noise source identification techniques

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Objectives

To locate and quantify the major sources of unwanted noise levels.

Definitions

Noise: Unwanted sound

Source: Any physical mechanism that generates audio-frequency sound

Purposes:

i. To aid the choice of appropriate noise control measures

ii. To rank the importance of various noise control measures

iii. To identify the causes of the various sources
HOW MANY SOURCES ARE PRESENT?

Example:

The interior noise in a vehicle is due to the vibrating walls.

This vibration is due to other source mechanisms.

Which is the source and how many are there?

For example, is the vibrating wall a single ‘source’ or a number of sources corresponding to a number of smaller sub-sources? What criteria do we use to decide this?
# MAJOR SOURCE LOCATION TECHNIQUES

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1. HUMAN AUDITORIAL SYSTEM

The human hearing system is directional in terms of perceived loudness above 300Hz. The human hearing system detects the differences in times between the signal arrival at the two ears. The effectiveness with which the ear can localise sounds depends upon:

i. number and directional distribution of significant uncorrelated noise sources. The fewer the better.

ii. relative strengths of direct and reverberant (reflected) sound. Localisation ability reduces with increasing reverberation (reflections).

iii. auto-correlation function of the signal (improves with decreasing correlation length).

Nevertheless, the ear is remarkably good at localising a single broadband source in very reverberant environments providing the direct sound is received.

The hearing system is very poor at localising sources in the geometric near field where there are many arrival directions, in small reverberant environments (such as a car) or when there are many sources of the same frequency in a reverberant room.
2. PARTIAL SCREENING TECHNIQUES

Typically uses lead covering – still in common use

Example: In order to identify crankcase radiated noise on an engine, the remainder of the engine could be lead covered, and the intake and exhaust pipes ducted away.

There are a number of problems with this approach

- Engine sources are likely to be correlated – the resulting spatial interference pattern will change and the radiation impedance of individual components can be altered. Ineffective at low frequencies.

- Covering can change running temperature and conditions.

- A badly designed system for ducting away an exhaust could change the back-pressure or engine running conditions, thus changing intake and engine radiated noise.
3. DIRECTIONAL MICROPHONES

Sensitivity (voltage output per unit pressure) depends on plane wave angle of arrival. Examples:

i. **Cardioid Microphones**

ii. **Ribbon Microphones for measuring particle velocity**

iii. **Pressure difference Microphone**

Directivity only useful at very high frequencies. Main lobe generally too broad to give acceptable spatial resolution. Ambiguity between strong off-axis sources and weak on-axis sources.
**END FIRE** (or tube, or wave interference microphones)

Single tube with a series of holes along the length and a microphone located at one end.

Pressure directivity $D(\theta)$ given by

$$D(\theta) = \sin \left[ \left( \frac{\pi L}{\lambda} \right) \left( 1 - \cos \theta \right) \right] / \left[ \left( \frac{\pi L}{\lambda} \right) \left( 1 - \cos \theta \right) \right]$$

**Advantages**

i. Cheaper and simple to construct
ii. Good rejection of sound from the rear

**Disadvantages**

i. Difficult to calibrate
ii. Tube length too long below 1kHz
iii. Very sensitive to flow (wind)
iv. Not effective in very reverberant sound fields
ACOUSTIC MIRRORS

Microphone located at the focus of parabolic ‘mirror’.

![Diagram of parabolic and elliptic mirrors](image)

**Advantages:** - Simple and therefore robust measurement principle - No signal processing required.

**Disadvantages:** Large and heavy. It has been estimated that a mirror diameter of at least 8m is needed for aero-engine source location. Aperture must be much longer than acoustic wavelength to be effective. Mirror must be constructed very accurately. Performance degrades in reverberant environments due to off-axis sources and diffraction effects by the large mirror.
Let \( f_n(t) \) denote the pressure signal received at the \( n \)th sensor as a function of time \( t \) due to an incoming plane wave. The (un-shaded) beamformed output \( b(t) \) by a linear array of uniformly spaced sensors is given by:

\[
b(t) = \sum_{n=1}^{N} f_n(t - \tau_n)
\]

\[
\tau_n = \frac{d_n \sin \theta}{c}
\]

Taking the Fourier Transform of \( b(t) \) gives:

\[
B(\omega) = \sum_{n=1}^{N} F_n(\omega) \exp[-i\omega \tau_n]
\]

where \( F_n(\omega) = \int f_n(t)e^{-i\omega t} dt \)
BEAMFORMING (cont’d)

Plane wave beamforming is exactly equivalent to cross-correlating the measured field $F_n(\omega)$ with the elementary plane wave field $\exp[i\omega\tau_n]$

The beam ‘power’ $|B(\theta)|^2$ due to a plane wave arriving at $45^\circ$ to the axis plotted against ‘look’ direction, or beam-steer angle $\theta$, is presented below.

Main response in the direction of the incoming plane wave.

