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Overview of Recent Advances in Active Noise Control and Future Trends

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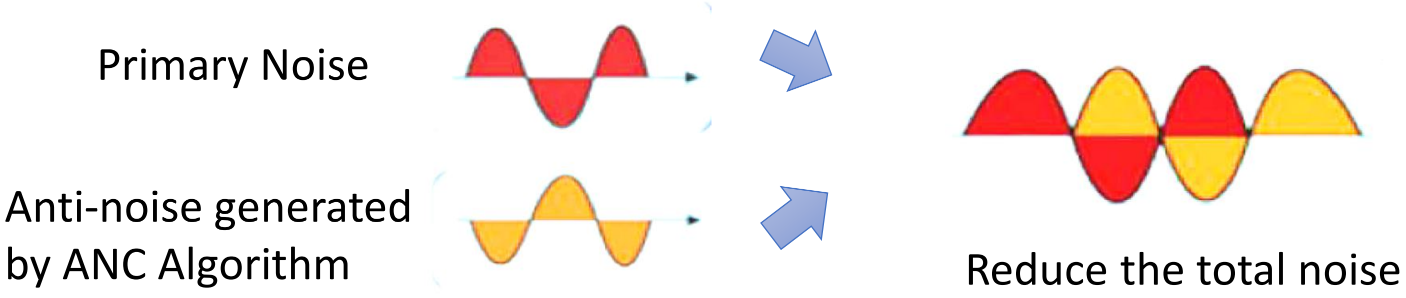
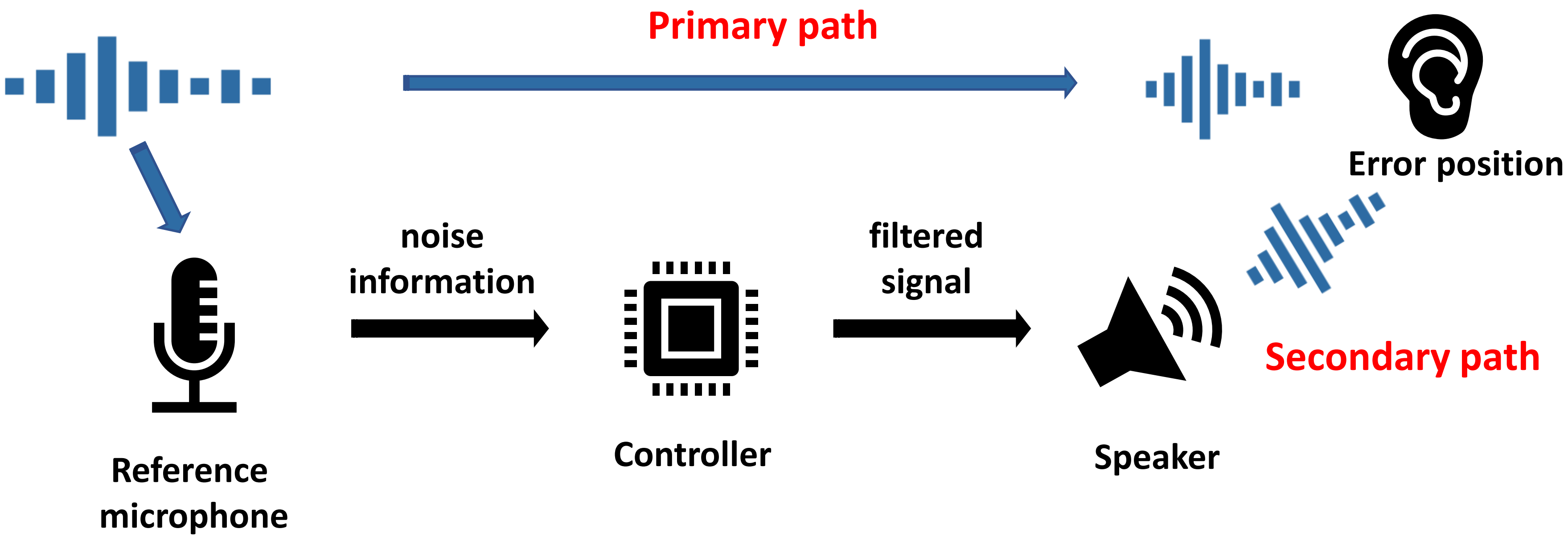
TECHNOLOGY FOR A QUIETER AMERICA TQA Engineering a Better Quality of Life

Introduction to Active Noise Control

- Intuitive understanding



- Typical system diagram



A Brief History of Active Noise Control

Technology for a Quieter America
TQA
Engineering a Better Quality of Life

1930s

- ANC can be **traced back** to Lueg's patent in 1936.

1950s

- Investigation of the **possibility** of ANC in transformer, rooms, ducts, headsets, and earmuffs.

1970s

- General theory developed, focused on **theoretical results**.

1980s

- Some **prototype systems** were developed after the development of control theory and microelectronics.
- However, the available transducers and actuators are **limited**.

1990s

- **Applied to engineering applications**: duct, headphone, automobile, after the development of inexpensive and robust electronic controllers, speakers, and microphones.

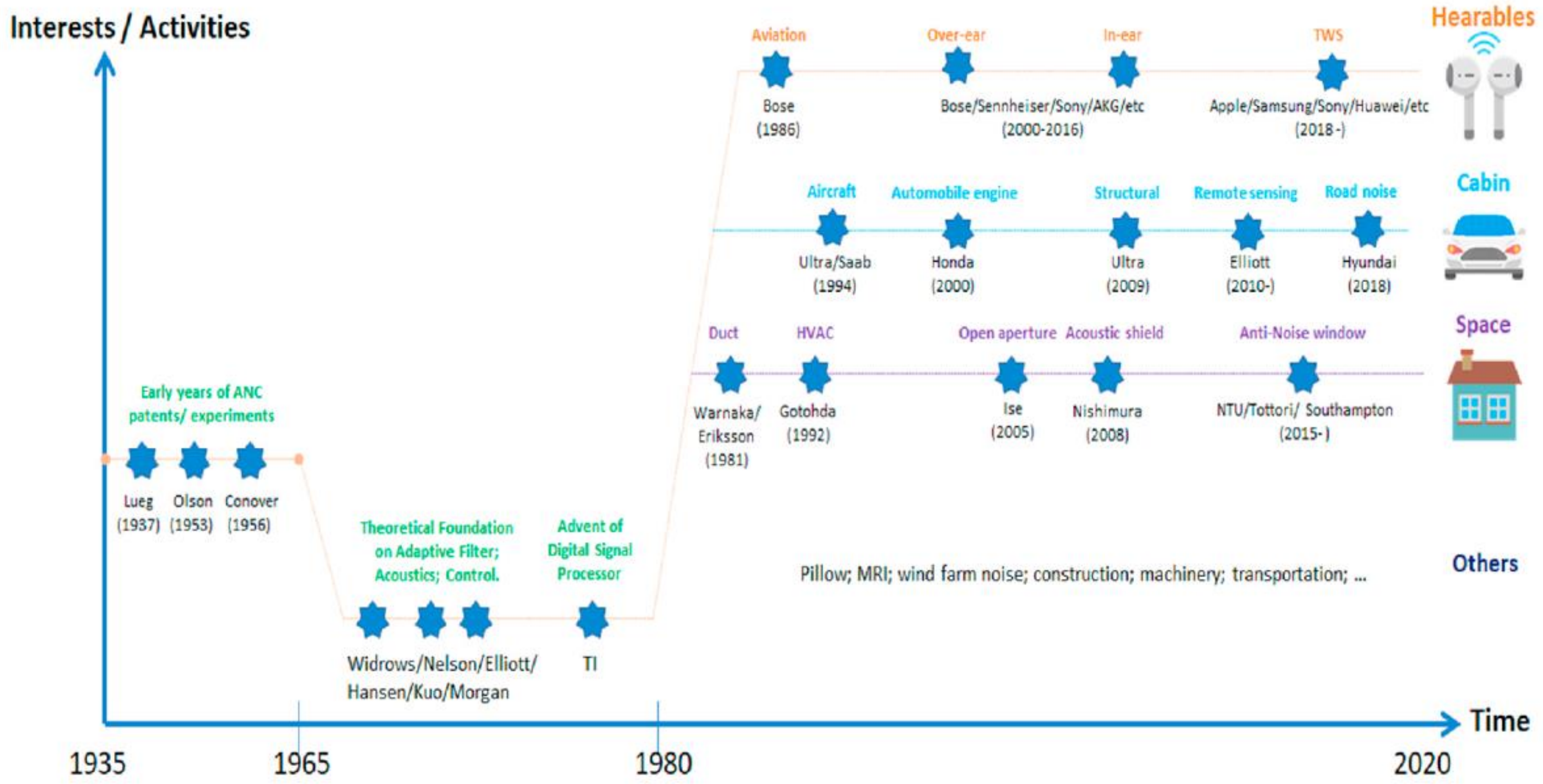
2000s

- **Commercialized ANC products** in various industries because the cost in electronic devices is lowering rapidly.

