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An Efficient Procedure for Visualizing the Sound Field Radiated by Vehicles During Standardized Passby Tests

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Objective

- Visualize noise sources on a vehicle during a passby test to guide noise control treatments

Overview

- Standard Vehicle Passby Tests
- De-Dopplerization (*propagation distance calculation*)
 - backward propagation procedure
 - forward propagation procedure
- Amplitude Correction (*compensating for spherical spreading*)
 - intuitive method
 - maximum likelihood estimation
- Array Design
- Experimental Results
- Conclusions

Standard Passby Tests

- accelerating moving source (acoustic holography cannot be used without an array of reference microphones attached to the vehicle)
- near field beamforming (spherical spreading)
- source strength reconstruction on the moving source frame (instead of pressure reconstruction received at stationary microphone array)

Kinematics of Moving Noise Sources

Source signals :

$$p_s(t) = A \exp(j\omega t)$$

Received signals :

$$y_m(t) = \frac{A}{R_m^0} \exp \left[j\omega \left(t - \frac{R_m^0}{c} \right) \right]$$

(Mach number effects on amplitude neglected)

Delay-and-sum beamformer :

$$z(t) \equiv \sum_{m=0}^{M-1} w_m y_m(t - \Delta_m)$$

$$\Delta_m = -R_m / c$$

$$R^2 = [x - x_s(t_e)]^2 + [y - y_s(t_e)]^2 + [z - z_s(t_e)]^2$$

(for constant velocity V)

$$R = \frac{M(x - Vt) + \sqrt{(x - Vt)^2 + (1 - M^2)(y^2 + z^2)}}{1 - M^2}$$

Backward Propagation

- Calculate the propagation distance, $R(t_r)$, for the samples received at t_r (receiver time)
- Generate the emission time vector corresponding to the receiver times

$$t_e = t_r - R(t_r)/c$$
- The resulting non-equi-spaced time history is resampled to obtain an equally-spaced time history in the source (i.e., emission) time frame

Forward Propagation

- (a) Calculate the instantaneous distance, $D(t_e)$, between the assumed source position and the microphone for an assumed signal emitted at t_e
- (b) Generate the corresponding receiver time vector by using the formula,

$$t_r = t_e + D(t_e)/c$$
- (c) The measured microphone outputs sampled at equally-spaced sample times in the receiver time frame are resampled using the unevenly-spaced receiver time vector obtained in (b)

Forward vs. Backward Calculations

simulated results for 35 km/h cruise test. $\oplus$ denotes simulated loudspeaker location; loudspeaker at 2950 Hz, front hub at $x = -1.24$ m, 50 Hz analysis bandwidth.

results from backward
propagation procedure

results from forward
propagation procedure

- The calculation time was reduced by a factor of three by using the forward propagation procedure when compared to the backward propagation procedure.

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Amplitude Estimation

Spherical spreading in near field

$$y_m(t) = \frac{A}{R_m^0} \exp \left[j\omega \left(t - \frac{R_m^0}{c} \right) \right]$$

Weighting factor R_m/M (intuitive weighting factor)

$$\begin{aligned} z(t) &\equiv \sum_{m=0}^{M-1} w_m y_m \left(t - \Delta_m \right) \\ &= \sum_{m=0}^{M-1} w_m \frac{A}{R_m^0} \exp \left[j\omega \left(t - \frac{R_m^0}{c} + \frac{R_m}{c} \right) \right] \\ &= A \exp(j\omega t) \end{aligned}$$

(with $R_m = R_m^0$ and $w_m = R_m/M$)

