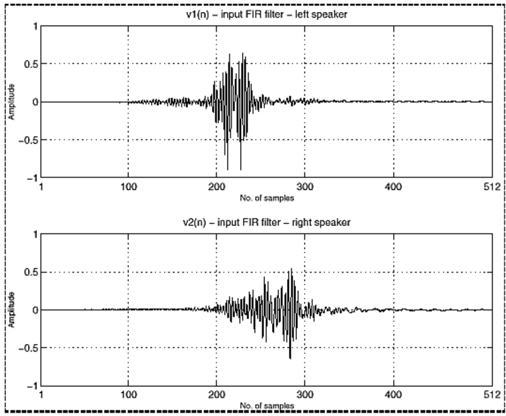
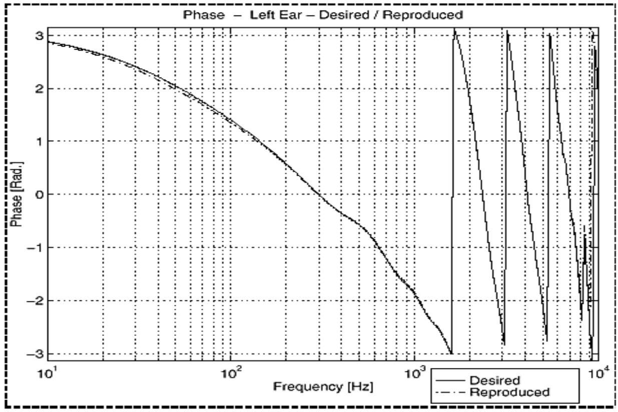
FILTER DESIGN AND MEASUREMENTS UNDER ANECHOIC CONDITIONS (cont.)

- Pilot study for ‘irregular’ loudspeaker arrangement
- Measurement of reproduced signals at dummy-head position for cross-talk cancellation and synthesis of virtual source
- Short FIR filters: 512 taps



Virtual source at 90°
(in front of the driver)





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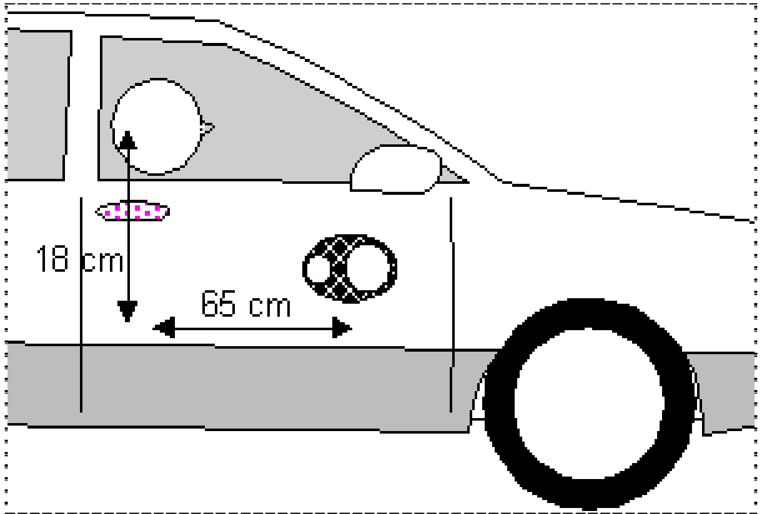
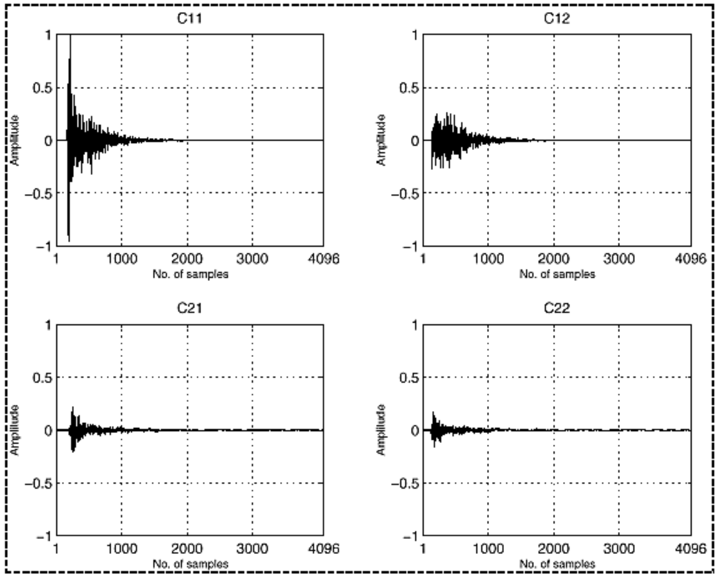
FILTER DESIGN AND MEASUREMENTS IN THE CAR