Categories of ANC Techniques

- Number of controller channels
  - Single input single output (SISO) system
  - Multi-input multi-output (MIMO) system
- Size of targeted control region
  - Local control
  - Global control
- Time-varying characteristics of noise
  - Non-adaptive filter
  - Adaptive filter
- Time advanced information of noise
  - Feedforward control
  - Feedback control
- Bandwidth of targeted noise
  - Broadband control
  - Narrowband control

Active Noise Control Applications: Overview

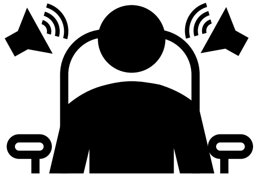


Application: Hearables

- One of the most popular type of ANC applications

Headphones and earphones:

- Research can be traced back to the 1980s. Various commercial products now.
- ANC in enclosed small space, error microphone can be close to ear drums.



Headrests:

- Relatively open space.
- Coupling between left and right sides.
- Coupling between control speakers and microphones (acoustic feedback path).
- Error microphones are away from ear drums. Virtual sensing shall be used.

Application: Hearables

- Current research focuses mainly on commercialization

Specialized ANC chip design:

- Trade off between high sampling rate (low latency) and computing effort.
- Choice of different filter structure (FIR or IIR filters)
- Incorporating parallel computing.

Various other related techniques:

- Adaptation or filter selection for different environments and sources.
- Impulsive sound rejection.
- Identify application environment (AI technologies), combine ANC with scene dependent VR, speech enhancement, etc.
- Trade off between active noise control and passive noise control performance.

Application: Cabins

- ❑ Examples of cabins related applications

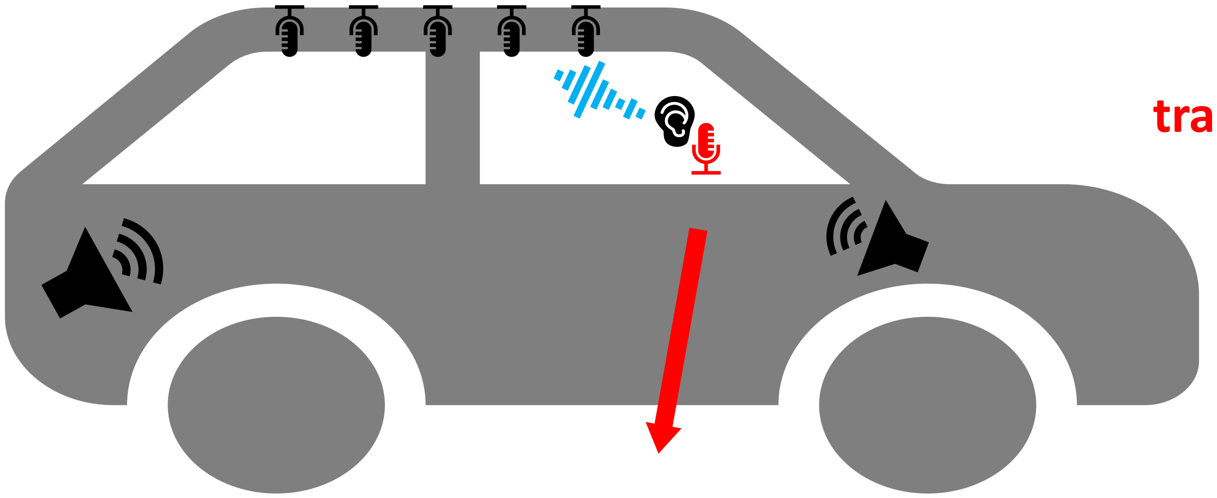
Automobiles, trains, and aircrafts:

- Cancelling engine noise (tonal and impulsive noise)
- Cancelling road-tire noise (higher frequency noise)
- Cancelling wind noise (complicated noise components depending on speed)
- Currently, ANC is usually used for tonal engine noise, and some broad band road-tire noise.
- Active sound design (create a more pleasant sound environment)

- ❑ One of the challenges is that the error microphones cannot be positioned near passengers’ ears, while ANC usually control the noise near error microphones.

Application: Cabins - Virtual Sensing

❑ An illustration of basic concept



- Sensor positioned at **training stage**
- It will be removed in **operation stage**

training stage

- **Place sensors at error sensor location and virtual sensor locations**
- **Pre-train filters between error sensor and virtual sensor**

operation stage

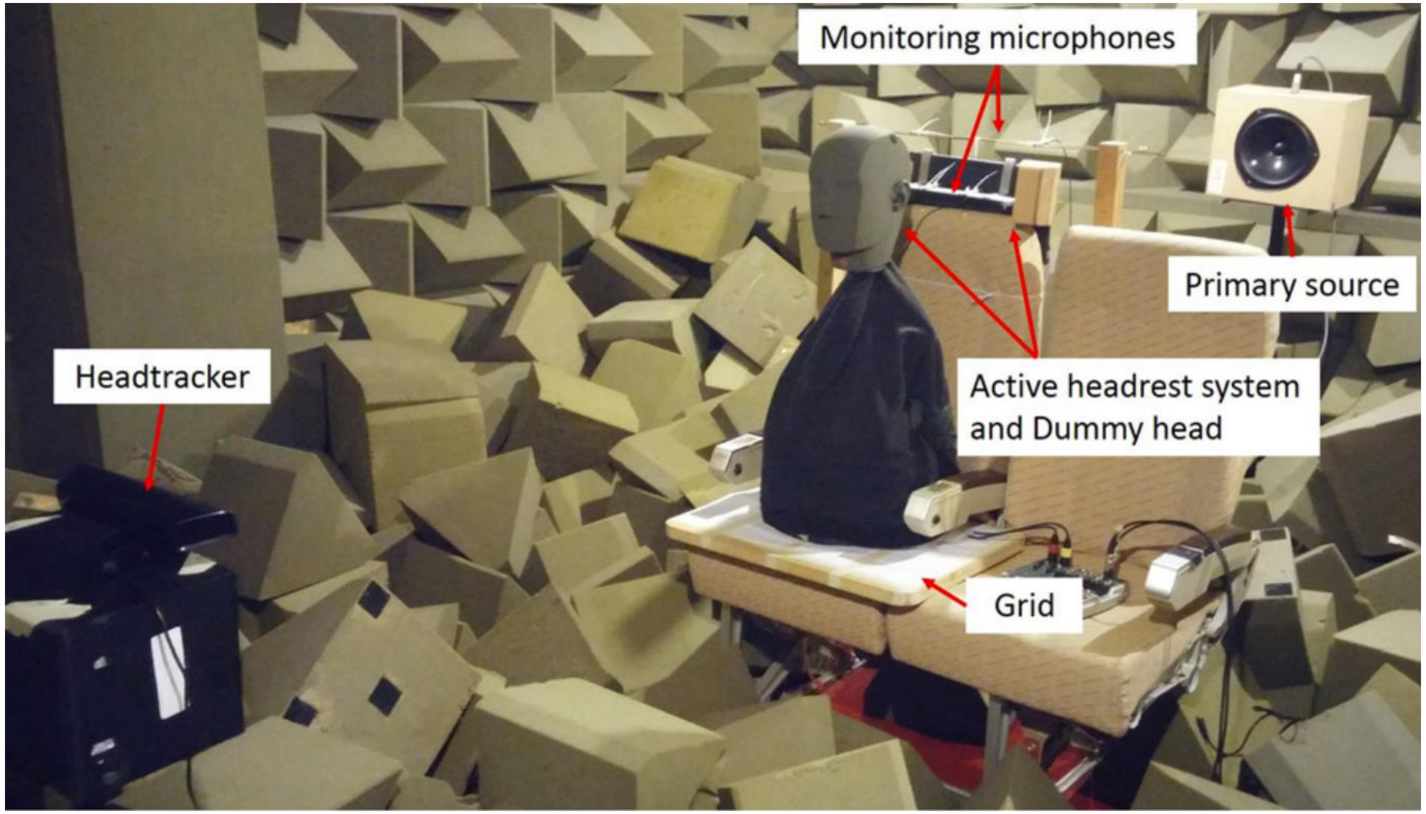
- **Remove sensors at virtual sensor locations**
- **Choose pre-trained filters to do ANC**

Challenges:

- Deal with time-varying environment (head tracking, selective filter, …).
- Investigate the robust performance when disturbance exists.
- When error microphone cannot be placed even at offline training stage.

Application: Cabins – Global/Spatial ANC

- ❑ Combined with virtual sensing techniques
  - Placing multiple error microphones in training stage
  - Head tracking to create quiet zone around the head

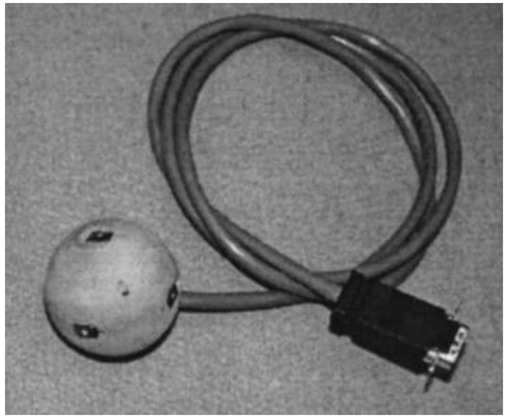


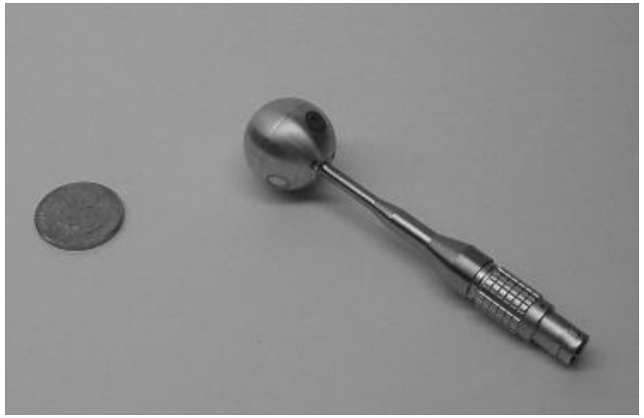
Picture from paper: Jung, Woomin, Stephen J. Elliott, and Jordan Cheer. "Combining the remote microphone technique with head-tracking for local active sound control." *The Journal of the Acoustical Society of America* 142.1 (2017): 298-307.

