

Overview on ANVC Systems and the Future with Smart Embedded Solutions

Thomas L. Lago
QirraSound Technologies Europe AB

ABSTRACT

How to decrease noise and vibration exposure has been of interest for many years. Empirical data have indicated that too high dose values can create multiple problems to a human body - often severe. Some years back, the European Machinery Directive has increased the responsibility for manufacturers and employers to make sure limits are complying with legislation. Classical technology often consists of passive solutions aiming at trying to cut back on noise and vibration levels. For low frequency, these methods are often lacking the needed performance especially if weight should be considered at the same time. A smart combination of passive and active techniques can make a real difference. Today, with possibilities for low cost and embedded electronics and the rapid development of new actuators, a vast range of applications are possible for this combined combat approach, with a financial advantage as well. Today, multiple products also utilize embedded "electronic muscles," able to counteract harmful sound and vibration in real-time - featuring advanced control systems. All this then becomes an invisible function in the vehicle, machine or tool. The launch of such systems and successful acceptance often requires international compliance with applicable standards. New sensor concepts and approaches in combination with consumer and automotive wireless and network solutions are often key ingredients for success. It is impossible to fully grasp how this smart and embedded technology can revolutionize the sound and vibration business and open new business segments. This paper will outline these new markets and applications and give some examples from a number of applications.

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INTRODUCTION

As early as 1400, Leonardo Da Vinci (1452-1519) realized that counteracting waves could be used to actually decrease the waves in a water canal as "destructive waves". In 1930, many years later, Coanda was awarded a patent for his own ideas on "active noise control". Paul Leug, a German, filed his own patent in 1936 and was banned from Germany as it was filed in the USA first! At the time, it was a bad idea. He moved to France and didn't want to work within the area ever since. Olson and May filed a patent in 1953 for an "active chair", making it possible to accomplish a local attenuation in a small silent zone. Due to the increased capabilities of DSP technology, the analog control systems used at the time, have been replaced by more and more digital control. In the beginning, most active systems focused attention on airborne sound. Today, the applications have extended well beyond the classical acoustic applications and now cover structural sound and vibration. This technology has also found its way into applications for ski's, mountain bikes, snowboards etc. in an effort to decrease unwanted vibrations that could either affect the performance or life expectancy of the equipment. It is very important to think "out-of-the-box" and it would not be surprising if some key applications of this technology would appear in the non-classical stable of applications. One example is the suppression of chatter in turning operations. Another is

semi-active dampers for trains, cars and motorcycle applications. Several companies have been able to develop and manufacture dampers with unique features, combining the best from the passive world with the best from the active world. In the active world, the wavelength is a common variable that limits the possible result. Often, the passive solution has started to be efficient before the active solution has given up. With the new embedded systems concepts, it is possible to accomplish cost effective and robust solutions with integrated algorithms. This includes both the needed sensor as well as the actuator. The embedded systems design also opens up possibilities for distributed small sensors and actuators to be used on more global control strategies. This paper is intended to give an overview of active control methods and applications, but also to stimulate an out-of-the-box thinking.

BACKGROUND

The concept of destructing waves was already documented by Leonardo Da Vinci in 1400. He talked about decreasing water waves in a canal by having a separate canal interacting with the first canal. By properly adjusting the length of the "destructing" waves in the second canal, he could then make the water surface be calm, after the two canals had interacted. Da Vinci mentioned that "nothing indicates that this would not work." [Figure 1](#) depicts his basic idea.

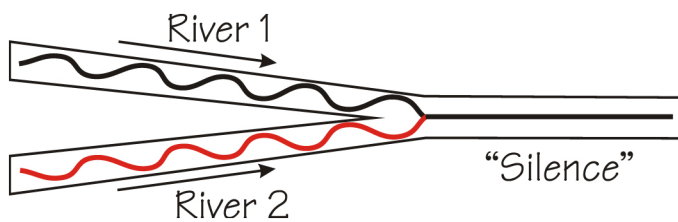


Figure 1. Illustration of Leonardo DaVinci's "cancellation approach" in a river.