- IR - 50 msec
- Long inverse filters - 131,072 taps
- Loudspeakers - distortion at high frequencies, limited power handling





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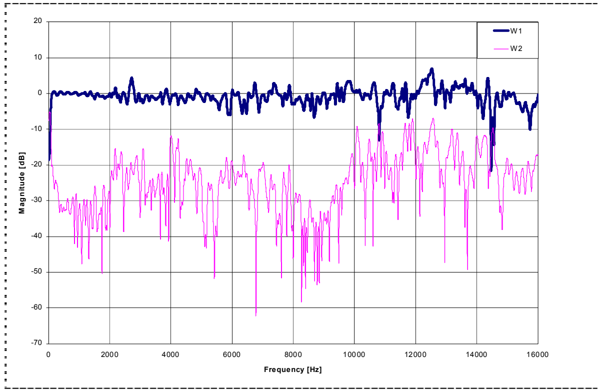
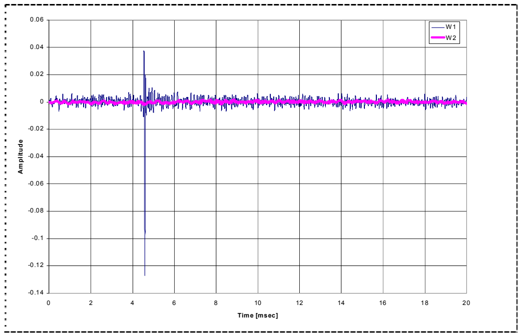
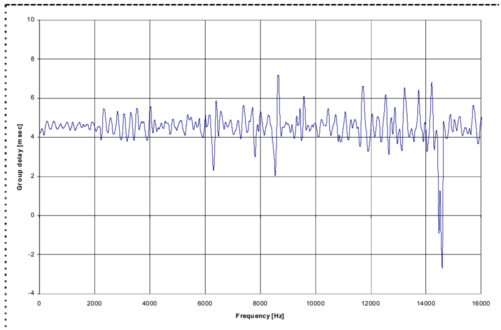
MEASUREMENT OF CROSS-TALK CANCELLATION IN THE CAR