The appearance of sidelobes which in the presence of correlated noise across the array, or a number of coherent plane waves at different angles, leads to ambiguity in the arrival angle of the incoming plane wave.

Sidelobe rejection and beamwidth (and hence resolution and accuracy) that
Same principle applied. For an arbitrary array of sensors with position vectors $\mathbf{r}$, the beam power output of the array in the direction of $\mathbf{u}$ is given by

$$|B(\mathbf{u})|^2 = E\left\{ \left( \mathbf{w}^H \mathbf{p} \right) \left( \mathbf{w}^H \mathbf{p} \right)^H \right\} = \mathbf{w}^H \mathbf{Rw}$$

where $w_i = a_i e^{j k r_i \cdot \mathbf{u}}$ and $\mathbf{R}$ is the spatial covariance matrix $R_{ij} = E\{ p(\mathbf{r}_i) p(\mathbf{r}_j) \}$.
Boeing acoustic phased array results. Scale model tested in LSAF in August, 1994. Full flap deflection, landing gear deployed. 1500 Hz model scale (93 Hz full scale). Noise cancellation beamforming technique applied to eliminate three noise sources (nose and two main gear sources). Remaining sources are labeled according to strength.
SOUND INTENSITY FOR SOURCE LOCATION

Time-stationary sound intensity vectors (3-D) are measured with intensity probes (see intensity lecture). Intensity contours showing the magnitude and direction of energy flow may be used to reveal the location and magnitude of the various noise sources. There are two principal modes of operation.

i. Reverse Vector Projection

Determine intensity vector distribution in geometric near field and project back energy flow contours to the source surface.

Intensity is the vector sum of intensities due to uncorrelated sources. It cannot therefore resolve such sources. Intensity techniques for source location is useful when there is only one dominant source. Narrow band, or tonal, intensity distributions in reverberant environments are very complicated. It can be difficult to project back to the source region. Broadband sources are more reliable.

ii. Near field rank ordering

Estimate sound power radiated by segments of the source surface by near field scans. Rank order the ‘sources’ on this basis. Technique is effective for efficient radiators. Caution should be exercised - not all local near field power propagates to the far field.
MODERN TECHNIQUES

Since the advent of the fast and inexpensive processing capabilities available on modern desktop computers new techniques have recently been proposed for source indication.

In this lecture we shall only briefly mention three and give details of a fourth.
COHERENCE ANALYSIS

A ‘source’ is regarded as any quantity such as vibration, fluid motion etc that is coherent with the acoustic pressure in some region of space. This method uses correlation functions or cross-spectra between near field and far field sensors to determine the relative contributions of incoherent sources. This has been done for example, to separate in-flow noise and trailing edge on an airfoil.

\[
\gamma^2 = \frac{|E[p_1(\omega)p_2^*(\omega)]|^2}{E[p_1(\omega)p_1^*(\omega)]E[p_2(\omega)p_2^*(\omega)]}
\]

Note

\[0 \leq \gamma^2 \leq 1\]
PRINCIPAL COMPONENT ANALYSIS (PCA)

Reduces a set of measured inputs to a set of principal incoherent inputs by weighting the actual inputs in such a way as to minimise the weighted signal correlation. The corresponding ‘source’ distributions are called virtual sources. Their relationship to the actual physical sources is often difficult to establish.

The aim is to decompose a vector of pressure measurements $\mathbf{x}(\omega)$ into a linear sum of equivalent uncorrelated signals $\mathbf{y}(\omega)$, i.e.,

$$\mathbf{x}(\omega) = \mathbf{U}(\omega)\mathbf{y}(\omega)$$

Evaluate the pressure cross spectral matrix $G_{pp}$

$$G_{xx} = E[\mathbf{x}\mathbf{x}^H] = \mathbf{U}G_{yy}\mathbf{U}^H$$

Since any Hermitian matrix $\mathbf{X}(\omega)$ may be decomposed in the form $\mathbf{X}=\mathbf{V}\Lambda\mathbf{V}^H$, the spectra of equivalent uncorrelated sources $G_{yy}(\omega)$ are equal to the singular values of $G_{xx}(\omega)$, $\Lambda(\omega)$.
SOURCE POWER BREAKDOWN FROM VELOCITY MEASUREMENTS

1. The mean square velocity is measured over a vibrating structure.

2. The structure is then suitably divided into a number of simple sub-structures that resemble simple vibrating elements, such as flat plate.