Stokes performed observations in 1868 and J.W. Strutt followed some years later. In 1878 S.P. Thompson made the first known real attempt and not long after, Thorncraft and Yarrow investigated how a ship's "rolling" could be compensated for using active means. Later, actually in 1930, the first known patent was granted and invented by Coanda (see figure 2). In 1936, the German engineer Paul Lueg applied for a US patent, covering an approach to active noise control in a duct. Since he didn't apply in Germany first, Hitler attempted to put him in jail. Thus, Lueg quickly moved to France, severely disappointed and it is told that he never wanted to work within this field again. At the time, it was expected that researchers applied in Germany first.

Olson and May applied for a patent in 1953, covering the fundamental concept of a "silent chair," depicted in figure 2. Some time after, W.B. Conover from General Electric, presented results from transformer sound attenuation using loudspeakers. In mid 1960, Jessel and his team proposed the possibility to use Huygen's principle for active noise control. He combined this with Young's principle and they accomplished some great results in ventilation ducts. Key people continuing this work include a group of: Russian medical doctors, Onoda and Kido from Japan, Leventhall and Swinbank from England. The researchers and inventors at the time used analog control, and these systems could not be made adaptive. Thus, they suffered from instability and often produced more sound than to begin with. The main principle was, however, correct, though the implementations could have been different. At the time, very few alternatives were available and thus almost naive implementations were made.

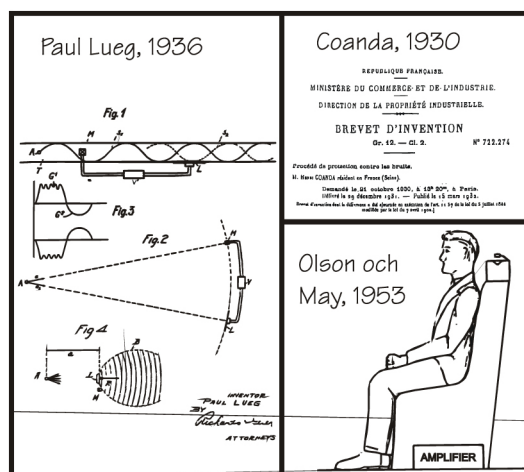


Figure 2. Illustration of some of the early patents in regards to cancellation of sound using sound waves.

With the advent of digital signal processors, digital control systems began to be developed. Around 1978, approaches began to emerge, covering mainly air borne active noise control. Most signal processing groups at the time focused on telecommunication, and a attenuation result in the range of 10-20 dB was more or less embarrassing and thus they often concluded: this is not a useful approach! What they didn't know was that there are many applications in acoustics where 10 dB represented a great result. This situation led to groups other than the classical signal processing teams started to develop systems and applications for active noise and vibration control. Professor Steve Elliott at ISVR (Institute of Sound and Vibration Research) in Southampton was one of the early researchers, and England as such was really into this area in a very early stage. Professor Chaplin applied for several patents and other people in England quickly followed.

Due to the commercial potential, financial and legal people from USA became very interested and tried to steer the development. A group was formed with the name NCT, Noise Cancellation Technologies in 1984. Due to a legal battle in regards to patents and ownership, Tom Hess decided to start another company ANVT, Active Noise and Vibration Technologies in 1987. A third group in USA was formed earlier, Digisonix, mainly focusing on ventilation noise. The legal and marketing battle in between NCT and ANVT was major and in 1994, the ANVT owner decided to sell his company to NCT "over night." All people were fired and part of that legal battle ended. Since then, both NCT and Digisonix have disappeared from the market. Only small "residues" of the companies still exist. NCT is focusing on close business areas, and other players have used the development and progress that Digisonix, NCT and ANVT initiated. Active headsets from Sony and Bose are two good examples, but the list could be made extensive. Due to the legal battles, the technology had a backlash, but today, focused applications are emerging and slowly the technology is finding its way into many markets. The Chaplin patents that were part of the legal battle have expired. That has changed the foundation.

Control Methods

When designing a system for active noise control, there are many parameters and assumptions in regards to the noise itself that should be properly handled. Some key parameters to consider are, [1][2][3][4]:

- Broadband noise or tonal?
- If tonal, how many frequency components?
- Stationary or varying? If varying, how fast?
- Is the primary source a point source or a distributed source?
- Noise/vibration in the structure or in air?
- What is the wavelength?
- Force or sound level needed to "counteract"?
- Global or local attenuation?
- Coherent sound?
- Deterministic or random?