Inversion under ideal conditions

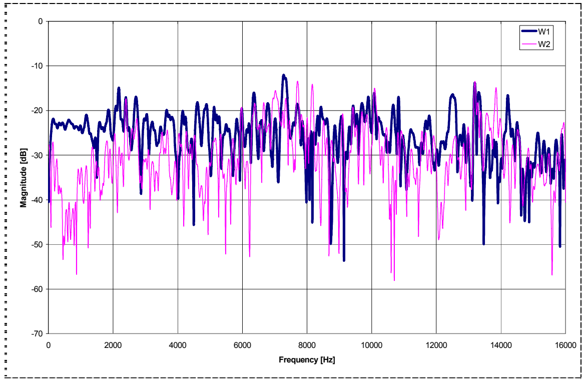




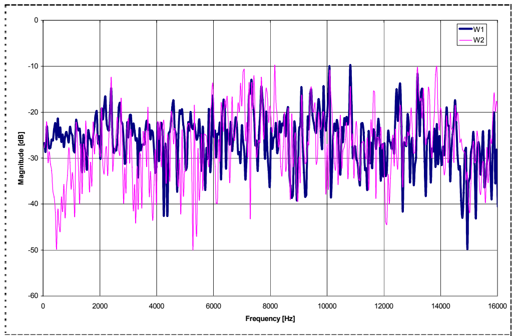


•10-30 dB reduction

Dummy-head 2cm to the right



2cm above optimal point



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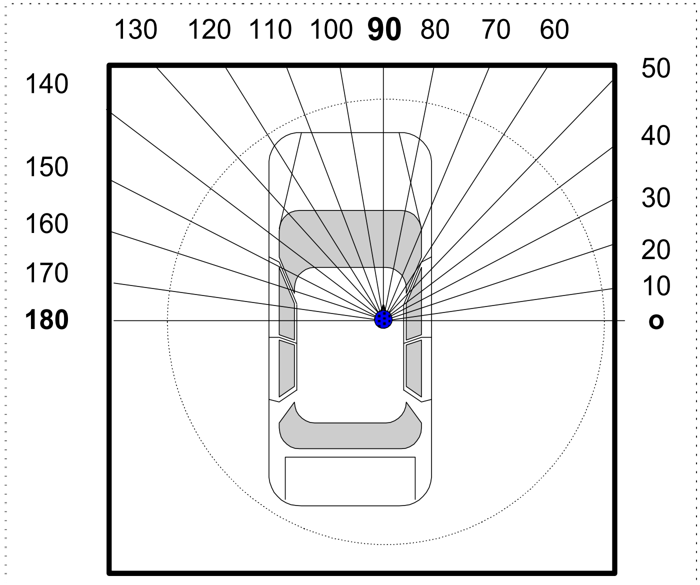
SUBJECTIVE EXPERIMENTS (LOCALISATION TESTS) IN A CAR

· Set #1: inversion of the entire response measured in the car.

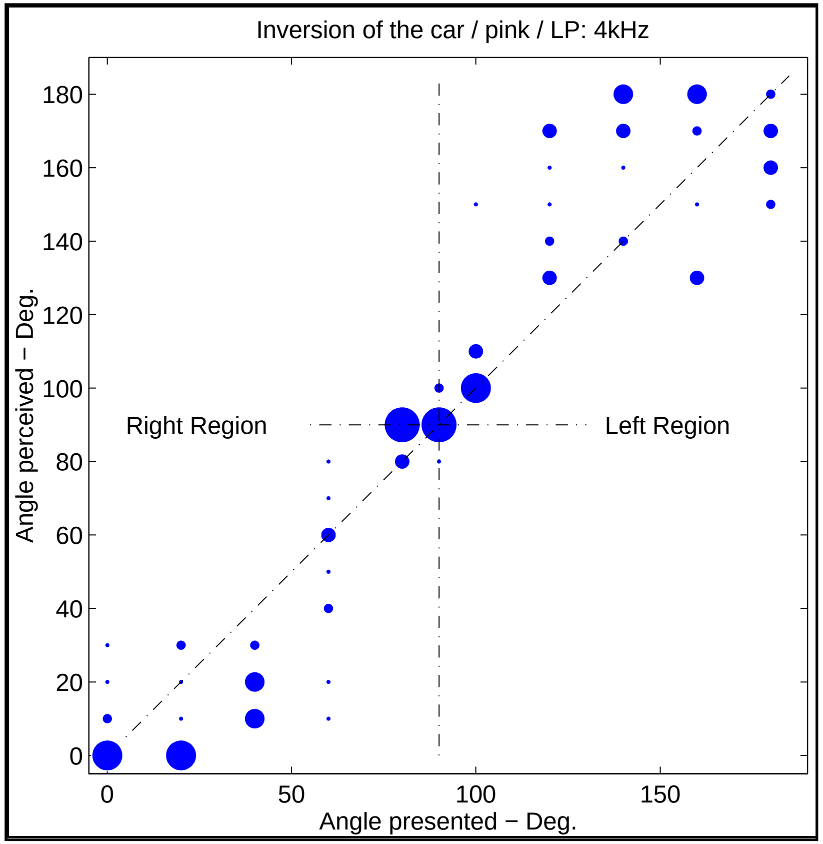
· Set #2: inversion of the "free-field" response.