Application: Cabins – Global/Spatial ANC

- New sensors to minimize acoustic energy density
  - Sound intensity measurement using multiple microphones.

    Not only control sound pressure level, but also the energy flux at a location.





Picture from paper:

Parkins, John W., Scott D. Sommerfeldt, and Jiri Tichy. "Error analysis of a practical energy density sensor." *The Journal of the Acoustical Society of America* 108.1 (2000): 211-222.

Wiederhold, Curtis P., et al. "Comparison of multimicrophone probe design and processing methods in measuring acoustic intensity." *The Journal of the Acoustical Society of America* 135.5 (2014): 2797-2807.

- Acoustic model based method
  - Wave field synthesis, or harmonics expansion method (use modes of the cabin).
  - Minimizing both sound pressure and sound pressure gradient in optimization.

Application: Space

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Ten questions concerning active noise control in the built environment

Bhan Lam [a], Woon-Seng Gan [a,*], DongYuan Shi [a], Masaharu Nishimura [b], Stephen Elliott [c]

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A R T I C L E I N F O

Keywords:
Natural ventilation
Active and passive noise control
Noise control applications
Noise barrier
Building façade
Soundscape

A B S T R A C T

Urban noise pollution is an omnipresent but often neglected threat to public health that must be addressed urgently. Passive noise control measures, which are less effective at reducing low-frequency noise and are often bulky and may impede airflow. As evidenced in automobiles, active control of cabin noise has resulted in lighter cars due to reduced passive insulation. Despite its long history and recent popularisation by consumer headphones, the implementation of active noise control in the built environment is still rare. To date, active noise control (ANC) has been demonstrated, at source, in construction machines and, in the transmission path, in noise barriers. Recent demand for naturally-ventilated buildings has also spurred the development of active control solutions at the receiving end, such as on windows. The ten questions aim to demystify the principles of ANC and highlight areas in which environmental noise can be actively mitigated. Since the implementation of active control in the built environment usually involves multiple stakeholders, operational concerns are addressed. To conclude, research gaps are identified that would enable increased adoption of ANC in the built environment. There is also renewed interest in applying intelligent ANC to tackle environmentally complex applications, such as varying noise levels in the earcup of ANC headphones, particularly with the advent of the low-cost, low-power, highly-efficient embedded electronics; advancing speaker technology; and new impetus from digital signal processing and artificial intelligence Algorithms.

[1] Ten questions concerning active noise control in the built environment
https://doi.org/10.1016/j.buildenv.2021.107928

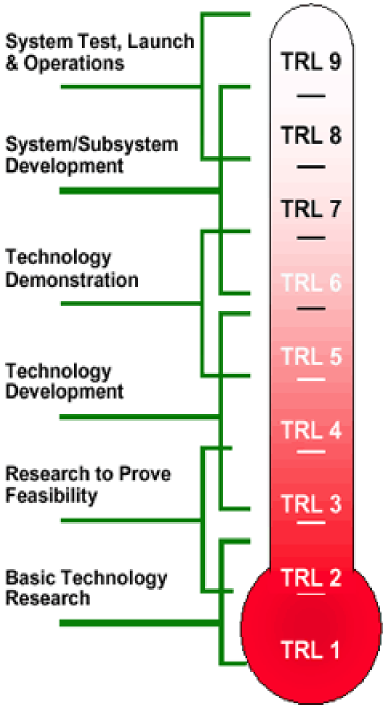
Application: Space – ANC at Source, Path, Receiver

Table 3
A collection of active noise control applications in the built environment with experimental demonstrations and their estimated technology readiness levels (TRL).

Noise intervention zone	Targeted noise type	ANC control zone	ANC application	Reference	Reported noise reduction	Estimated TRL
Source	Construction[a]	Local	Construction machine exhaust	INC Engineering Co. Ltd [72]	19 dB at 103 Hz and 17 dB at 206 Hz	7–8
	Construction[a]	Local	Genset exhaust	Matsuoka et al. [74]	23 dB at error microphone (Idle) 17 dB at error microphone (40 kW load)	8–9
	Construction[a]	Global	Construction machine exhaust	Kobayashi et al. [87,88]	27.1 dB at error microphone 11.4 dB–16.8 dB 8 m away	8–9
	Construction[a]	Not stated	Construction machine exhaust	ANC-Labo [73]	21 dB (near machine) 17.7 dB (in building)	7–8
	Transformer	Shadow zone	Noise barrier	Zou et al. [25]	0.3–4.3 dBA below 400 Hz	6–7
	Transformer	Global	Virtual barrier	Tao et al. [26,27]	~18 dB	6–7
	Transformer	Global	Virtual barrier	Ying et al. [89] [c]	5 dBA in desired area	6–7
	Transformer	Not specified	Virtual barrier	Sonobex	6 dB (100 Hz); 13 dB (200 Hz) Overall (4.3 dBA)	8–9
Propagation Path	Construction[a]	Shadow zone	Noise barrier	INC Engineering Co. Ltd [48]	Virtually extends height of noise barrier by 3–5 m	8–9
	Road traffic[a]	Shadow zone	Noise barrier	Ohnishi and Saito [81] [c] Ohnishi et al. [82] Saito et al. [90]	3 dB–4.3 dB at pavement	8–9
Receiver	Road traffic[a] Train[a] Aircraft fly-by[a]	Room interior (Global)	Façade Element (Window)	Lam et al. [54] [c]	Traffic (100–1000 Hz): 8.67 dB; Train (100–1000 Hz): 10.14 dB; Aircraft (100–1000 Hz): 7.51 dB	5–6
	Aircraft fly-by[a] Motorbike[a] Road traffic[a] Compressor[a]	Room interior (Global)	Façade Element (Window)	Lam et al. [53] [c]	Aircraft (100–700 Hz): 5.76 dB; Motorbike (100–700 Hz): 4.84 dB Traffic (100–700 Hz): 4.56 dB; Compressor (100–700 Hz): 10.51 dB	5–6
	Real aircraft pass-by[a]	Room interior (Global)	Façade Element (Window)	Paimes et al. [91] [c]	~3 dB (0.2–0.16 kHz)	6–7
	Road traffic[a]	Not stated	Façade Element (Window)	Carme et al. [86]	15.5 dB (<300 Hz)	5
	Floor impact noise[b]	Room interior (Global)	Ceiling	Terai et al. [92]	3.8 dB (63 Hz octave band) ~10 dB (25 Hz peak)	3

[a] Environmental noise.
[b] Interior noise.
[c] Peer-reviewed.

Table from [1]



Application: Space – ANC at Source

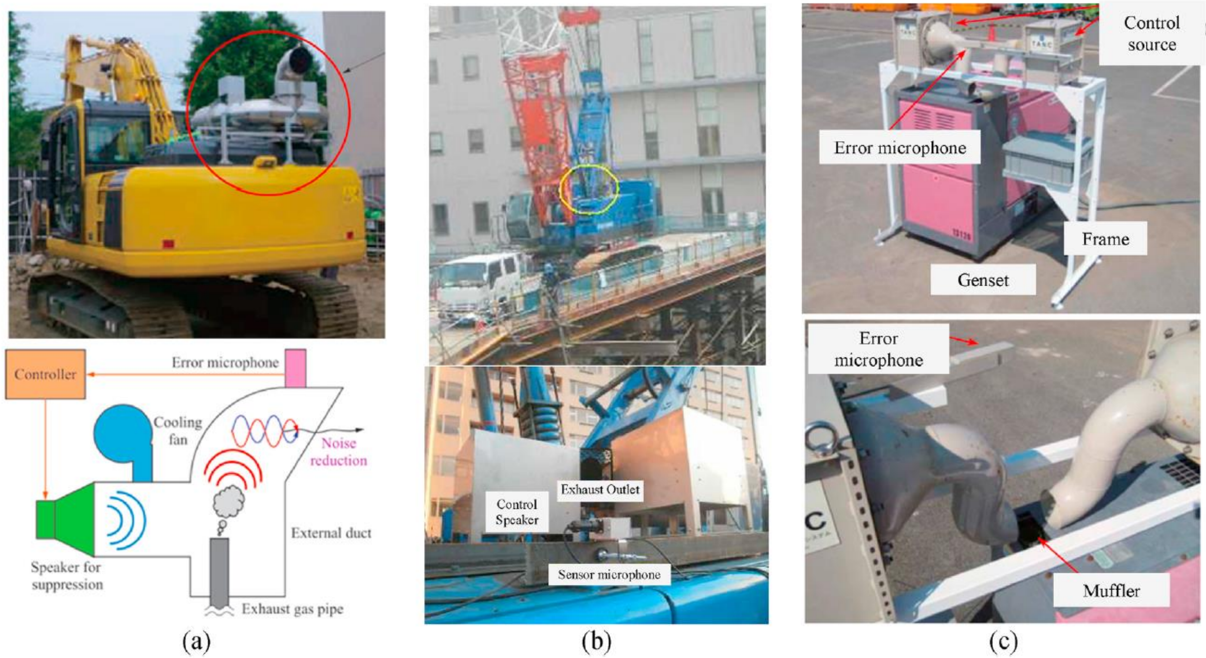


Fig. 5. Operational demonstrations of (a) an active silencer prototype for the active control of noise at the exhaust of an excavator [72], (b) implementation of ANC at the exhaust of a crawler crane [73], and (c) an active control implementation at the exhaust outlet of electrical power generators [74].

