Sixty years of active noise and vibration control - a tentative balance

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ABSTRACT
It was in the fifties of the last century when first experimental studies in active noise and vibration control were to launch intensive investigations in exploring the physical and conceptual nature of this fascinating approach. Driven by realistic hopes to overcome any constraints in computational power in the foreseeable future, these efforts caused euphoric expectations and promises which, in turn, were able to raise substantial funding for research and development.

Today, the overall result of sixty years of respective work allows us to reliably figure out the practical potential of controlling sound and vibrations by superposition of additional sound and vibration fields. While the physical concepts and mechanisms are well understood and the signal processing capabilities exceed most of the real time requirements, actuator performance and economic feasibility still limit the area of application to acoustically simple fields and/or very specific cases. Based on a short review of the historic development, the paper will summarize and demonstrate the practical potential of active noise and vibration control by successful implementations.

Keywords: active noise control, active sound design, active vibration control,

1. INTRODUCTION
Starting from the very first formulation of controlling some given (primary) sound by superposing some other coherent (secondary) sound in the thirties of the last century ([1]), this technological approach of active sound control has fascinated generations of acousticians and noise control engineers. Today, after many phases of enthusiastic hopes and gushing confidence, a realistic assessment has gained wide acceptance.

This enthusiasm was likely to maintain exaggerated expectations which then - together with the thus raised promises - were able to initiate and find financial support for many non-coordinated research and development activities. Together with the fact that for many years the needs of active sound and vibration control were at the front of state of the art technology in digital signal processing and actuator design, this particular scenario has slowed down the process of focusing on the feasible.

At first, in the 1930s, however, nothing happened for a while. It needed the optimism of the postwar era to venture on first experiments and then to start continuous explorations, research and development in active sound and vibration control. Today we thus look back to some 60 years of exploring and applying this new approach and this should encourage us to try a tentative balance to what extent we were able to turn first hopes and dreams to clear conceptual and technical insight.

2. HISTORICAL BACKGROUND
Starting from the above mentioned patent formulation of the basic concept, it took two decades to put these first ideas to first action ([2],[3]). Simple experiments mainly carried out in the US in the fifties gave first insight into practical aspects of implementing the approach by controlled interference. It immediately got obvious then that active approaches were attractive for controlling low-frequency sound and vibration. In spite of all fascination practical difficulties with technical applications seemed to withstand concrete technological targets. At that time, this was mainly due to

- incomplete understanding of the physical possibilities,
- complexity of the whole task,
- restricted possibilities of analogue control technology and
- efficiency limitations of sound actuators, particularly at low frequencies.
Consequently, technology readiness levels (TRL) obtained at that time were not to go beyond values of 4, “validation in laboratory environment”. For this reason, further research concentrated on particular theoretical and analytical considerations how to control the excitation and propagation of acoustical and vibrational wave fields.

It took until the seventies then that these considerations were picked up systematically in France and England first, then in the US and Germany. This finally resulted in comprehensive investigations on the general possibilities of active field control. With singular demonstrators being developed in parallel, technology readiness levels of up to 6, “prototype demonstration in relevant environment”, could be obtained ([2],[3]).

When the immense future possibilities of digital signal processing were to be expected in the 80s, all existing fascination turned to euphoric hopes for the future. Extremely exaggerated confidence and optimism together with untenable promises caused high pressure to succeed for both, engineers and investors. The resulting hype together with a counterproductive patent euphoria prevented a clear and coordinated sequence of developments and thus hindered the realistic assessment of technological implementations. In the late eighties this consequently ended in disillusionment with respect to the methodology. Although sporadic demonstrators were able to obtain a technology readiness level of 7, “prototype demonstration in operational environment”, it needed a thorough consolidation of technology and expectation to reestablish new confidence.

An example of such a successful out of lab implementation is given in fig. 1 where, 72 bass loudspeakers being applied on a circle around the outlet of a gas turbine exhaust were able to reduce the far field sound pressure level by more than 10 dB between 20 and 50 Hz ([4]).

![Figure 1 – Sound pressure level in the far field of a gas turbine exhaust without (a) and with (b) active compensation sources at the outlet ([4])](image)

Research efforts in the nineties then mainly focused on experiments with multi-channel control and the integration of distributed actors into so-called smart or intelligent structures. However, because of high actuator and control efforts, related engineering solutions are expected to be implemented in singular applications only ([5],[6]).

