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Extended summary

Innovative methods for modelling and design of compression drivers

Curriculum: Ingegneria Elettronica, Elettrotecnica e delle Telecomunicazioni

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Abstract. Loudspeakers design is a very complex task, since it involves different physical phenomena that have to be taken into account. Moreover, the driver mathematical description is quite complex and unfortunately it is not always available.

Considering the aforementioned scenario, a complete analysis of the compression driver de-sign process is reported in this dissertation. Since traditional design techniques may not be available for the driver, more advanced methods should be employed. Simulation is nowadays a very common approach in many engineering problems. Most of the available simulation soft-ware are based on the finite element method (FEM), which is a widespread technique for solving partial differential equations systems (PDEs). Compression drivers behaviour is based on a set of equations that involves not only acoustic, but also mechanics and electromagnetism, so specific simulators have to be use, capable of handling the interactions between different physics. The FEM simulators accuracy can be employed to optimize the driver design process. Starting from the above mentioned idea, a complete tool to support the compression drivers design process is presented in this thesis. The proposed approach makes use of an evolution strategies algorithm on the results obtained by the simulation of the driver with a commercial multiphysics FEM software, in order to optimize the driver parameters. The proposed algorithm has been tested on a

real driver design under different conditions and proved to be effective in enhancing the quality of the driver frequency response.

Another important aspect to understand the compression driver is the study of its nonlinear behaviour. The correct identification of these nonlinearities is fundamental, since it allows to evaluate flaws in the driver design or in its production process. Three different methods for the identification of nonlinear systems are presented in this thesis. The first one is based on the dynamic convolution method, exploiting the principal component analysis to improve the algorithm efficiency. The other two are adaptive techniques, that take advantage of orthogonal polynomial and of cubic splines characteristics. All the algorithms have been tested and compared with other methods already reported in the literature.

Keywords. Compression Driver, COMSOL Multiphysics, Evolution Strategies Optimization, Finite Element Methods, Nonlinear Systems.

1 Problem statement and objectives

Loudspeakers are widespread transducers in everyday life. They are present in most of our activities, even if we do not think about it. Every time we listen to music, there is a loudspeaker playing it, even when we talk at the phone there is a loudspeaker that reproduce what our interlocutor says. The early development of the direct radiator loudspeaker is due to Ernst Werner Siemens, who described in 1874 a radial magnet structure with a coil wire placed in it [1]. Over the years loudspeakers technology evolved enormously, thanks also to the very wide scientific production on the topic. New categories of loudspeaker models were created, in order to satisfy the applications needs, and special loudspeakers have been created for specific requirements. For instance, the small sizes of portable devices led to the development of very small loudspeakers, commonly called "micro-speakers". On the contrary, the high sound pressure levels needed in modern professional market and in public address applications, encouraged the diffusion of compression drivers. Compression drivers are horn loaded loudspeakers, capable of delivery a great amount of acoustic energy with very high efficiency. The development of horns technology dates back to the early XX century, since it was the only way to achieve high sound pressure levels from the contemporary loudspeakers.

Compression drivers are particular devices, since high efficiency are achieved through the insertion of a specific component, called "phase plug" [2]. The design of this element is crucial for the quality of the driver. Even if some models have been proposed for the analysis of the phase plug [3] [4], the description of its behavior is still problematic. Moreover, it is often difficult to find a closed form mathematical description of the driver, if it exists.

In this scenario, the application of modern analysis methods, based on the power of modern calculators, is essential. A very common technique to solve complex partial differential equations systems is the finite element method (FEM), which is based on the subdivision of the computation domain into many smaller and more simple regions. At the present time, there are many advanced commercial and academic software that implement this algorithm. Anyway, their application to compression driver is not always trivial, and some aspects require particular care in order to obtain correct results.