Maximum Likelihood Estimation

assumptions : source waveform unknown, source position known

source signals : $a(t)$ noise : $n_m(t)$

time shifted measured signals : $y_m(t + R_m/c) = \frac{1}{R_m^0} a\left(t - \frac{R_m^0}{c}\right) + n_m\left(t + \frac{R_m}{c}\right)$

in vector form : $\mathbf{y} = a(t)\mathbf{s} + \mathbf{n}$

where

$$\mathbf{y} = \{y_0(t + R_0/c), y_1(t + R_1/c), \dots, y_{M-1}(t + R_{M-1}/c)\}^T$$

$$\mathbf{s} = \left\{ \frac{1}{R_0^0}, \frac{1}{R_1^0}, \dots, \frac{1}{R_{M-1}^0} \right\}^T$$

$$\mathbf{n} = \{n_0, n_1, \dots, n_{M-1}\}^T$$

Maximum Likelihood Estimation (cont.)

$p_{y|a(t)}$ denotes the joint probability density function of the vector y being observed when the signal source amplitude was $a(t)$ at time t

$$\ln p_{y|a(t)} = -\frac{1}{2} \ln \det[2\pi \mathbf{K}_n] - \frac{1}{2} [y - as]' \mathbf{K}_n^{-1} [y - as]$$

where $\mathbf{K}_n$ noise covariance matrix

Then $\hat{a}_{ML} = \frac{s' \mathbf{K}_n^{-1} y}{s' \mathbf{K}_n^{-1} s}$ maximizes the pdf $p_{y|a(t)}$

$\hat{a}_{ML} = \frac{s' y}{s' s}$ (for spatially white background noise)

$$\Rightarrow \hat{a}_{ML}(t) = \frac{\sum_{m=0}^{M-1} y_m(t + R_m/c) / R_m}{\sum_{m=0}^{M-1} 1/R_m^2} \Rightarrow w_m = \frac{1/R_m}{\sum_{m=0}^{M-1} 1/R_m^2}$$

new weighting factor

Results (1D-simulation, intersensor space 50 cm)

16-microphone array
($f = 500$ Hz, $x_0 = 0$ m)

64-microphone array
($f = 500$ Hz, $x_0 = 0$ m)

----- $w_m = R_m / M$

_____ $w_m = \frac{1/R_m}{\sum_{m=0}^{M-1} 1/R_m^2}$

- Sidelobe levels decreased by more than 5dB as either the number of microphone or array aperture size is increased.

Source Location Estimates

$f = 1\text{ k Hz},$
 $x_0 = -10\text{ m}$

$f = 1\text{ k Hz},$
 $x_0 = -15\text{ m}$

$f = 500\text{ Hz},$
 $x_0 = -10\text{ m}$

$f = 500\text{ Hz},$
 $x_0 = -15\text{ m}$

- Both weighting factors slightly misposition the true source location.
- Discrepancies increase at lower source frequencies and at extreme source positions.

Source Location Estimates (cont.)

- These discrepancies occur since the amplification resulting from the amplitude correction factors exceeds the attenuation resulting from destructive interference, when the source is positioned at an oblique angle to the array plane.
- The source position discrepancies were less than 0.5 m ($f = 500$ Hz) at extreme vehicle locations in the test section of standard passby tests.

Array Design

positions of microphones

array pattern at 2000 Hz

- Random array was randomly generated and snapped to an underlying grid.
- Random array reduces the number of redundancies in the co-array.

Experimental Setup

Velocity Parameterization

- 10th order polynomial was used to approximate the vehicle velocity as a function of time.

Experimental Results (cont.)

Source localization results for 50 km/h cruise test, loudspeaker
at 1005 Hz, $x = 0.29$ m, 50 Hz band

Experimental Results

Visualization results for acceleration test, loudspeaker at 1850 Hz, $x = 2.34$ m

Conclusions

- *Noise source visualization successful for non-constant velocity (capable of resolving loudspeaker and tire noise)*
- *improved computation time by using forward propagation procedure*
- *reduced sidelobe levels by using maximum likelihood estimation for amplitude of the source strength*

Recommendations

- *Develop improved correction factor that can resolve the source location discrepancy problem*
- *Establish array design method for 2-D sparse arrays*