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HOLOGRAPHIC VISUALIZATION OF
SOUND RADIATION FROM COMPUTER
HARD DRIVES

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INTRODUCTION

• Sound radiation from computer hard drives
  - Computer hard drives are relatively compact in size.
  - Source of hard drives are closely spaced.
    e.g., disc, disc bearing, head mechanism, surface vibration
  - Span wide frequency range
    e.g., 120 Hz ~ 10 kHz.
  - Coherent or incoherent
  - Limited position for reference measurement
• Statistically Optimized Nearfield Acoustical Holography
  - High resolution
     - Multi-reference acoustical holographic procedure
- **SONAH formulation (1)**
  - The sound pressure, $p(r)$, can be expressed as linear combination of the measured sound pressure $p(r_n)$,
  
  $$p(r) \approx \sum_{n=1}^{N} c_n(r)p(r_n)$$

  - If a good representation of the sound field can be obtained by using a finite subset of wave functions, the coefficients $c_n$ can be determined.

  $$\Phi_{km}(r) \approx \sum_{n=1}^{N} c_n(r)\Phi_{km}(r_n), \quad m = 1 \ldots M$$
Sound Radiation from Hard Drives

- SONAH formulation (2)

\[ p(x, y, z) = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(K) \Phi_K(x, y, z) dK \]

• Defining wave function,

\[ \Phi_K(x, y, z) \equiv e^{i(k_x x + k_y y + k_z(z + d))}, \quad z \geq z_s = -d \]

where,

\[ k_z = \begin{cases} \sqrt{k^2 - |K|^2} & \text{for } k \geq |K| \\ -i\sqrt{|K|^2 - k^2} & \text{for } k < |K| \end{cases} \]
Sound Radiation from Hard Drives

- SONAH formulation (3)

\[
A \equiv \left[ \Phi_{Kq,m} (r_{h,j}) \right] , \quad \alpha(r) \equiv \left[ \Phi_{Kq,m} (r) \right] , \quad c(r) \equiv \left[ c_j (r) \right].
\]

• Estimated pressure \( p(r) \) is,

\[
 p(r) \approx \sum_{n=1}^{N} c_n (r)p(r_n) = p^Tc(r) = \ p^T \left( A^+A + \theta^2I \right)^{-1} A^+\alpha(r)
\]

where, \( p^T \) is measured pressure vector at \( r_n \)

• Estimated normal particle velocity \( u_z (r) \) is,

\[
 u_z (r) \approx \ p^T \left( A^+A + \theta^2I \right)^{-1} A^+\beta(r)
\]

where, \( A^+\beta(r) \) is a correlation vector that relates measured pressure and particle velocity.
Sound Radiation from Hard Drives

- Hard drive measurement

**Top surface**

\[(z_o = 1 \text{ cm}, N_x = 14, N_y = 17)\]

- Array Microphones
- Reference Microphones
- \(x_{inc} = 1 \text{ cm}, y_{inc} = 1 \text{ cm}\)

**Bottom surface**

\[(z_o = 1 \text{ cm}, N_x = 14, N_y = 17)\]

- Head mechanism
- PCB
- Foam
- Bearing
- Disc
- \(x_{inc} = 1 \text{ cm}, y_{inc} = 1 \text{ cm}\)
Sound Radiation from Hard Drives

- Hard drive measurement result

Singular values of reference measurement

First Singular Values

Second Singular Values

Difference between first and second singular values > 7 dB
However, six singular values with regularization are used for reconstruction
Sound Radiation from Hard Drives

- Sound intensity estimate, 120 Hz

Rocking motion of hard drive
Sound Radiation from Hard Drives

- Sound intensity estimate, 600 Hz

![Image of sound radiation maps showing top and bottom surfaces of a hard drive with color scales indicating radiation levels.]

Radiation due to vibration of hard drive
Sound Radiation from Hard Drives

- Sound intensity estimate, 1172 Hz

Radiation due to vibration of hard drive
Sound Radiation from Hard Drives

- Sound intensity estimate, 1672 Hz

Radiation due to vibration of hard drive
Sound Radiation from Hard Drives

- Sound intensity estimate, 2332 Hz

Radiation by disc from the top surface
Sound Radiation from Hard Drives

- Sound intensity estimate, 2884 Hz

Top surface

Bottom surface*

Power connector and head mechanism
Sound Radiation from Hard Drives

- Sound intensity estimate, 3068 Hz

Top surface

Bottom surface

Disc bearing
Sound Radiation from Hard Drives

- Sound intensity estimate, 3592 Hz

Top surface

Bottom surface*

Disc bearing
Sound Radiation from Hard Drives

- Sound intensity estimate, 5764 Hz

Top surface

Bottom surface*

Disc bearing
Sound Radiation from Hard Drives

- Sound intensity estimate, 8648 Hz

Top surface

Bottom surface*

Disc bearing
Sound Radiation from Hard Drives

Animation coordinate

Source surface: $z = -1 \text{ cm}$
Sound Radiation from Hard Drives

**Velocity, 1672 Hz**

Base model: Top and Bottom

W/o Foam: Top and Bottom

Radiation due to vibration of hard drive
Sound Radiation from Hard Drives

Velocity, 2884 Hz

Base model: Top and Bottom

W/o Foam: Top and Bottom

Power connector and head mechanism
Sound Radiation from Hard Drives

Velocity, 8648 Hz

Base model: Top and Bottom

W/o Foam: Top and Bottom

Velocity at 8648 Hz (z = -1.0 cm, y = 12 cm)

Disc bearing
- Conclusions

• Possible to visualize closely located sources on compact machine accurately by using high resolution, multi-reference acoustical holographic procedure over a wide range of frequencies

• Sound radiation from disc bearing, disc, head mechanism, and hard drive shell were clearly visualized over wide range of frequencies

• Clearly shown that sound radiation above 3 kHz is primarily from disc bearing

• Sound absorption by using relatively thin sound absorption material placed beneath the PCB was clearly visualized