Another common problem in compression driver is their nonlinear behaviour. In fact, their small sizes and the presence of the phase plug may cause the distortion of reproduced signals. In the literature there are many methods, commonly called linearization methods, aimed at mitigating loudspeaker nonlinearities [5] [6]. All of them are based on the identification of the distortion to reduce, thus effective nonlinear models have to be introduced in order to apply linearization techniques. Nonlinear identification algorithms are very common in many application fields, from chemistry to medicine and biology.

The main topic of this thesis is the study of innovative techniques to model the behaviour of compression drivers and to support their design. In this sense, the development of suitable nonlinear identification techniques is central in this work. Moreover, advanced methods to support the driver design have been developed. The proposed approach is based on the exploitation of FEM simulators accuracy and on the versatility of "meta-heuristic" optimization techniques. The former is used to evaluate a possible driver configuration performance, while the latter leads the analysis towards the optimum solutions, on the base of the FEM results. The combination of these two elements allows to obtain high quality results in a relative short time, and without the need of human supervision.

2 Compression driver design optimization

Although there are some well-known techniques for the driver design and optimization [7] [8], nowadays the use of calculators and modern algorithms and methods are fundamental for quality driver development.

The finite element method (FEM) is a powerful mathematical theory that allows to approximate the solution of differential equations by dividing the solution region of the problem into many small, simple interconnected sub-regions called finite elements. COMSOL Multiphysics® ver.4.3b was adopted to study the driver in more detail and to use the simulation results for the driver optimization. The compression driver working principles involve different physical models that have to be taken into account in order to accurately simulate its behaviour. In the COMSOL software, each physic is represented by an interface, which implements the equations and the boundary conditions necessary to solve the finite element problem. For the driver simulation two interfaces have been inserted in the model, one to analyze the electromechanical part of the driver, and derive the driving force applied to the coil; and the second to study the structural behaviour of the diaphragm, and the sound pressure wave propagation through the phase plug and the surrounding volume. Even though FEM is a very common approach in compression drivers design, there are only few examples of complete simulations reported in the literature [9].

In this dissertation a new application is presented, which takes advantage of the accuracy of the results from multiphysic simulation in order to optimize the compression driver design process. In fact, the compression driver performance is influenced by many parameters related to the driver geometry and to the characteristics of its material. To derive an accurate model to support the design and to correctly set its parameters can be a very long task and may require a try and error procedure. Many algorithms that are capable of finding an optimal solution over an extended set of parameters are reported in the literature, but to the authors knowledge these techniques have never been applied to loudspeaker design process. Among them, stochastic optimization procedures are particularly suited whether a mathematical description of the problem is not available. The proposed approach makes use of the FEM simulator to get an accurate evaluation of the performance of the driver, and employ this information to adapt the optimization process. A scheme of the optimization cycle is reported in Figure 1. The adaptation of the parameters is performed through the iteration of four consecutive steps:

1. a set of driver configurations is simulated with Comsol;
2. results are evaluated in the Matlab® environment;
3. using the results of each configuration, a value of a predefined target function is calculated;
4. the parameters of the driver are modified according to the optimization algorithm, generating a new set of configurations to be simulated again in the first step.

The use of Comsol makes the integration of the algorithm quite simple, because of its strict connection with the Matlab environment.

The proposed tool makes use of an optimization algorithm to drive the simulation always towards better results, without any particular a priori knowledge, with the exception of the geometrical structure of the driver and its material properties. In this sense, the choice of a suitable optimization algorithm is of utmost importance since it constitutes the core of the application. The tool is based on the (μ-λ)-evolution strategy (ES) algorithm [10]. This technique is particularly suited for the drivers optimization, because it is able to search for optimal solutions on continue real valued spaces, and to evaluate even nonlinear