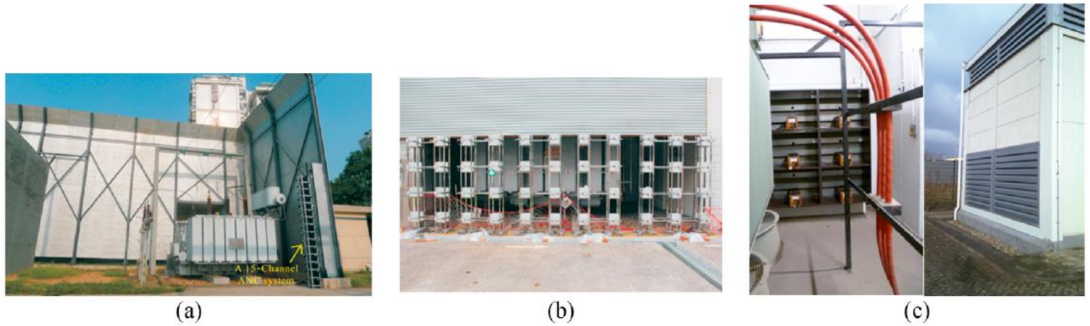
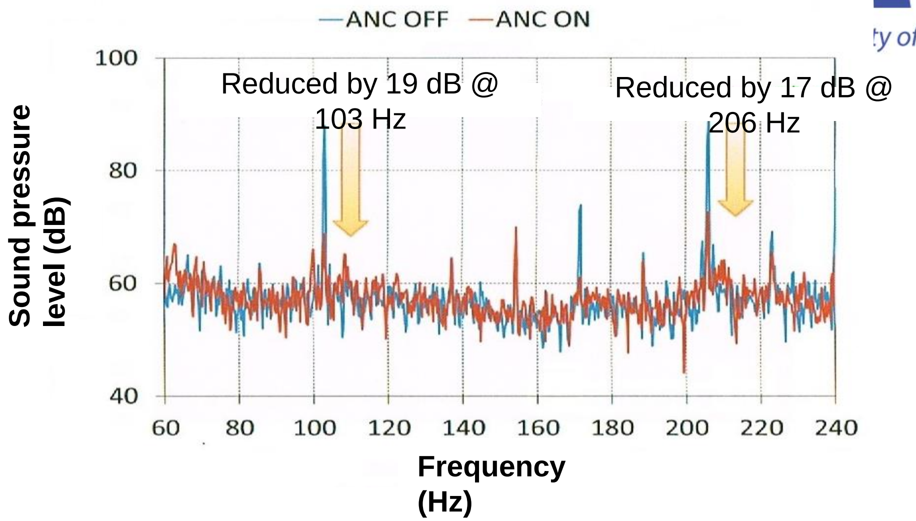


Fig. 6. Active noise control implementation for (a) a 110 kV power transformer in Hunan, China [25,27], (b) two 110 kV power transformers in a semi-enclosed building in Guilin, China [26], and (c) at a transformer station in Poeldijk, South Holland, Netherlands [75].



Virtual sensing Techniques

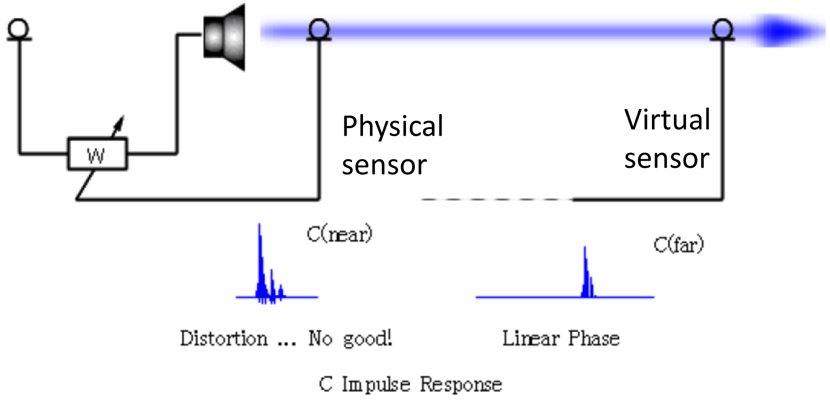
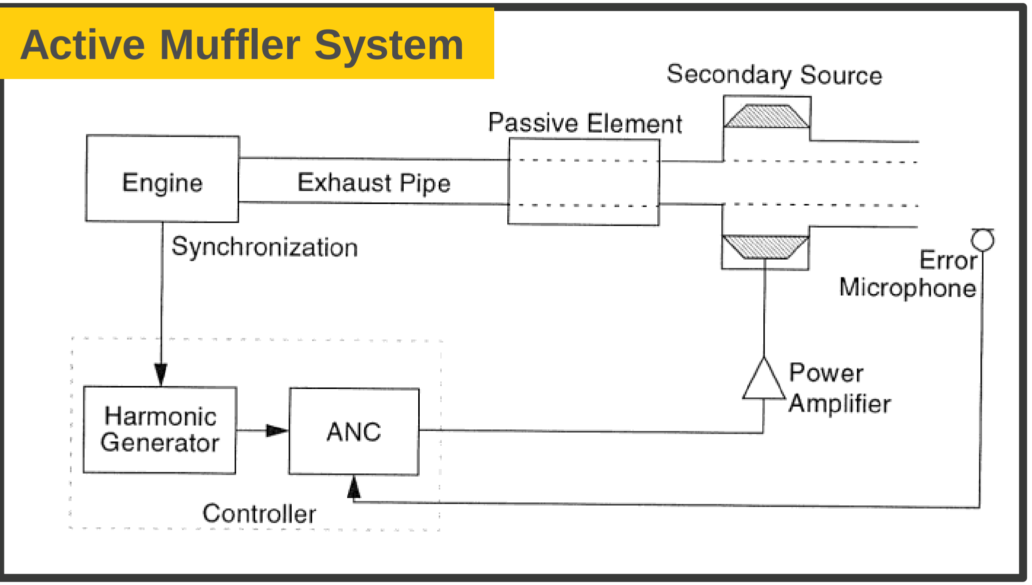
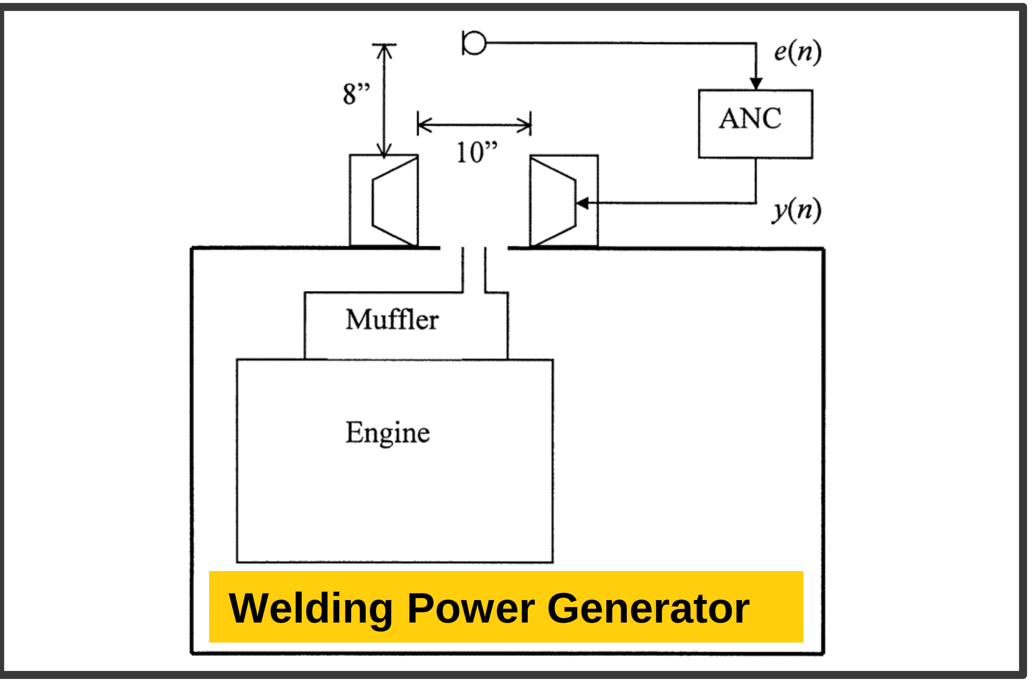
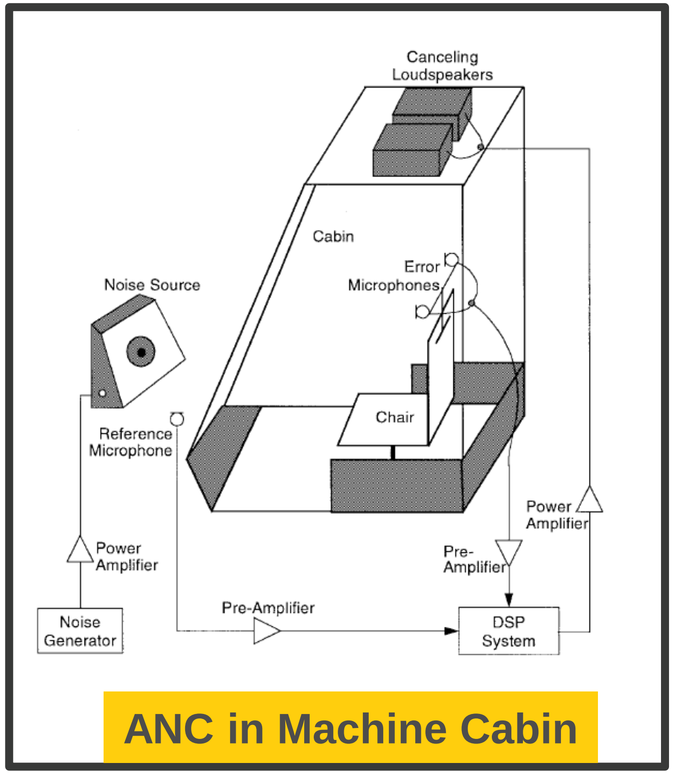
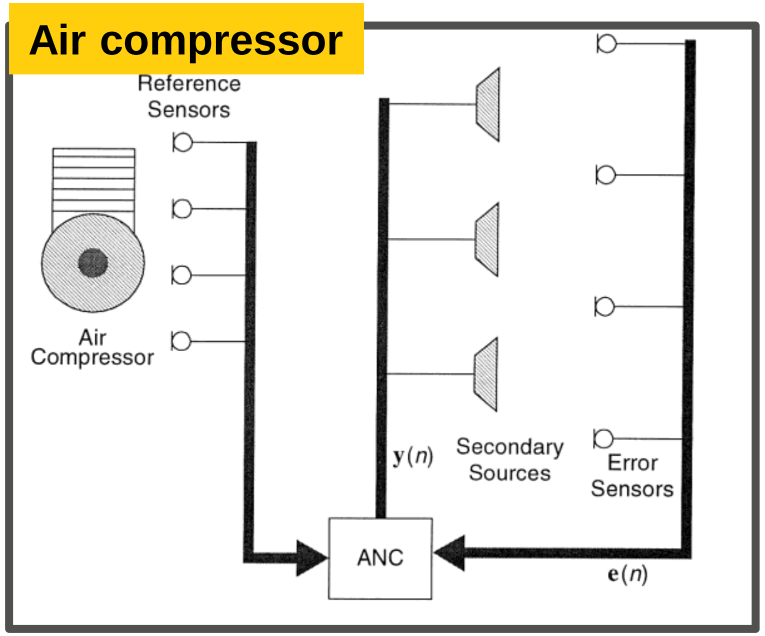


