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Multi-Reference Methods for Nearfield Acoustical Holography

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NAH Measurements

Snap-shot measurement

- Non-stationary
- Large number of microphones

Scanning measurement

- Small number of scanning microphones
- Use of reference microphones to provide phase information
- Assumption: **stationary** sound field

Source non-stationarity compensation

Partial field decomposition

Uncorrelated or partially correlated sources

Decomposition

Partial field decomposition methods

SVD method

Partial Coherence (PC) method

SVD method: Orthogonal partial references.

PC method: Incoherent, but not orthogonal partial references.

- D. L. Hallman and J. S. Bolton, "Multi-reference nearfield acoustical holography," *Proceedings of INTER-NOISE 92*, pp. 1165-1170 (1992).
- D. L. Hallman and J. S. Bolton, "A comparison of multi-reference nearfield acoustical holography procedures," *Proceedings of NOISE-CON 94*, pp. 929-934 (1994).
- H.-S. Kwon and J. S. Bolton, "Partial field decomposition in nearfield acoustical holography by the use of singular value decomposition and partial coherence procedures," *Proceedings of NOISE-CON 98*, pp. 649-654 (1998).

Partial field decomposition methods

$\mathbf{p} = \mathbf{H}_{pr} \mathbf{r}$ $\mathbf{p}$: hologram sound pressures
 $\mathbf{r}$: reference microphone measured sound pressures

$\mathbf{S}_{pr} = \mathbf{p} \mathbf{r}^H = \mathbf{H}_{pr} \mathbf{S}_{rr}$ Cross-spectra between hologram and reference signals

Decompose reference cross-spectra $\mathbf{S}_{rr}$

SVD-based

$$\mathbf{S}_{rr} = \mathbf{V} \mathbf{\Sigma} \mathbf{V}^H$$

$\mathbf{V}$ is a unitary matrix

$$\mathbf{H}_{pr} = \mathbf{S}_{rp}^H \mathbf{V} \mathbf{\Sigma}^{-1} \mathbf{V}^H$$

$$\mathbf{S}_{pp} = \mathbf{H}_{pr} \mathbf{V} \mathbf{\Sigma} \mathbf{V}^H \mathbf{H}_{pr}^H$$

$$\mathbf{S}_{pp} = \mathbf{p} \mathbf{p}^H$$

Partial field: $\mathbf{p} = \mathbf{H}_{pr} \mathbf{V} \mathbf{\Sigma}^{1/2} = \mathbf{S}_{rp}^H \mathbf{V} \mathbf{\Sigma}^{-1/2}$

PC-based

$$\mathbf{S}_{rr} = \mathbf{L} \mathbf{D} \mathbf{L}^H$$

$\mathbf{L}$ is the lower triangular matrix with diagonal entries equal to unity

$$\mathbf{H}_{pr} = \mathbf{S}_{rp}^H \mathbf{L}^H \mathbf{D}^{-1} \mathbf{L}^{-1}$$

$$\mathbf{S}_{pp} = \mathbf{H}_{pr} \mathbf{L} \mathbf{D} \mathbf{L}^H \mathbf{H}_{pr}^H$$

Partial field: $\mathbf{p} = \mathbf{H}_{pr} \mathbf{L} \mathbf{D}^{1/2} = \mathbf{S}_{rp}^H \mathbf{L}^H \mathbf{D}^{-1/2}$

Partial fields are different but the total fields are same if references sense all contributing sources.

Experimental design and selection of references

2 incoherent sources & 5 reference candidates

- Y.-J. Kim, J. S. Bolton, and H.-S. Kwon, "Partial sound field decomposition in multireference nearfield acoustical holography by using optimally located virtual references," J. Acoust. Soc. Am. **115**, 1641-1652 (2004).