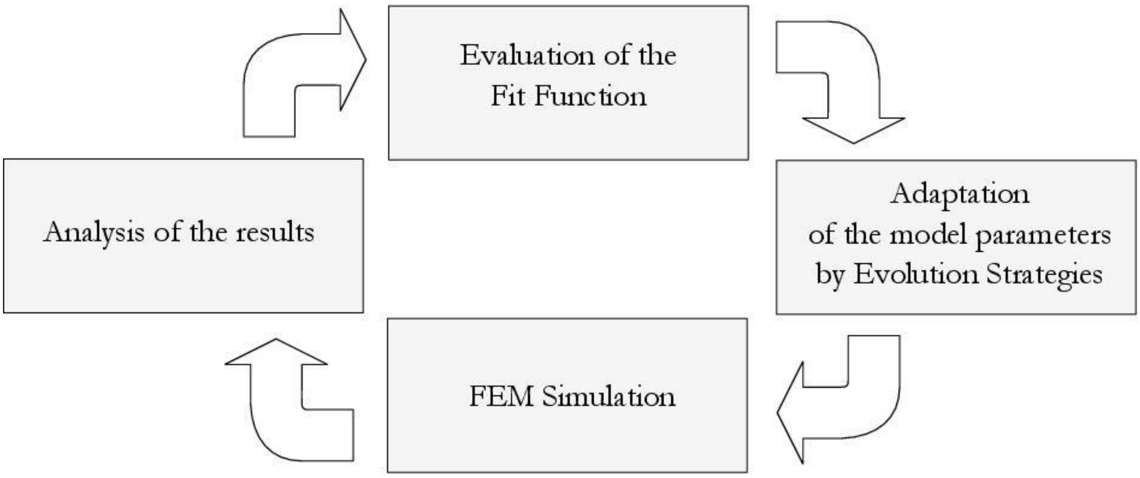

Figure 1 - Proposed algorithm structure.

or non-analytical target functions. Moreover, the (μ-λ) extension of the classic ES algorithm allows to use parallel computing and enables the self adaptation of the parameters that control the optimization process. The algorithm operates on a population of individuals, each one representing a point in the space of the possible solutions, identified by a set of parameters. The evolution of the parameters is regulated by random mutation, recombination, and selection. The quality of a solution is evaluated according to a fitness function, which influences the selection process in order to favour the better individual to reproduce more often, thus leading the set of parameters towards the optimum. A very simple version of the ES algorithm can be synthesized as follows:

1. initialization of the population;
2. recombination of the individuals;
3. mutation of the individuals;
4. evaluation of the individuals and selection of the fittest.

The set of operations is then repeated until a stop condition is met. Moreover, the (μ-λ) version of the ES algorithm introduces the idea of self adaptation of the parameters.

2.1 Proposed approach evaluation

In order to prove the effectiveness of the proposed approach, the algorithm has been applied to the optimization of a real driver design. In its original configuration, the driver frequency response had two evident notches at about 5.4 kHz and 6.5 kHz. Since we wanted to solve this specific issue, the optimization process has been limited in the frequency band from 5 kHz to 10 kHz. A 2D axial-symmetric Comsol model of the driver with a parametric phase plug has been developed. The geometry of the plug has been described by a set of 12 parameters corresponding to the coordinates of the phase plug vertices and a frequency domain analysis with a logarithmic sweep of 26 frequencies has been carried out. The choice of the parameters is arbitrary and related to the specific case study, other solutions may include for instance the material properties as optimization variables. The implemented model is completely coupled and takes also into account the thermo-viscous effects. The on axis sound pressure level at a distance of 1 meter has been evaluated as output for each simulation. The optimization process has been programmed in the Matlab environ