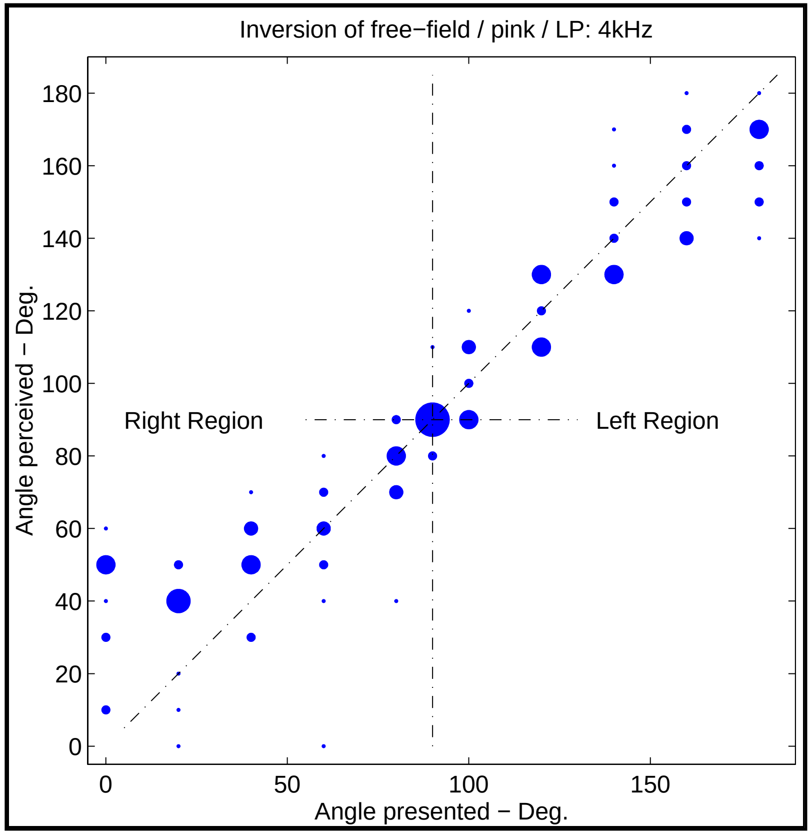
· Set #3: Inversion of the windowed response measured in the car. (The matrix C included only the first 256, 512 samples).

· All the above signals were filtered with a 4 kHz low pass filter, and also with a 10 kHz low-pass filter.



