Transducer Placement Strategy for Active Noise Control of Power Transformers

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Introduction

The application of active noise control (ANC) [1] as a substitute for passive methods in power transformer (PW) noise reduction has been a constant research topic over the last 20 years.

One of the main challenges to a successful ANC application on PW is determining the quantity and location of control sources (CS) and error sensors (ES). The definition of these parameters is not an obvious task, and there are yet no closed-form expressions that yield their optimal value, which depends on the sound field generated by the PW, the frequency band where attenuation is desired and many other factors.

Genetic algorithms (GA) have been used for optimizing the position of a given quantity of transducers with very interesting results [2,3]. This article investigates the performance of GAs regarding the choice of fitness functions and optimization order (or chromosome construction).

Genetic Algorithm

Global attenuation of PW noise is usually not required, and attenuation on a given solid angle where a building is located suffices. A so-called control surface is defined and the genetic algorithm is used to define transducer positions that maximize attenuation over this surface, ignoring possible increase in pressure elsewhere. Wright e Vuksanovic have shown that the best possible attenuation is achieved when the ES are positioned over the control surface [4]. Unfortunately such arrangement is not always possible, since the signal-to-noise ratio at the ESs decreases as theirs distance to the CSs increase, what may lead to control system instability.

Given a set of possible CS locations, a set of possible ES locations and a desired control surface a GA searches for the transducer arrangement that maximizes a fitness function (FF), usually some sort of measurement of attenuation over the control surface. Baek proposes the positions of CS and ES to be coded as a binary string in the chromosome [2]. Each gene represents a possible transducer location and may have value 0 or 1, indicating, respectively, absence or presence of a transducer in a given location.

Because PW noise holds most of its energy on lower frequencies, CSs will also be excited only in low frequencies and can thus be modelled as spherical point sources (SPS) with volume velocity q_s. The optimal CS volume velocity vector that minimizes the sound pressure on the ES is given by

$$\boldsymbol{q}_0 = \boldsymbol{Z}_s^+ \boldsymbol{p}_s, \tag{1}$$

where $\boldsymbol{Z}_s$ is the complex transfer-matrix between CS and ES and $\boldsymbol{p}_s$ is a vector with the primary sound pressure generated by the PW on the ES. $\boldsymbol{Z}_s^+$ stands for the Moore-Penrose pseudoinverse of $\boldsymbol{Z}_s$.

The resulting sound pressure on the control surface is given by

$$\boldsymbol{p}_r = \boldsymbol{p}_c + \boldsymbol{Z}_c \boldsymbol{q}_0, \tag{2}$$

where $\boldsymbol{Z}_c$ is the complex transfer-matrix between CS and the control surface points and $\boldsymbol{p}_c$ is the vector with the primary sound pressure generated by the PW on the control surface points.

The FF is then calculated based on the sound pressure with and without ANC, namely $\boldsymbol{p}_r$ and $\boldsymbol{p}_c$.

Simulated Model

Simulations where undertaken to verify the GA performance and the influence of some parameters on the final outcome. The primary noise source (until now considered to be a power transformer) was modelled as a group of eight SPS distributed on the vertices of a cube centered on the origin and with 2m side. Each SPS had a random complex volume velocity. As noise a 120Hz tone was used. 21 possible positions for the CSs were chosen in three planes in front of the octopole and 65 possible positions for the ESs where chosen on a sphere sector with 10m radius. The transducers were considered to be in free-field.

Influence of Fitness Function

The GA was used to choose five CS and six ES positions among all possible combinations (combined optimization, as discussed on the next section, was used). All optimization procedures were initialized with the same seed for the random number generator. Three FF were defined and compared.