Decomposed holograms (1200 Hz)

SVD method

PC method

Experimental setup of tire noise measurements

Tire driven by a roller

8 reference microphones

8 by 8 scanning mic array (10 cm spacing)

Hologram height: 6 cm

**16 Point Measurement
with 5 cm Sampling Space**

Smooth Roller Surface

**32 Point Measurement
with 5 cm Sampling Space**

Virtual reference signals

Virtual reference procedure allows to decompose physically meaningful partial fields during post processing.

$$\mathbf{Y} = \mathbf{H}_{yr} \mathbf{V} \Lambda^{1/2} = \mathbf{H}_{yl} \Lambda^{1/2}$$

Virtual reference signals are selected from the reconstructed field signals

$\mathbf{Y}$: Partial field matrix on hologram surface

$\Lambda^{1/2}$: Principal reference signal matrix

$\mathbf{H}_{yl}$: Transfer matrix

$$\mathbf{Y}' = \mathbf{H}_{y'y} \mathbf{Y} = \mathbf{H}_{y'y} \mathbf{H}_{yr} \mathbf{V} \Lambda^{1/2} = \mathbf{H}_{y'y} \mathbf{H}_{yl} \Lambda^{1/2} = \mathbf{H}_{yl} \Lambda^{1/2}$$

$\mathbf{Y}'$: Partial field matrix on reconstruction surface

$\mathbf{H}_{y'y}$: Transfer matrix (NAH projection procedure)

$$\mathbf{X} = \begin{bmatrix} \mathbf{c}_1^T \mathbf{Y}'_1 \\ \mathbf{c}_2^T \mathbf{Y}'_2 \\ \vdots \\ \mathbf{c}_K^T \mathbf{Y}'_K \end{bmatrix} = \begin{bmatrix} \mathbf{c}_1^T \mathbf{H}_{y'l} \\ \mathbf{c}_2^T \mathbf{H}_{y'l} \\ \vdots \\ \mathbf{c}_K^T \mathbf{H}_{y'l} \end{bmatrix} \Lambda^{1/2} = \mathbf{H}_{xl} \Lambda^{1/2}$$

$\mathbf{X}$: Virtual reference signal matrix

$\mathbf{c}_m$: virtual reference selection vector on reconstruction surface

$\mathbf{Y}'_m$: Partial field matrix for reconstruction surface

Note that the principal reference signals can be obtained from real reference signals

- Y.-J. Kim, J. S. Bolton, and H.-S. Kwon, "Partial sound field decomposition in multireference nearfield acoustical holography by using optimally located virtual references," J. Acoust. Soc. Am. **115**, 1641-1652 (2004).

Virtual reference locations

- Location of a virtual reference in a 3-D space is determined by the position of the reconstruction surface in combination with the reference selection vector.
- MUSIC power is maximized at the optimal reference microphone location.

$$P_{\text{MUSIC}} = \frac{1}{\mathbf{u}^H \mathbf{R}_{\text{noise}} \mathbf{u}}$$

P_{MUSIC} : MUSIC power

$\mathbf{u}$: trial vector

$$\mathbf{R}_{\text{noise}} = \sum_{n=K+1}^N \mathbf{w}_n \mathbf{w}_n^H : \text{Noise subspace}$$

$\mathbf{w}_n$: Noise - related eigenvectors of $\mathbf{S}_{\mathbf{y}'\mathbf{y}'} (\mathbf{S}_{\mathbf{y}'\mathbf{y}'})^H$

K is the number of incoherent sources (i.e., rank of system) .

MUSIC power for selection of virtual references (216 Hz)

maxima at $n = 15$ and 19

Partial fields based on real and virtual references (216 Hz & 21 mph)

Allows successful separation of radiation from leading and trailing edges of contact patch.

Source non-stationarity compensation

- No realistic source is perfectly stationary.
- Assumptions for compensation
 - Slight source level changes do not affect sound radiation pattern
 - Acoustical transfer functions between reference and field microphones are only determined by their locations.
- Acoustical transfer function are invariant regardless of source level changes.
- Use of acoustic transfer functions between reference and field signals

$$\mathbf{H}_{pr} = \mathbf{S}_{rp}^H \mathbf{S}_{rr}^{-1}$$

$$\mathbf{S}_{yy} = \mathbf{Y} \mathbf{Y}^H$$

$$\mathbf{Y} = \mathbf{H}_{yr,(\text{step})} \mathbf{S}_{rr,(\text{avg})}^{1/2} = \mathbf{S}_{ry,(\text{step})}^H \mathbf{S}_{rr,(\text{step})}^{-1} \mathbf{S}_{rr,(\text{avg})}^{1/2}$$

- Source non-stationarity causes scanned hologram to appear “patchy” and typically add spatial noise to the hologram image.