A successful way for larger scale implementations of active technologies could be pointed out around the year 2000 by limiting related efforts to feasible applications in “simple cases”. These promising applications are
- actively supported headsets and ear protectors
- active elastic mounts (vibration isolators)
- active sound attenuators in ducts and pipes and
- active control of interior sound in small volumes (e.g. cars)

While active ear protectors have become mass products, active isolators are available technology which, for operational application in practice, needs particular circumstances or requirements (including financial aspects), however. This is equally true for active duct- and pipe-attenuators where further limitations are caused by acoustic power and thermal constraints.
3. TECHNOLOGY REVIEW

Altogether active methods are well understood today and this applies to both, the conceptual, i.e. physical/acoustic part and the control engineering part of the whole electro-acoustic system describing any active system. Both areas have been investigated systematically and described comprehensively ([2],[3],[5],[6]). As presently available signal processors allow real-time computations for highly complex algorithms even, current technological limitations are mainly due to actuators (loudspeakers) and their low-frequency constraints.

Nevertheless, many prototype demonstrations in relevant (TRL 6) and operational (TRL 7) environments were able to settle for such limitations or to overcome them even. Examples of milestones may be seen - and shall be illustrated here - in active control of wave propagation and active vibration isolation.

![Figure 2 – Reflection coefficient without (a) and with (b) active absorber at the free end of a beam](image)

Control of wave propagation is not restricted to airborne sound waves. Fig. 2 illustrates this for bending waves in beams by giving an example where incoming waves may even be absorbed by appropriately driven secondary sources ([2]). The reduction of the reflection coefficient by 32 dB (in the mean) could be obtained by an electrodynamic shaker at the free end of a beam and by negative reproduction of the passively reflected primary field. Thus, 99.95% of the incoming power could be absorbed.

The high degree of technological development of active mounts may be substantiated by the fact that general information on their possibilities and design have been compiled in the German engineering guideline VDI 2064 “Active vibration isolation” (published 2010). To give a concrete illustrating example we refer to the application of secondary forces to the car body of an ICE passenger train car in close proximity of the bogie’s secondary spring. By this active measure, the low frequency noise components excited by wheel harmonics under special track conditions could be essentially reduced in the passenger compartment around 90 Hz. Comparing the spatial sound pressure distributions of fig. 3 (measured at the rolling test site of Deutsche Bahn AG at a speed of 200 km/h) it can be seen that the related reductions were up to 20 dB for some seats. The average reduction for a group of 6 seats was up to 12 dB ([2]).

The use of sliced piezo elements placed in the interior volume of the secondary springs resulted from a systematic feasibility study investigating various active concepts for the bogie and the passenger compartment with respect to their applicability and effectiveness. It turned out that immediate control of the sound field in the passenger compartment by loudspeakers would also be possible. However, in sum, the global compensation by compensating forces applied to the excitation points was shown to be advantageous.

These examples may illustrate that technological solutions exist and may be derived systematically from a conceptual understanding of active approaches. Nevertheless this does not mean that they have the potential to serve as state of the art technology. Apart from limitations with actuator efficiency the main difficulty can be seen in the high effort, complexity and cost which then prevents the technology from being applied in many cases. Therefore, although being a proven part of the engineering toolbox, implementation of active control measures is restricted to particular cases only where special requirements may justify special efforts.
Examples of such successful singular applications for active control measures in practice are
- active vibration isolators of high standard,
- active sound attenuators and mufflers in ducts and pipes including air intake and exhaust systems,
- active improvement of the shielding effect of sound barriers and
- active stabilization of self-excited systems.
A more comprehensive survey of available technology for practical applications can be found in [2] and the respective literature survey given there.

4. ACTIVE CONTROL OF CAR INTERIOR SOUND
Today’s most promising application area may be seen in active control of small volumes like the interior (passenger compartment) of cars. Starting from a demonstrator being able to compensate the second engine order and, at the same time, to generate additional controlled engine orders, this approach allowed to extend the scope from compensating existing sound components (Active Noise Control, ANC) to adding new sound components (Active Sound Design, ASD). This was the basis for further product oriented developments.

Fig. 4 shows how the sound characteristics (i.e. the particular composition of engine orders) can be changed within the same car by just switching the operational modes of an ASD system. It should be noted that all engine sounds were perceived and assessed as highly authentic in all aspects: in its load dependence, its combustion characteristics and in the spatial localization. This authenticity together with the technical feasibility encouraged further development of the system as an individual tool to assist and support context true subjective assessments of engine sounds under real driving conditions.