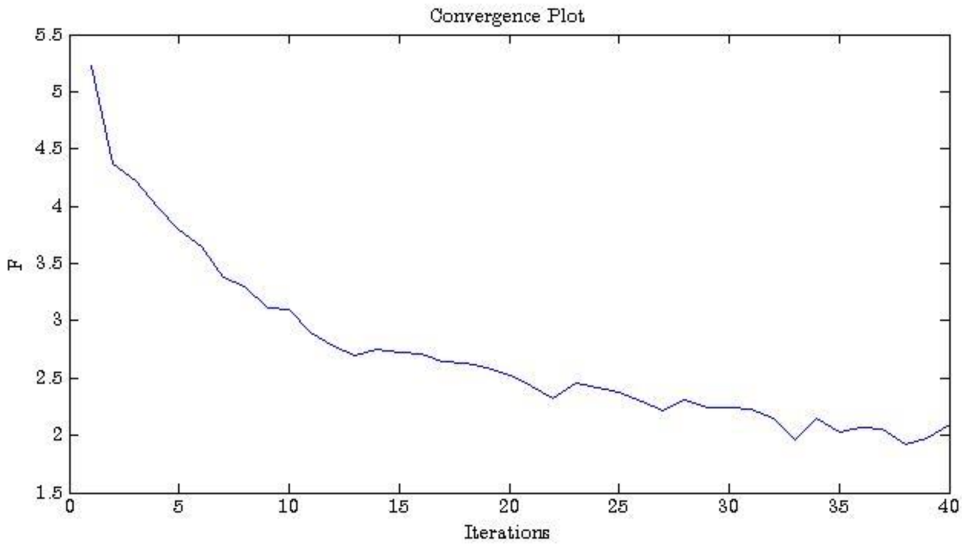

Figure 2 - Convergence plot of the optimization algorithm. The value of the fit function of the best individual is reported against the iteration number.

ment, defining the initial conditions for the parameters and their limits, together with the control variables of the algorithm. The population is composed of 10 configurations, that generate 20 new individuals at each iteration. Population is initialized with a random variation around the original driver configuration and σ and Δσ has been set to 0.2. In order to reduce the notches we applied a 13 point smoothing to the frequency responses obtained by the simulation, and compared the result with the same unsmoothed responses. In order to choose the fittest individuals we applied a minimax decision criterion to the difference in the frequency domain between the smoothed and the unsmoothed version of the responses. The fit value for each individual is therefore calculated at the iteration *g* as:

$$F^g = Max\left[\left|\hat{f} - f\right|\right],$$

being $\hat{f}$ and f the smoothed and unsmoothed version of the frequency response, respectively. Then, the optimization algorithm tries to minimize the value of the fit function, choosing at each iteration the individuals with the lower values of *F*.

3 Results discussion

The convergence of the optimization algorithm is shown in Figure 2 by plotting the value of the fit function of the best configuration at each iteration. The process reaches a relative optimum after about 35 iterations. In Figure 3 the frequency response of the optimized configuration against the original configuration is reported. It is clearly visible that the optimization process succeeded in eliminating the notches in the frequency response as we expected. It is worth noting that the optimized result has been identified without any a priori indication about the driver behaviour and without any need of human