Figure from [1]

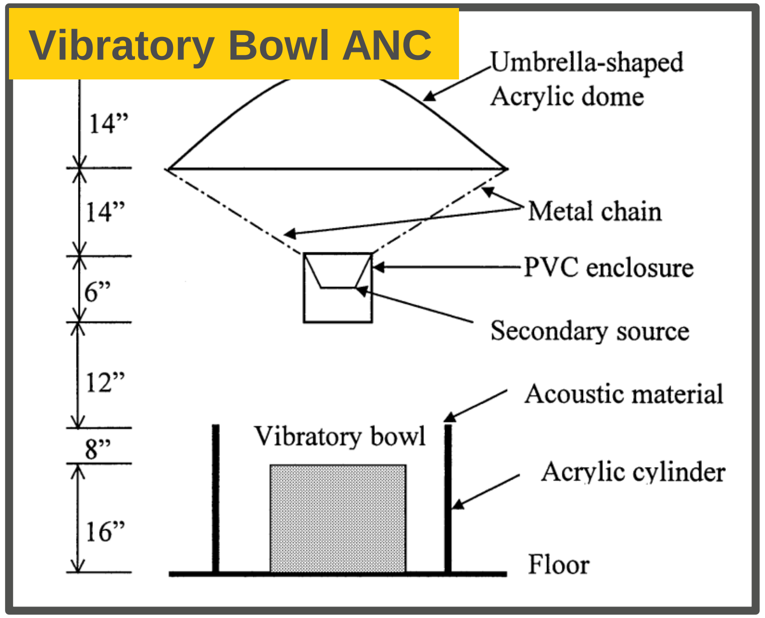








Single and multi-channel feedforward / feedback ANC techniques are employed



Side view

Source: S. M. Kuo and D. R. Morgan, *Active noise control systems: algorithms and DSP implementations*: Wiley, 1996.

Application: Space – ANC along the propagation path

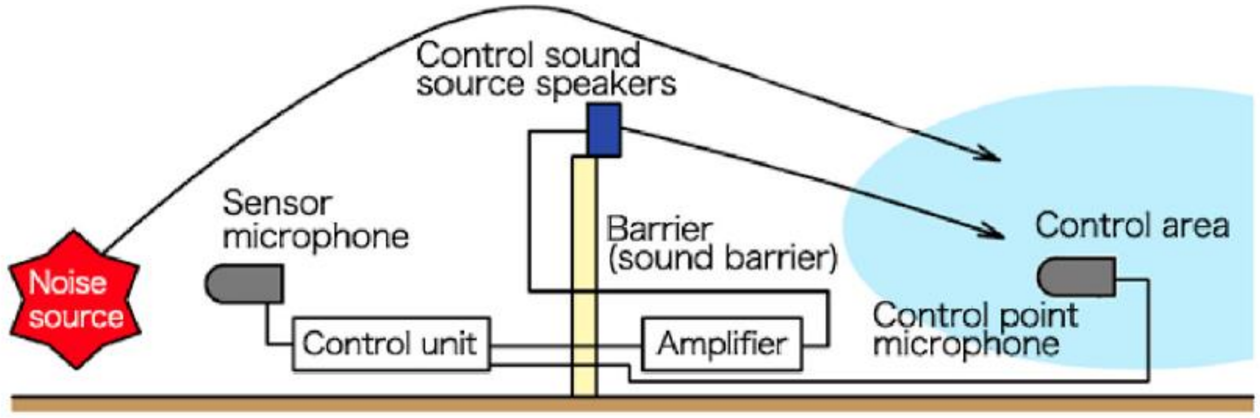


Fig. 11. Commercialized ANB system for stable noise sources by making quiet direction or zone [48].

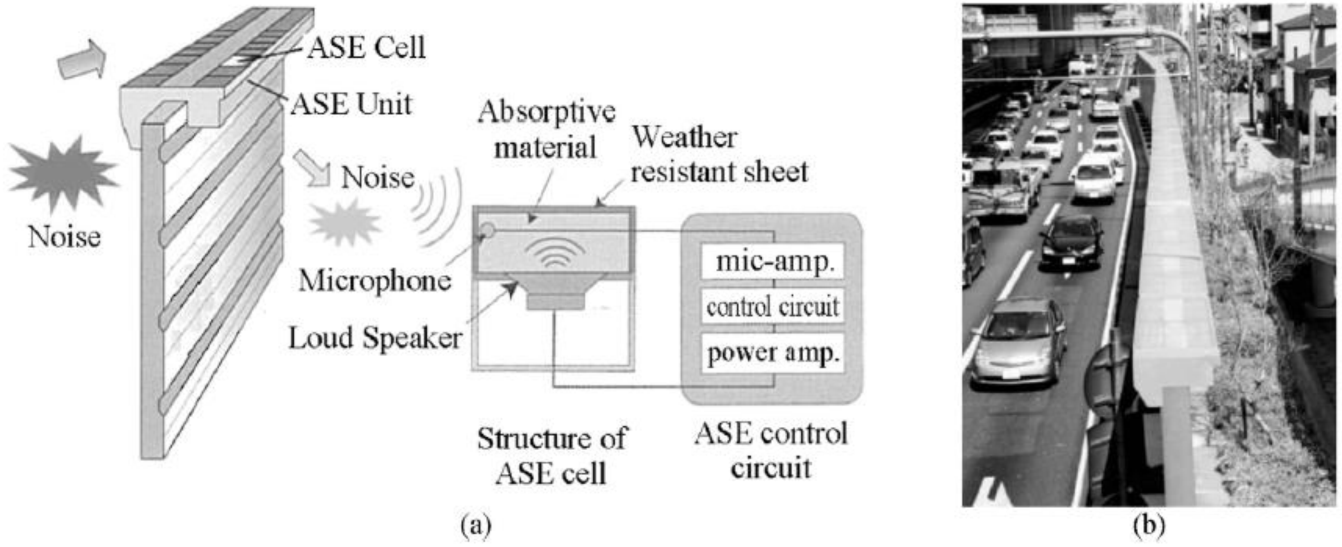
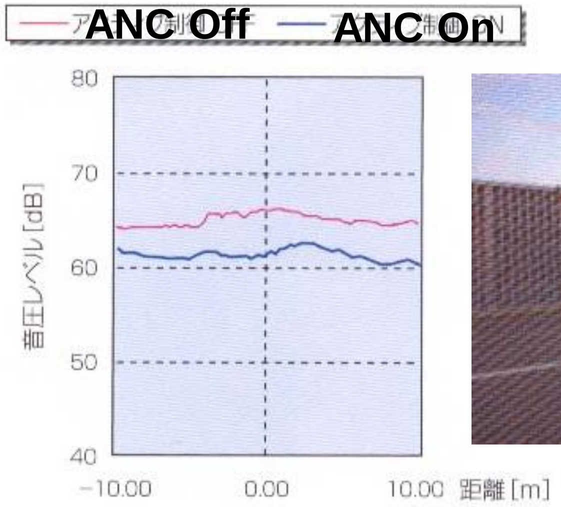
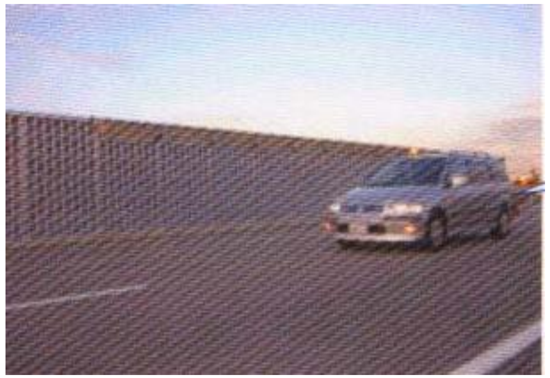


Fig. 12. (a) Configuration of Active Soft Edge (ASE) [23], (b) photo of ASE [23].