For test cars equipped with a set of typically four to six microphones and access to some CAN bus signals (rpm and load), a set of hard- and software equipment (later called m|klang®, [7]) was available to allow for real time modifications of the perceived engine sound while driving the car. The frequency range of operation was specified up to about 250-300 Hz, allowing extensions to higher frequencies for particular microphone positions. This tool was highly welcome and used by the automotive industry as a most valuable extension of stationary sound studios and simulators (providing “virtual reality”) to driving test labs (providing “real virtuality” [7],[8]).

Starting from the success of this flexible ASD system development tool it was just consequent to take this system and technology as a basis for model customized solutions in OEM series applications. The motivation to go this step was manifold but has been dominated perhaps by the high flexibility in adapting car interior sounds to specific target requirements. However, although being very attractive since long, this option had to overcome some fundamental reservation against “synthetic”, non-mechanical sounds within mechanical, engine driven environments before getting accepted in reality. But the authenticity of test implementations may have helped to pave the way for a breakthrough in series applications.
In this context special attention had been given to active control of car interior sound for engines with cylinder on demand technology. This technology is attractive to increase fuel efficiency by switching from 8 to 4 cylinder operation at specific operation conditions. The main task of such ANC systems then is to compensate for the characteristic 4-cylinder 2nd engine order. To illustrate this approach, an example of an Audi S-series solution (for the 4.0 TFSI engine with cylinder on demand technology) shall be described here. More details can be found in [9].

The respective ANC system utilizes 5 speakers which are part of the regular interior sound system and 4 microphones mounted into the headliner. The system is integrated into the “advanced sound” audio DSP amplifier and based on a SHARC floating point DSP. The amplifier is networked via MOST, an extra RPM pulse signal is added to reduce relevant latencies. Basic features include engine order based ANC for up to 8 relevant engine orders to be controlled in the whole passenger compartment. The ANC control frequency range is 32 to 250 Hz.

Figure 4 – Active control of car interior sound (active sound design, ASD)

Figure 5 shows the typical block diagram of a modern vehicle interior ANC system. It comprises an engine rpm pick-up with the engine rpm used to generate some harmonic signal of the appropriate engine order frequency. This signal is then fed through some adaptive signal processing in the filtered-x configuration already discussed, Ŝ denotes the acoustical transfer function estimate (model, typically based on a FIR-filter to be adapted to eventual changes in the transfer characteristics) used for filtered-x filtering while S denotes the physical transfer function (plant). So, from a traditional

Figure 5 – Block diagram of in-vehicle ANC system. blue part: feedback control loop
ANC perspective, we have (adaptive) feedforward control and setting up the adaptation in a stable way will guarantee good system performance ([9]).

To summarize this overall system performance, we use spectrogram plots of a full-load/wide open throttle run-up for both, 4 and 8-cylinder mode. This is not an easy measurement to be done especially at 4-cylinder mode because full load here means the maximum torque below the ECU 8-cylinder switching limit. Figures 6 and 7 ([9]) show the results for 4th gear inside an S8 vehicle. All of these measurements were taken on a roller dynamometer, so there is significant low order rolling noise captured during the measurements (below 1st engine order). However, this is not related to the ANC system and its performance.

As can be seen from figures 6 and 7, the ANC system is capable of reducing several (up to 8) engine orders at the same time for both, the front left and the rear right measurement positions. Also, by comparing corresponding 4- and 8-cylinder mode operations, it can be stated that the initial spectral differences between the related sounds are smoothed down to much more similarity, thus reducing the acoustical perception of the switching process.

5. SUMMARY AND CONCLUSIONS

Active noise and vibration control had a long way to go from the fixation of the idea in the 30s of the last century to

- identify its physical and signal theoretical possibilities and limitations,
- provide proven preconditions for practical realizations within well-defined technological limits,
- create and apply a proven instrumentation for engineering solutions in singular applications.
This has led to impressive technical solutions for particular applications involving state of the art technology in both, actuator design and integration as well as signal processing algorithms and devices. However, with respect to technological maturity for market take-over, a breakthrough in application technology could only be achieved for acoustically simple cases so far, in particular for

- compact sources including active mounts and
- small target volumes like headsets and car interiors.

Such systems have shown to be technically reliable and economically attractive. They thus can be assumed to become and continue to be a widely acknowledged technology for flexible sound design. Although a rational series of step by step approaches was frequently overridden by short-sighted prospects and the expectation of short-term benefit, progress in the iterative interaction of research, development and technological implementation finally succeeded in assessing and providing this complex technology.

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