3. Together with an estimate for the radiation efficiency, this information is used to assess the individual component sound power contributions to total radiated sound power.
NEAR FIELD ACOUSTICAL HOLOGRAPHY (NAH)

A technique for reconstructing the source by taking the wavenumbers transforms of the acoustic pressure made close by. The technique is fundamentally dependent upon the following Fourier relationships:

Wavenumber spectrum of pressure related to spatial variation by

\[ p(k_1, z) = \int_{-\infty}^{\infty} p(x, z) e^{jk_1x} \, dx \]

Wavenumber spectrum of surface velocity related to spatial variation by

\[ u(k_1) = \int_{-\infty}^{\infty} u(x) e^{jk_1x} \, dx \]

Measurable pressure wavenumber spectrum and surface velocity (source) wavenumber spectrum related by

\[ p(k_1, z) = \frac{\omega \rho_0 u(k_1) e^{-j\sqrt{(k^2 - k_1^2)z}}}{\sqrt{(k^2 - k_1^2)}} \]

Note that wavenumber components propagate for \( |k_1| \leq k \) and decay for \( |k_1| > k \)
NEAR FIELD ACOUSTICAL HOLOGRAPHY (NAH)

A practical application of NAH (courtesy of Bruel and Kjaer)
Assume a model of the form

\[ \mathbf{p} = \mathbf{G} \mathbf{q} \]

which can be written in full as

\[
\begin{bmatrix}
    p_1 \\
    p_2 \\
    \vdots \\
    p_M
\end{bmatrix} =
\begin{bmatrix}
    G_{11} & G_{11} & \cdots & G_{1N} \\
    G_{21} & G_{22} & \cdots & G_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    G_{M1} & G_{M2} & \cdots & G_{MN}
\end{bmatrix}
\begin{bmatrix}
    q_1 \\
    q_2 \\
    \vdots \\
    q_N
\end{bmatrix}
\]
Find the discrete source strengths that “best fit” the measured pressures. Assume:

\[ \hat{p} = Gq + e \]

Need to find optimal \( q \) that minimises

\[ J = e^H e = \sum_{m=1}^{M} |\hat{p}_m - p_m|^2 \]

For \( M > N \), this quadratic function of \( q \) is minimised by

\[ q_0 = [G^H G]^{-1} G^H \hat{p} \]

Or when \( M = N \)

\[ q_0 = G^{-1} \hat{p} \]

Note that solution is unique for the assumed source model
Assuming stationary random time histories, the optimal estimate of the acoustic source strength is given by

\[ S_{qq0} = \lim_{T \to \infty} E \left[ \frac{1}{T} \mathbf{q}_{io} \mathbf{q}_{io}^H \right] \]

where \( E[ \ ] \) denotes expectation over time.

\[ S_{qq0} = \mathbf{G}^{-1} \mathbf{S}_{\hat{p}\hat{p}} \left( \mathbf{G}^{-1} \right)^H \]

where \( \mathbf{G}^+ = [\mathbf{G}^H \mathbf{G}]^{-1} \mathbf{G}^H \) is the pseudo inverse of \( \mathbf{G} \) and the measured cross-spectral matrix is given by

\[ \mathbf{S}_{\hat{p}\hat{p}} = \lim_{T \to \infty} E \left[ \frac{1}{T} \hat{\mathbf{p}}_i \hat{\mathbf{p}}_i^H \right] \]
EXPERIMENTAL EXAMPLE
EXPERIMENTAL RESULTS – NEAR FIELD

Directly measured

Reconstructed

a) Autospectrum of source 1
b) Autospectrum of source 11
c) Magnitude of cross-spectrum between sources 1 and 11
d) Phase of cross-spectrum between sources 1 and 11
FAR FIELD MEASUREMENTS
EXPERIMENTAL RESULTS – FAR FIELD

Directly measured
Reconstructed

a) Autospectrum of source 1
b) Autospectrum of source 11
c) Magnitude of cross-spectrum between sources 1 and 11
d) Phase of cross-spectrum between sources 1 and 11
APPLICATION TO PROPELLER AIRCRAFT INTERIOR NOISE

(Taken from E G Williams et al, Proc. Sixth Int. Congress on Sound and Vibration, 2, 859-868, 1999).
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Figure 11: The hologram pressure, looking aft, measured at 103.7 Hz using the outer 43 microphones of the array, acquired during the in-flight experiment. The real part of the field is plotted after the phase of all the data in the hologram was shifted by a fixed amount so that the maximum pressure level has zero phase (was only real). One can see that the pressure is 180 degrees out of phase on either side of the aircraft. The quality of the data is outstanding. The smoothness of the pressure is proof that the synchro-phaser was an excellent time reference for the triggering of the data acquisition system.
APPLICATION TO PROPELLER AIRCRAFT INTERIOR NOISE

(Taken from E G Williams et al, Proc. Sixth Int. Congress on Sound and Vibration, 2, 859-868, 1999).

Figure 12: Magnitude on a decibel scale of the reconstructed normal velocity looking aft. Only the top 20dB of data is shown as indicated by the color bar. The velocity is normalized by the velocity of an accelerometer located on a fuselage panel in the prop plane. The unwrapped display on the right indicates the positions of the windows and some of the major frames as well as the location of the floor and spar (support between the wings).

Figure 13: Magnitude in dB of the normal velocity reconstruction for the first overtone of the BPF, at 207 Hz. The top 20dB of data is displayed. The highest vibration levels are just in front of the propeller plane (latter indicated by vertical dashed line). The floor just in front of the spar also appears to be vibrating at a high level.