- Several Active Soft Edge unit placed on top of the noise barrier
- Decentralized system controlling the boundaries of sound field have been proposed and developed for Active Soft Edge noise barrier
- Using analog feedback controller





Application: Space – ANC at Open Aperture

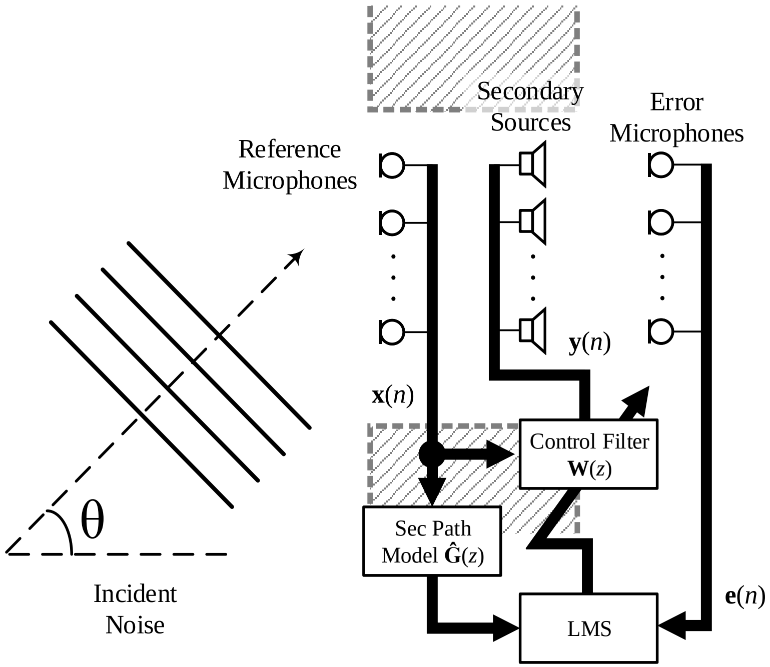
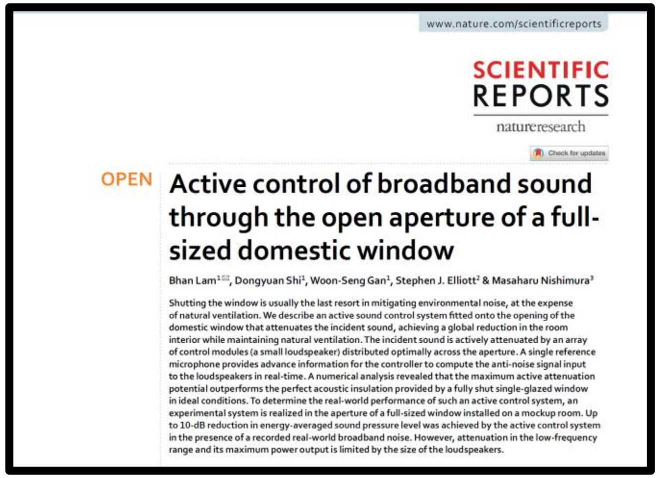


Figure from [1]

Lam, B., Shi, D., Gan, W. *et al.* Active control of broadband sound through the open aperture of a full-sized domestic window. *Sci Rep* **10**, 10021 (2020). https://doi.org/10.1038/s41598-020-66563-z



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Active control of broadband sound through the open aperture of a full-sized domestic window

Bhan Lam[1], Dongyuan Shi[1], Woon-Seng Gan[1], Stephen J. Elliott[2] & Masaharu Nishimura[3]

Shutting the window is usually the last resort in mitigating environmental noise, at the expense of natural ventilation. We describe an active sound control system fitted onto the opening of the domestic window that attenuates the incident sound, achieving a global reduction in the room interior while maintaining natural ventilation. The incident sound is actively attenuated by an array of control modules (a small loudspeaker) distributed optimally across the aperture. A single reference microphone provides advance information for the controller to compute the anti-noise signal input to the loudspeakers in real-time. A numerical analysis revealed that the maximum active attenuation potential outperforms the perfect acoustic insulation provided by a fully shut single-glazed window in ideal conditions. To determine the real-world performance of such an active control system, an experimental system is realized in the aperture of a full-sized window installed on a mockup room. Up to 10-dB reduction in energy-averaged sound pressure level was achieved by the active control system in the presence of a recorded real-world broadband noise. However, attenuation in the low-frequency range and its maximum power output is limited by the size of the loudspeakers.

(a) (b) (c)

Fig. 8. (a) A 24-channel ANC system on a full-sized open sliding window in a mock-up room [54], (b) a 4-channel ANC system on an open top-hung window in a full-scale bedroom [53], a 5-channel ANC system on a scaled down partially open window [86].

Multi-channel feedforward ANC Techniques are commonly used. But, with high computational load

Application: Space – ANC at Open Aperture

[Results from Nature Scientific Report https://www.nature.com/articles/s41598-020-66563-z.pdf](https://www.nature.com/articles/s41598-020-66563-z.pdf)

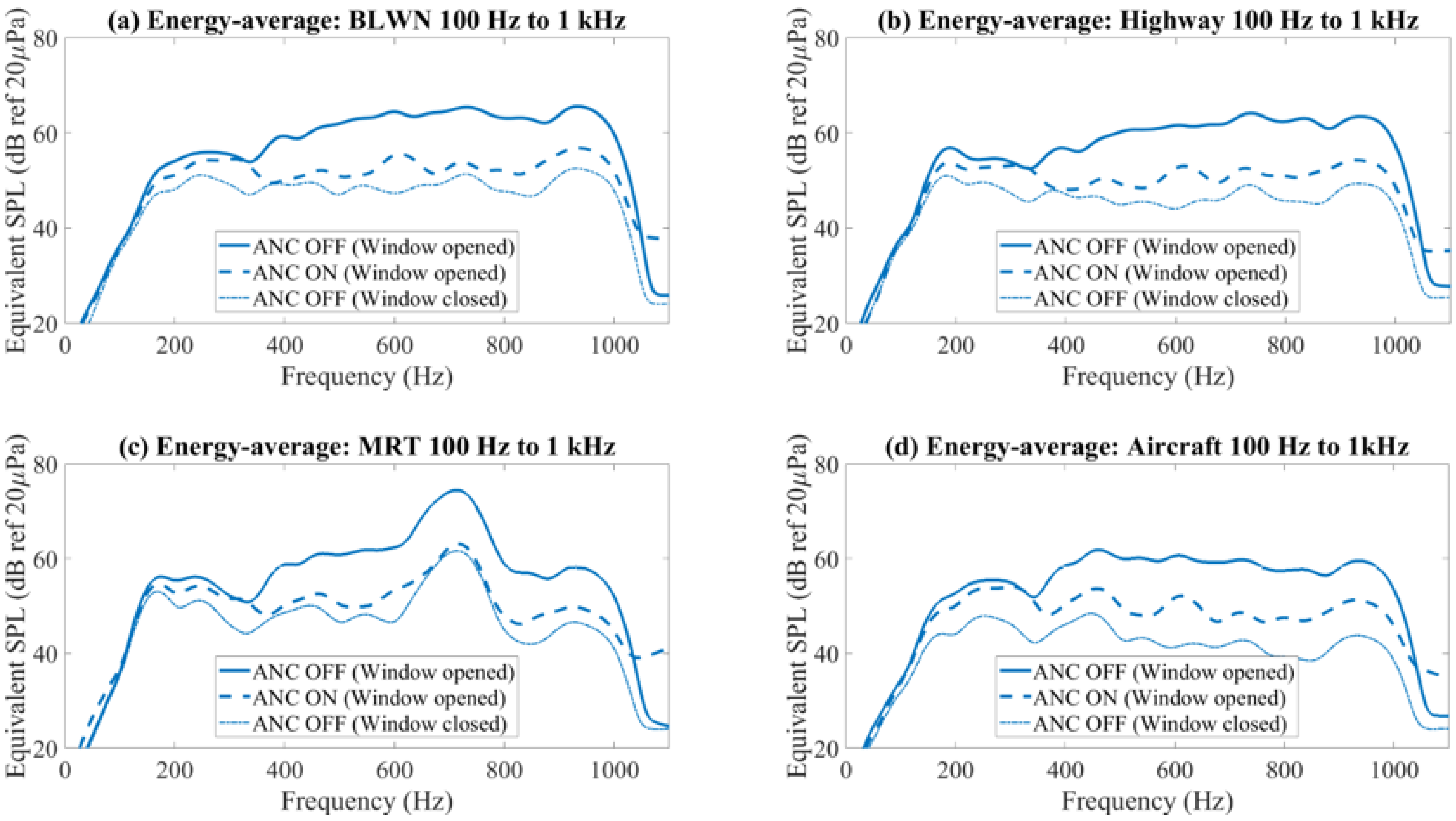
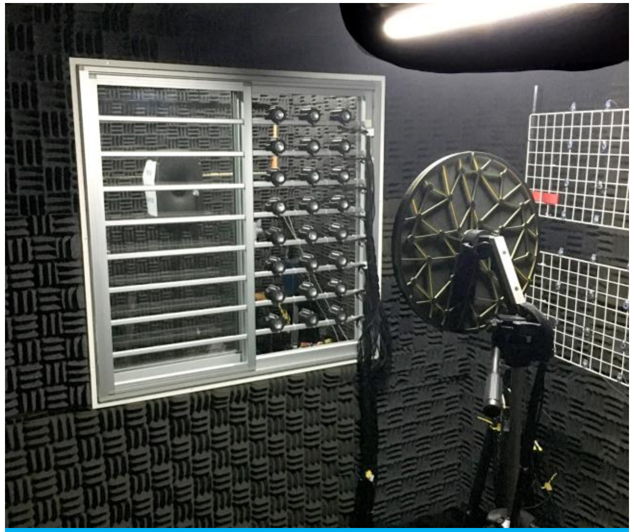