After answering these questions, it is possible to start deciding on an approach and what control strategy should be used. Actuators and sensors must be placed where they can **Observe** the system but also **Control** it. The well known **Observability** and **Controllability** aspect from control system theory cannot be neglected. If so, the system will not perform properly and advanced algorithms cannot really compensate this.

There are many possibilities when designing a control system for active noise and vibration control. When using a feed-forward system approach, it is important to have some information on the parameter to be controlled. A common approach for ventilation systems is to use an upstream microphone for prediction of the sound to be controlled and then using a downstream microphone as an error sensor.

Multi-Disciplinary

ANVC is a demanding area but also rewarding. It often involves: acoustics, mechanics, mathematics, physics, electronics, signal processing, actuators, sensors, optimization, sound and vibration etc. If a research group is only covering one part, they typically redefine the industrial ANVC application into a lumped model with a clear focus on that group's competence. The project will then act more as an "educator project" than a "research project" since the results are not really useful but with time, the group might learn from it. Unfortunately, there are too few teams with a multi-disciplinary competence and it is thus often hard for different groups to work together. After all, universities are supposed to be highly specialized in one topic only. For a robust and low cost system, with proper performance, it takes a different arrangement - multi-disciplinary research teams with an open mind.

Robustness

The robustness is a term often used to describe how insensitive the system solution is toward parameter changes and/or noise. It is not uncommon that research teams without proper background demonstrate an ANVC solution after months of system parameter tweaking. Then, with some small changes in parameters, the system might become unstable or not performing correctly. The requirements and understanding of what it takes to design robust solutions is often lacking. In principle, many research teams can demonstrate almost any ANVC system but very few can make them robust, enabling them to function in a real life environment. Developing a volumetric ANC system for vehicles that can be installed in hours without any a-priori information, still functioning very well is the real challenge. The system must also be low cost and easy to maintain. There are some very good examples of ANVC implementations with such properties.

Out-of-the-Box Thinking

Knowledge is not always good. Many difficult problems have been solved by persons, not being told that the problem was "unsolvable." There are many examples of this. If an Electrical Engineering (EE) person is presented a problem he will use his electronics background when viewing the problem. If the Mechanical Engineers are stuck, the EE "observation angle" might change the solution dimension

drastically, or vice versa. Therefore, by having a team of experts with a variety of background and education, the likelihood for a successful solution is much better when handling ANVC applications.

Common Challenges

In ANVC applications it is important to have a good understanding in regards to multiple topics, as mentioned before. Some common "mistakes" or challenges that will create some unwanted effects are listed below. These are only some examples, there are more!

- Using the error sensor when evaluating performance. In e.g. a car, the "listener" does not have his ear where the error microphone is placed and hence, an "evaluation microphone" should be used. This will, of course degrade the performance, but will be a better description of what the end result might be.
- Looking at how much damping the ANVC systems has accomplished for the fundamental frequency. Since the human ear will "fill in" the "missing fundamental" it is possible to have 25 dB measured damping but the listener does not hear it! It is very important to have a good understanding of psycho-acoustics and how humans handle changing "some frequency components".
- Trying to compensate a poor implementation with an advanced algorithm. This is a bad strategy and will not result in a robust system. It turns out, that if the physics is well understood and the implementation is using proper actuators and sensors, placed properly, most algorithms will do a rather good job. Then, it is possible to tweak and enhance the performance using a more advanced algorithm.
- Implementing algorithms in a simulation only. Many of the real world challenges will often not show, like wavelength limitations, size of silent zones and noise impact.
- Not fully understanding the wavelength dependence. This is especially important when ANC in air is handled. The wavelength often limit the damping to below 200 Hz since the "silent zone" around the error microphones otherwise becomes too small. A good "rule of thumb" is 1/10:th of the wavelength as the silent zone.
- Coherence is paramount in ANVC applications. Despite that, it is often not reported in papers etc. If coherence is low, damping (or results) are also low.

Machine Chatter Vibrations

The Acticut system was developed based on this methodology. Mechanical engineers with a focus on the cutting process had tried to actively compensate the chatter without managing to solve it. Their basis is that the chatter is self-induced vibrations and thus RPM dependent. Early investigations verified that the correlation in between RPM and the self-induced vibrations was zero and thus the basis must be wrong. Even today, more than 15 years after these results were presented, experts on metal cutting have difficulties understanding why the Acticut system is working that efficiently. In the figure below, an illustration of a typical result switching the system on and off is depicted. The result speaks for itself!