RESULTS - LOCALISATION TEST / PINK NOISE





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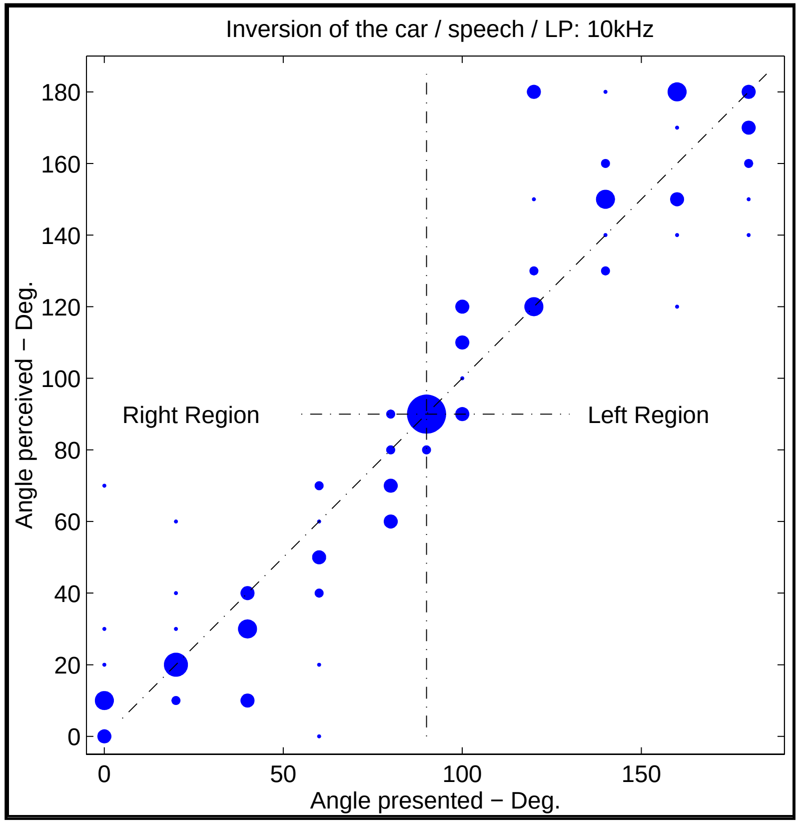
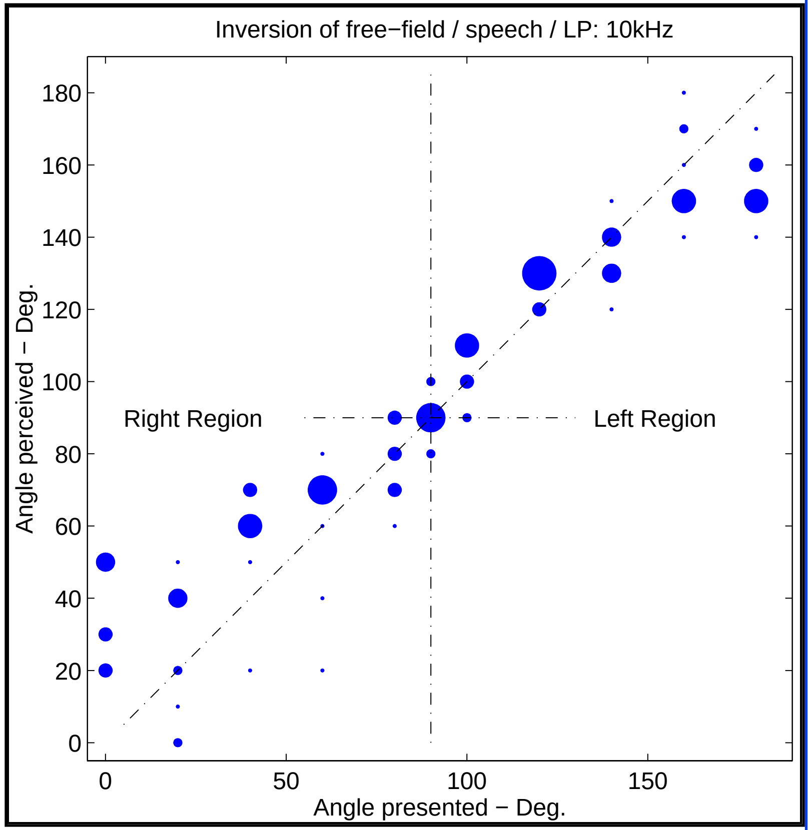
RESULTS - LOCALISATION TEST / SPEECH





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CONCLUSIONS

- Inversions of non minimum phase room responses are problematic, and can reproduce an accurate approximation of the desired signal only at a single point

- Although the electro-acoustic paths are known in advance, it is shown that only the inversion of the 'free-field' IR produces superior results both for localisation and sound quality

- The success of this method is based on the significant role of ITD at low frequencies

- Further work is required for the assessment of performance at high and very low frequencies