Figure 2. A-weighted energy-average spectrum of 100 Hz to 1 kHz band-limited (**a**) gaussian white noise, (**b**) highway noise, (**c**) MRT pass-by noise, and (**d**) aircraft fly-by noise, before active control (——), after active control (– –), and with windows fully shut without active control (-·-··).



Require fast responsive ANC system using selective ANC approach

New ANC Techniques

❑ Selective ANC Technique

- Recognize noise types
- Select pre-trained filters based on common noise types
- Apply control filter to reduce noise
- Fast response and able to track noise changes
- Recently, implement a deep learning approach for selective ANC

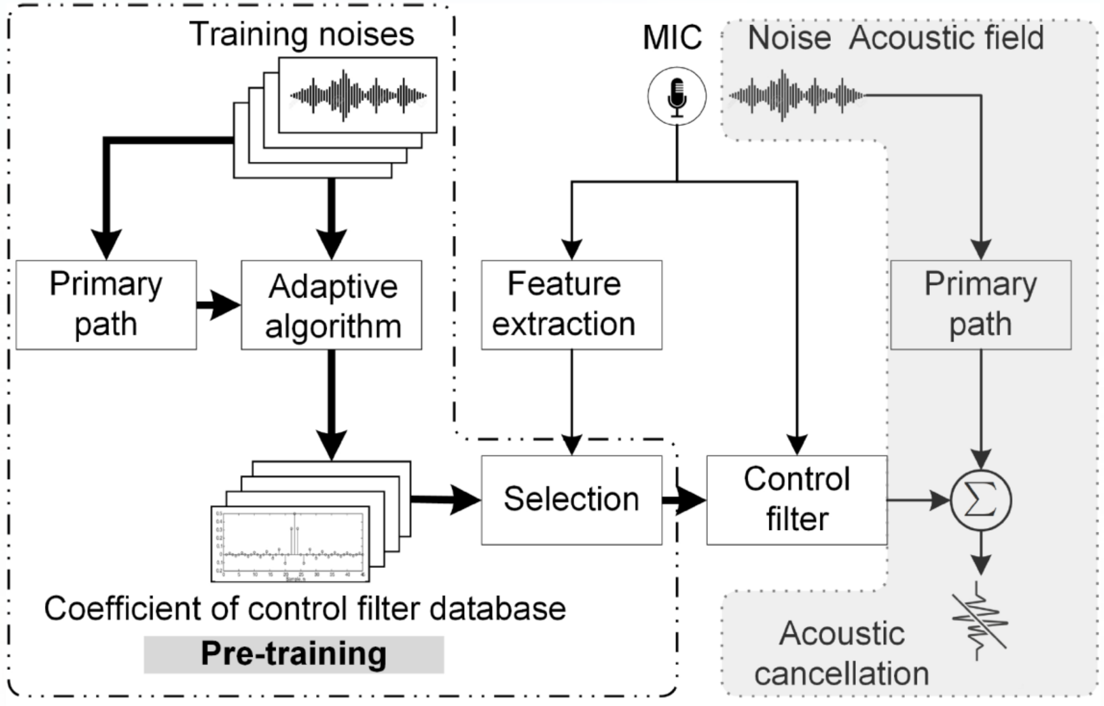


FIGURE – 5.1 The processing block of the SANC method, which features the first stage of deriving a set of control filters based on commonly encountered noise types and noise paths. Subsequently, selective algorithm extracts the closest control filter to filter out the actual noise in real-time.

D. Shi, W. Gan, B. Lam and S. Wen, "Feedforward Selective Fixed-Filter Active Noise Control: Algorithm and Implementation," in IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 28, pp. 1479-1492, 2020, doi: 10.1109/TASLP.2020.2989582.

New ANC Techniques

❑ Ultra-broadband local ANC control with remote acoustic sensing

- Using laser Doppler vibrometer in headrest.
- Lightweight retro-reflective membrane attached ear concha
- 10 dB sound reduction from 500Hz-6,000Hz
- "Virtual ANC headphones"
- Track head movement

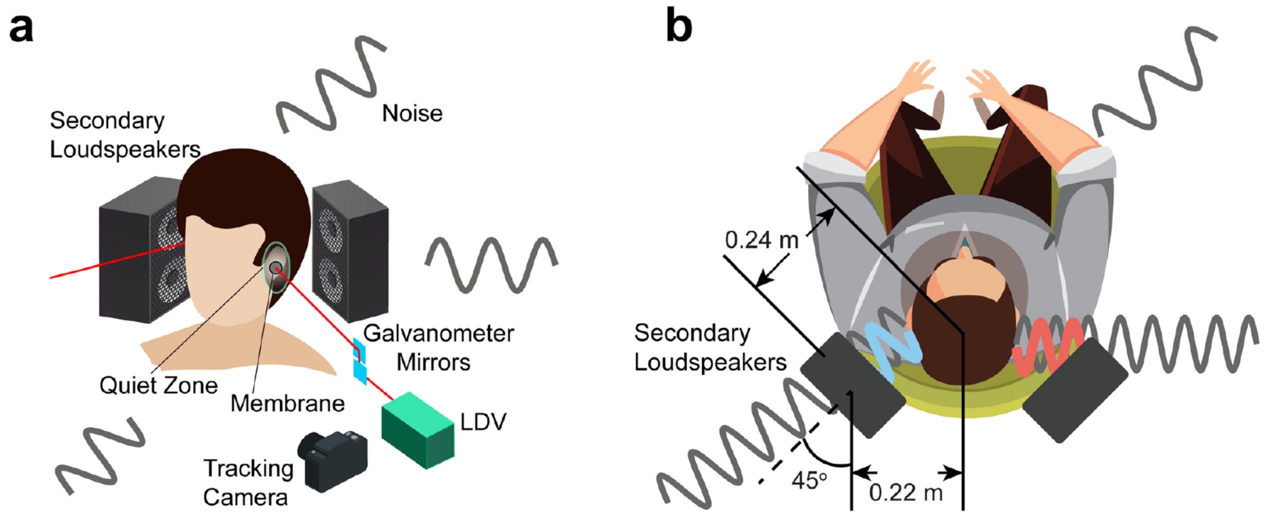


Figure 1. A virtual ANC headphone. (**a**) A quiet zone is formed in each ear by using a nearby secondary loudspeaker pair to reduce the sound in the ear, the required error-signal being determined from an LDV measurement of the vibration of a small membrane pick-up located close to the ear canal. Movement of the user is accommodated by a camera-based tracking system, which actively controls the galvanometer-driven mirrors to steer the laser beam and maintain its position on the membrane. (**b**) The locations of the secondary loudspeakers. Each secondary loudspeaker generates anti-noise signals through the ANC controller (not shown).