The first defined FF is the most usual on ANC transducer optimization literature and calculates the ratio between total sound energy on the control surface with and without ANC. The total sound energy is estimated by summing the sound energy on every sensor used to represent the control surface. This FF may be written as

$$J_1 = 10 \log \left(\frac{\boldsymbol{p}_r^* \boldsymbol{p}_r}{\boldsymbol{p}_c^* \boldsymbol{p}_c} \right). \tag{3}$$

The second defined FF is the maximization of the smallest attenuation (or minimization of the largest gain). This is done by verifying which sensor on the control surface shows the smallest attenuation (or largest gain) and using this value as the FF, which can be described as

$$J_2 = \max_i \left[10 \log \left(\frac{p_r^*(i) p_r(i)}{p_c^*(i) p_c(i)} \right) \right]. \quad (4)$$

The last defined FF is an average of the attained attenuations over the control surface and can be described as

$$J_3 = \frac{1}{N} \sum_{i=1}^{N} 10 \log \left(\frac{p_r^*(i) p_r(i)}{p_c^*(i) p_c(i)} \right). \quad (5)$$

The conclusions that will be described shortly were reached after analyzing the results of several simulation outputs, which will not be shown in this document for brevity.

It was verified that the FF J_2 does only a punctual analysis of the control surface. The output is usually a very small region with very high attenuation and the rest of the control surface remains without considerable attenuation. Since for the optimization of ANC transducers' positioning a constant attenuation throughout the whole control surface is desired, this FF is not considered suitable for such application.

Comparing the results of FF J_1 and J_3, it is possible to note that the latter presents a much broader attenuation region. This occurs because J_1 tries to reduce the total sound power, which is obtained with a large attenuation over a small region of the control surface. On the other hand, J_3 tries to maximize attenuation (minimize gain) over every control surface sampling point, which results in a more widespread attenuation pattern.

Influence of Optimization Order

As stated by Snyder and Vokalek, the ANC transducer optimization is usually done independently, i.e., first the CS positions should be optimized (without regard to microphone position) and then, with a fixed CS position, the ES positions are optimized [5].

It is reasonable to say that after defining the optimal CS positions, and subsequently defining the optimal ES positions for the previously defined CS positions, there may exist new CS positions that enhance attenuation over the control surface, now considering the newly defined ES positions (that were not taken into account for the first CS optimization). Following this line of thought, it is now necessary to optimize the ES positions in regard to the newly defined CS positions, which leads to an iterative optimization process. It is important to mention that there is no warranty if the iterations of this iterative process indeed converge or if they converge to a global optimum.

To avoid bias from one optimization cycle to another, we propose a combined optimization procedure (used on the simulations from last section), that tries to optimize CS and ES positions simultaneously. For this method a new chromosome type must be generated, namely a concatenation of two chromosomes, one related to the CS possible positions and another related to the ES possible positions. Even though this approach increases the number of possible combinations at each population (slowing down the search speed), it may still be advantageous since it needs a single GA realization – while iterative optimization requires several GA realizations to converge (and may eventually not converge to the global optimum).

Simulations[1] show that with combined optimization a better result is obtained than with optimization of CSs followed by the optimization of ESs. The attenuation region obtained with the combined process was usually larger than that obtained with the iterative process.

If a second optimization cycle is added to the iterative method, first updating the CS positions for fixed ES positions and later optimizing again the ES positions keeping the last obtained CS positions unchanged, one verifies that the obtained attenuation region and chosen transducer position will be closer to those obtained with the combined method. The advantage of the combined method makes itself clear, since it arrives with a single GA run at the same result as the compound process arrives with several GA runs[2].

Conclusion

Genetic algorithms (GA) are a common tool used to optimize the position of control sources and error sensors used for active noise control. This article proposes two new fitness functions to be minimized by GAs, and concludes that the better approach is to maximize the average of the attained attenuation on every point of a given control surface. The other aspect of GA optimization investigated in the article was the optimization order. It was verified that the proposed usual optimization process suffers a bias effect. Two new methods were investigated, and it was verified that the "combined method" shows better results without increase in calculation time.

References

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[1] Using fitness function J_3

[2] Using a AMD Athlon XP3000 2, 1GHz with 512MB RAM each GA run takes about 10 minutes