Effect of source non-stationarity (216 Hz & 21 mph)

SVD-based partial field decomposition is applied.

Without source non-stationarity compensation

With source non-stationarity compensation

- (a) First partial pressure field
- (b) Second partial pressure field

Effect of the number of reference microphones (1)

- Cylindrical scanning surface around subsonic jet.
- 48 fixed reference microphones in 6 linear arrays.

Three array configurations

- Case 1: use 48 references
- Case 2: use 18 references (3 references from each array)
- Case 3: use 16 references (array #1 and #2)

- M. Lee and J. S. Bolton, "Scan-based nearfield acoustical holography and partial field decomposition in the presence of noise and source level variation," J. Acoust. Soc. Am. **119**, 382-393 (2006).
- M. Lee and J. S. Bolton, "Source characterization of a subsonic jet by using nearfield acoustical holography," J. Acoust. Soc. Am. **121**, 967-977 (2007).

Effect of the number of reference microphones (2)

< Singular values >

Case 1

48 references

Case 2

18 references

Case 3

16 references

< Sum of the virtual coherence functions at 1 kHz >

Case 1

11 partial fields

Case 2

18 partial fields

Case 3

16 partial fields

The use of a large number of spatially-well-distributed references allows clean separation of signal and noise related singular values – The number of partial fields is minimized.

Effect of the number of reference microphones (3)

< Sum of the virtual coherence functions at 1 kHz >

< averaged value >

< smallest value >

- The 48-reference array used in this test was nearly optimal

Conclusions

- In scan-based, multi-reference NAH measurements, reference signals can be used to decompose a composite sound source into coherent partial fields. The partial fields can be physically meaningful or not depending on the decomposition methods.
- SVD-based and PC-based partial field decomposition methods were presented along with their applications to decompose the multi-component sound fields.
- The use of a source non-stationarity compensation procedure is implemented when measuring realistic, multi-component noise sources.
- The Virtual Reference Method can be used to decompose a total sound field into physically meaningful partial fields regardless of the locations of actual references during a measurement.
- The number of reference transducers should be much larger than the number of incoherent sound sources to model measurement noise components and to identify a minimum set of noise-suppressed partial fields.

References

- D. L. Hallman and J. S. Bolton, "Multi-reference nearfield acoustical holography," *Proceedings of INTER-NOISE 92*, pp. 1165-1170 (1992).
- D. L. Hallman and J. S. Bolton, "A comparison of multi-reference nearfield acoustical holography procedures," *Proceedings of NOISE-CON 94*, pp. 929-934 (1994).
- H.-S. Kwon and J. S. Bolton, "Partial field decomposition in nearfield acoustical holography by the use of singular value decomposition and partial coherence procedures," *Proceedings of NOISE-CON 98*, pp. 649-654 (1998).
- H.-S. Kwon, Y.-J. Kim, and J. S. Bolton, "Compensation for source non-stationarity in multireference, scan-based nearfield acoustical holography," *J. Acoust. Soc. Am.* **113**, 360-368 (2003).
- M. Lee, J. S. Bolton, and L. Mongeau, "Application of cylindrical nearfield acoustical holography to the visualization of aeroacoustic sources," *J. Acoust. Soc. Am.* **114**, 842-858 (2003).
- Y.-J. Kim, J. S. Bolton, and H.-S. Kwon, "Partial sound field decomposition in multireference nearfield acoustical holography by using optimally located virtual references," *J. Acoust. Soc. Am.* **115**, 1641-1652 (2004).
- M. Lee and J. S. Bolton, "Scan-based nearfield acoustical holography and partial field decomposition in the presence of noise and source level variation," *J. Acoust. Soc. Am.* **119**, 382-393 (2006).
- M. Lee and J. S. Bolton, "Source characterization of a subsonic jet by using nearfield acoustical holography," *J. Acoust. Soc. Am.* **121**, 967-977 (2007).
- Y. T. Cho, J. S. Bolton, H.-S. Kwon, and Y.-J. Kim, "Holographic visualization of multi-component sources by using reference measurements only," *Noise Control Eng. J.* **55**, 257-265 (2007).