Active Noise Control: Physical Principles and Practical Applications

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Award of Queen’s Prize to ISVR

Awarded for

“Improving the quality of life for the profoundly deaf and reducing noise pollution”.
Active Noise Control: Physical Principles and Practical Applications

- Active vs Passive noise control
- Physical limits of Global Active Control
- Applications in cars and aircraft
- Physical limits of Local Active Control
Passive control relies on **barriers**, **absorption** and **damping**.

It works well when the acoustic wavelength is **short** compared with typical dimensions ⇒ **Higher frequency solution**.
Active Control of Sound

Acoustic or structural actuators are driven to cancel waves:

It works well when the acoustic wavelength is long compared with typical dimensions ⇒ **Lower frequency solution.**
A time-advanced estimate of the disturbance waveform from the primary sound source ($A$) is measured by the microphone ($M$) and fed forward to the loudspeaker ($L$) via the controller ($V$) so that its pressure field ($s_2$) destructively interferes with incident disturbance ($s_1$)

**Good active control performance relies on:**

1) Spatial matching *(physics)*
2) Temporal matching *(signal processing)*
Performance of active control systems

Performance

ACTIVE

PASSIVE

100Hz  1kHz  Frequency  10kHz

340mm  35mm  3.4mm

One-tenth of an acoustic wavelength
Idealised sound source: the monopole

• Assume that the primary source, which needs to be controlled such as an engine exhaust, is compact and radiates as a simple monopole source
Power output from two monopole sources

\[ W = \frac{1}{2} \text{Re}\{p_p^*(r_0)q_p\} + \frac{1}{2} \text{Re}\{p_s^*(r_0)q_s\} \]

But now

\[ p_p(r_0) = p_{pp} + p_{ps} \quad \text{and} \quad p_s(r_0) = p_{ss} + p_{s1} \]

due to \( q_s \)
due to \( q_p \)

So that

\[ W = \frac{1}{2} Z_0 \{|q_p|^2 + q_p^*q_s \text{sinc}(kd) + q_p^*q_s \text{sinc}(kd) + |q_s|^2\} \]

where sinc\((kd) = \sin kd / kd \)
Minimised power output

The optimum secondary source strength and the attenuation in power output can be plotted as function of \( kd \), which can either be considered as \( 2\pi d/\lambda \) i.e. normalised distance, or \( 2\pi f d/c_0 \), i.e. normalised frequency.

So \( q_s \) has to be separated from \( q_p \) by less then about \( \lambda/10 \)

i.e. one-tenth of an acoustic wavelength, to get 10 dB attenuation.
Sound radiation after control at low frequencies

At low frequencies the secondary source is out of phase with the primary and the two create a dipole source that radiates sound much less efficiently that the monopole primary source.
Early Experiments on the Active Control of Transformer Noise

Due to changes in the response of the system under control and the disturbance, it is generally necessary to continuously adapt the controller to maintain control, as recognised for the control of transformer noise by William Conover in 1956. The control system then becomes closed loop.
Results from Conover

Fig. 2. Acoustic sound cancellation test being conducted on a 15,000-KVA transformer.

Fig. 3. Sound-level readings taken at different angular positions at constant radius. Measurements made with the speaker turned off and on and without changing the loudspeaker.
Experimental Results
(After Hesselmann)

Two loudspeakers used to control sound radiated by a 100 kVA transformer tank.

Results are shown for the sound pressure level averaged over several directions at 100 Hz.

Fig. 4. (a) Directivity pattern of transformer fundamental noise (plotted line). Points represent value from compensation set-up alone. (b) Directivity patterns of reduced sound pressure level. Curve measurement. Curve b: compensation (dashed line). Curve a: same as in Fig. 4a.)
Physical limits of Active Control inside a Cabin

The enclosure is similar in size to a car interior:
1.9m × 1.1m × 1.0m
Guidelines on Number of Secondary Sources

The number of secondary sources required for a given level of control is approximately given by the number of modes significantly excited at the excitation frequency, which equals the modal overlap,

\[ M(\omega) = \frac{4\zeta L}{\lambda} + \frac{4\pi \zeta S}{\lambda^2} + \frac{8\pi \zeta V}{\lambda^3} \]
Some cars currently using active noise control

Lexus Infiniti (low frequency exhaust noise)

Honda Accord (V6 Variable cylinder management)

Jaguar XJ6 (diesel engine mount)

Chevy Equinox (low speed tick over)
Active control in cars

The trend towards *lighter weight vehicles*, for greater fuel efficiency, inevitably increases low frequency internal noise and the need for active control.

Previously considered too costly, but costs now reduced by *integration* of DSP amplifiers and loudspeakers with audio system.

Recent systems do not just attenuate all orders but control them to target levels at each speed and load to give required *sound quality*, this is particularly important in hybrid vehicles.
Active control of propeller induced cabin noise; Q400

Recent announcement that 1000\textsuperscript{th} Active Noise Control system now in service  (Ultra Electronics, Cambridge UK)
Periodic Excitation of Fuselage by Propeller

www.bombardier.com
Spectrum of Pressure Inside Propeller Aircraft before and after active control

Dash-8 Series 200: Reduction 11.3 dB(L), 8.2 dB(A)
Centralised digital system made by Ultra Electronics controls 5 harmonics with 48 structural actuators at 72 acoustic sensors, distributed throughout cabin.

Active Noise Control System for Propeller Aircraft

Adaptive feedforward controller with 46 structural actuators and 72 microphones working at 4 harmonics, built by Ultra Electronics.
Overall levels of active control of propeller induced cabin noise
LOCAL ACTIVE SOUND CONTROL
Spatial Extent of the Zone of Quiet

Contours of the 10dB reduction (———) and 20 dB reduction (-------) in a plane through the piston secondary source (at x=0, y=+a to –a). The frequencies refer to a piston of diameter 100mm.
Spatial Extent of the Zone of Quiet On-Axis

Plotted below is the axial extent to the zone of quiet, within which the pressure has been reduced by 10dB, calculated after a 100mm diameter loudspeaker has been adjusted to cancel the pressure a distance $r_0$ on axis.

Note that the diameter of the predicted zone of quiet is never larger than one-tenth of an acoustic wavelength, a limit which can be derived analytically for cancellation by a remote secondary source in a diffuse sound field (Elliott et al., 1988).
Test Arrangement in vehicle

25 microphones mounted in two planes over 0.4m by 0.4 m grid in front of the headrest and two loudspeakers acting as secondary sources mounted in the headrest.

Ford S-MAX
Spatial distribution of road noise attenuation

(a) 100 Hz

(b) 200 Hz

(c) 300 Hz

(d) 400 Hz
Current work: tracking of head position

To maintain the quiet zones at the ear locations as the head moves, head tracking is currently being investigated using a Kinect system.
The performance of active control systems is determined by:

1) Technological advances (e.g. signal processors)
2) Fundamental physical limits (related to acoustic wavelength)

For good global control, the secondary source should be positioned within one-tenth of an acoustic wavelength of a compact primary source.

For local active sound control, the zone of quiet is limited to about one-tenth of an acoustic wavelength.
Performance of active control systems

Performance vs Frequency

100Hz  1kHz  10kHz
34cm   35mm  3.4mm

One-tenth of an acoustic wavelength