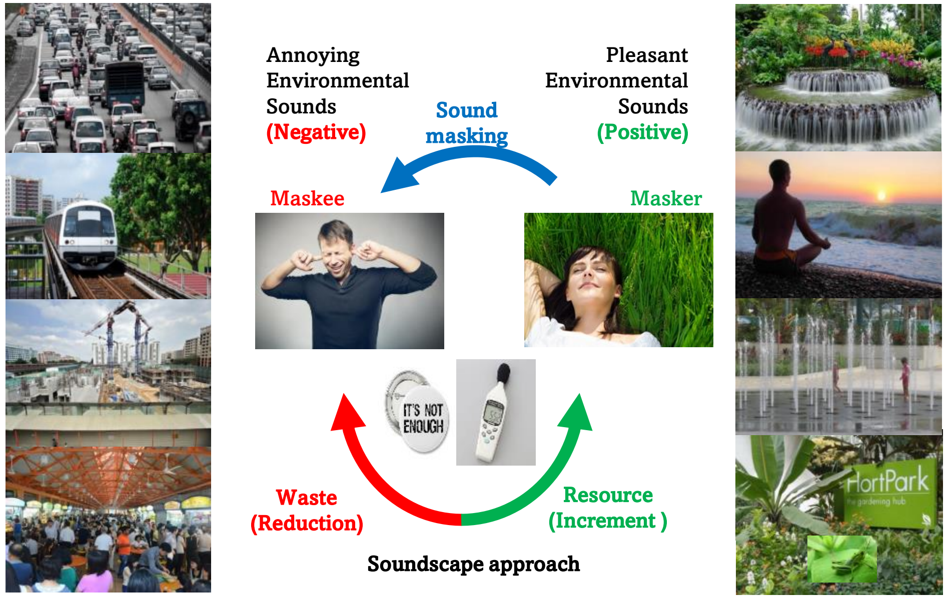
Tong et al., "Ultra-broadband local active noise control with remote acoustic sensing," Nature Scientific Reports, 2020

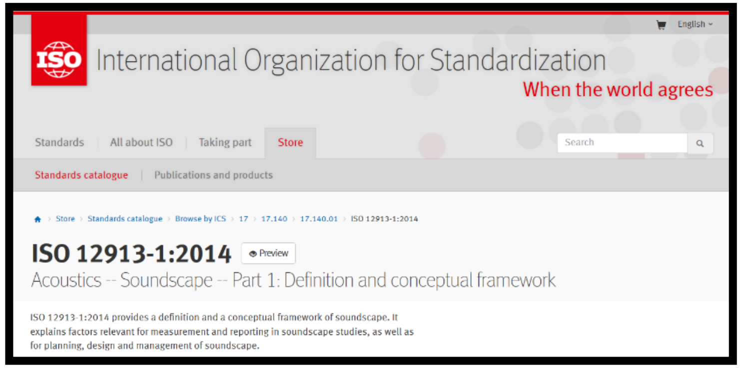
New ANC Techniques

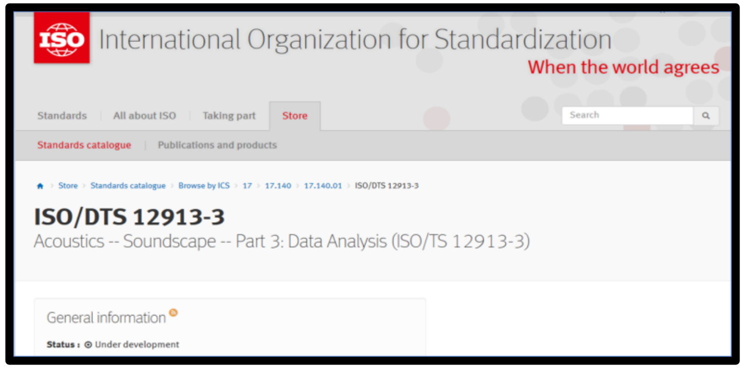
❑ Soundscape

Soundscape: "acoustic environment as perceived or experienced and/or understood by a person or people, in context"

- Closely related to **perceptually-driven ANC** research; not just reducing sound pressure level measurements.
- By incorporating urban soundscape predictive models into the training of the ANC system for outdoor built environment.
- Smart enough to attenuate the most annoying noise
- ANC provides an element of controllability that can be built into the soundscape approach.







New ANC Applications

Hansen et al, Wind Farm Noise: Measurement, Assessment, and Control

Reduce LF turbine noise inside a residential room.

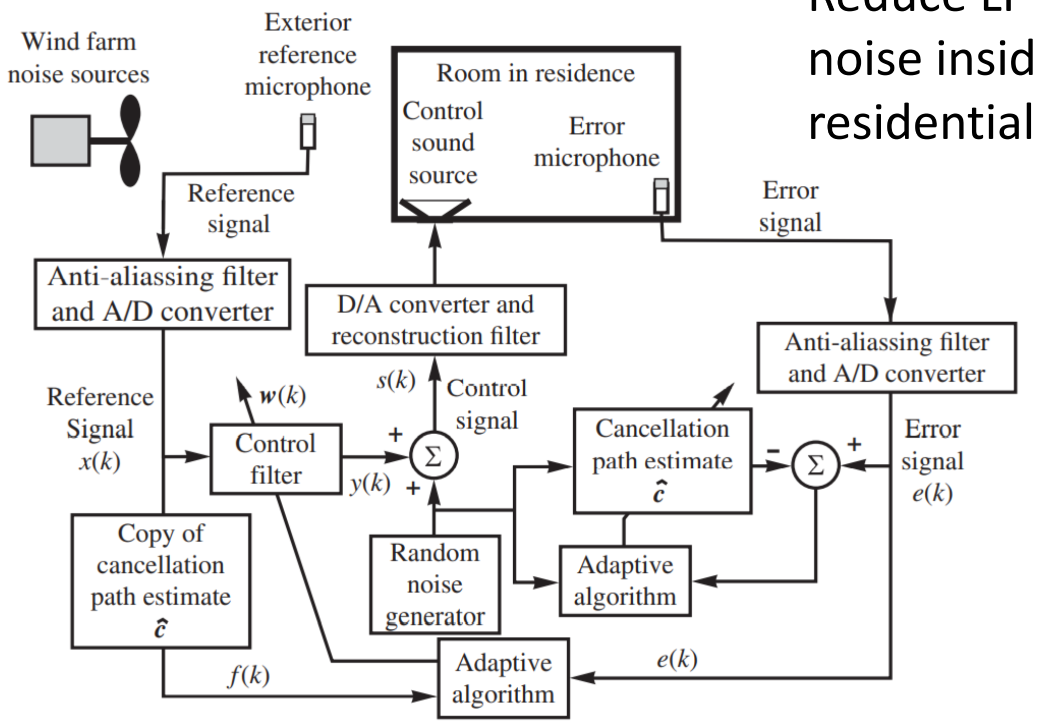


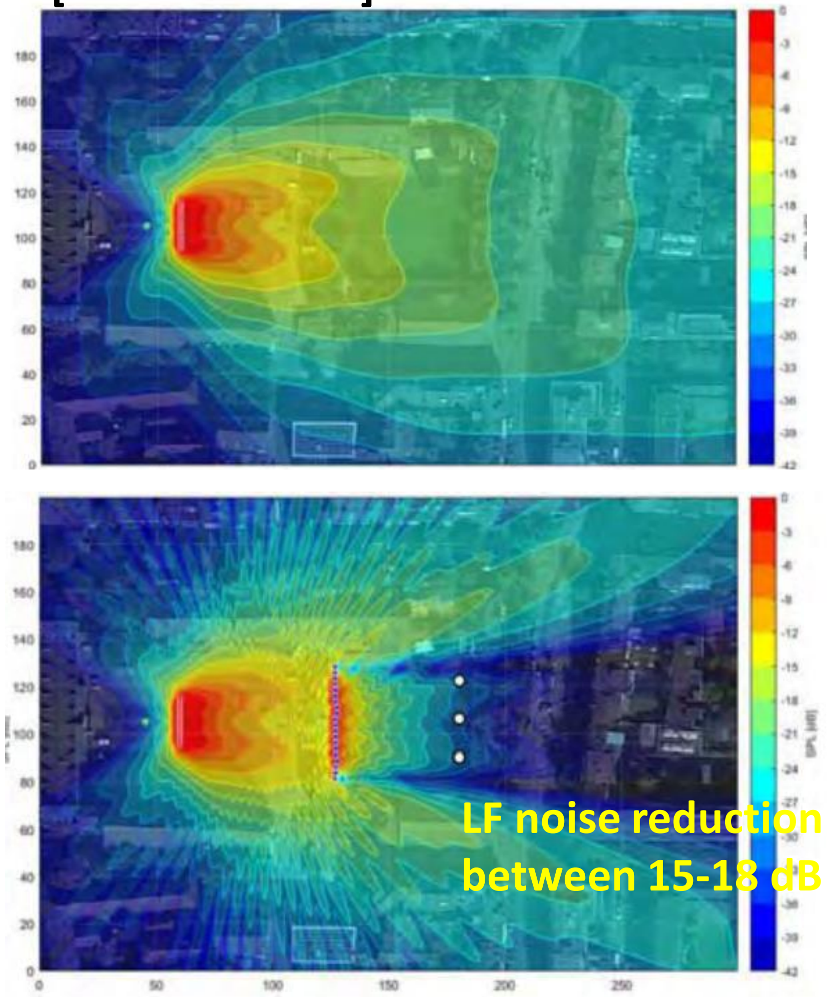
Table 8.1 Recommended 1/3-octave white-noise masking spectra for an A-weighted level of 30 dBA

1/3-octave band centre frequency	160	200	250	315	400	500	630	800	1000
Level (dB)	29	28	27	26	24	23	22	20	19
1/3-octave band centre frequency	1250	1600	2000	2500	3150	4000	5000	6300	8000
Level (dB)	18	16	15	13	11	9	6	3	1

Minimize sound propagation in on-axis to the primary sound system using ANC [Rocket Science] in outdoor events

before

after



Conclusions

- [ ] Seeing more successful trials and deployments of ANC in New Applications.

New Electroacoustic Components and Digital Processors

+

New DSP , AI, Soundscape processing techniques

=

Efficient & Low-Cost Implementations of ANC Applications

Physical Acoustic Understanding

Understanding of sound perception

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