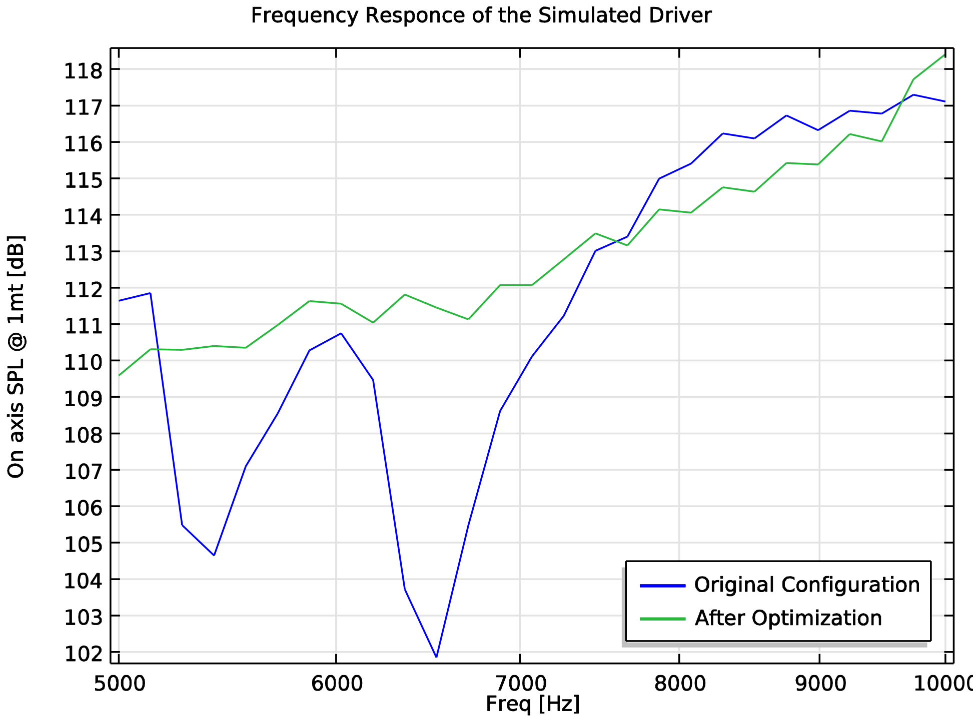

Figure 3 - Comparison of the driver frequency response before and after the optimization process.

supervision during the process. For this reason, the correct choice of the decision function is of utmost importance in the spot of the optimal solution.

4 Driver nonlinearities identification algorithms

Loudspeakers present several nonlinear behaviours when driven with high level signals. The causes of the distortions are various and related to different phenomena, such as movement of the coil, variable stiffness of the suspensions, pressure dependent sound speed [11] [12]. Even though these effects are poor in compression drivers, compared with low and medium frequencies loudspeakers, due to the narrow movement of the coil above the resonance, the study of nonlinear effects can be of great importance in order to identify anomalous behaviours in the driver development.

Nonlinearities can be indicative of design or construction issues, therefore to be able to correlate a nonlinearity measure to its cause, it can be a useful diagnosis tool. The measurement and identification of distortions and of their causes from some accessible signal is not straightforward and many techniques have been reported in the literature over the time in order to do this. Some new methods for the identification of nonlinearities have been presented in this dissertation. The algorithms are both static and adaptive. In the first case an extension of the dynamic convolution technique, exploiting principal component analysis has been presented in order to improve the efficiency of the traditional algorithm. Moreover, two adaptive techniques have been proposed. The first one is based on the orthogonalization of the input signals, using the Legendre's polynomials features. Orthogonalization allows to use simple adaptation algorithms without loss of accuracy. The second method is based on a parametric representation of the nonlinearities (i.e. by using a cubic Catmull-Rom spline) and is particularly suited with asymmetrical nonlinear characteristics.

5 Conclusions

A complete review of the compression driver design theory and techniques has been presented in this dissertation. The study of the compression driver reveal a very complex scenario, since there are many different and variegate factors that influences the driver response. It has been also shown how the driver, when excited with sufficiently high signals, may exhibits nonlinear behaviours.

The nonlinear behaviours, together with the intrinsic complexity of the compression driver, makes the formulation of a closed form mathematical expression of the design process as a whole quite impossible. In this case, some advanced tools can succeed in analyzing the driver behaviour. It has been shown that the finite element method is particularly suited to solve driver models, also by integrating the different physics from which it belongs to. In order to exploit the FEM results in an efficient way, an advanced optimization algorithm, namely the (μ-λ) version of the evolution strategies method, has been implemented and integrated with a commercial multiphysics FEM simulator. The optimization algorithm retrieves the results of a parametrized driver FEM simulation and, analyzing them on the basis of specific fitness functions, is capable of driving the design process toward an optimal solution, thus allowing the engineer to save time and to achieve high quality levels. To the author knowledge, the integration between an optimization software and a FEM simulator has never be adopted in the field of compression driver design, even if it is a widespread method in other engineering fields. The proposed design technique has been integrated into a specific tool and a custom user interface has been created, by using the MATLAB Guide environment and the COMSOL Java APIs. A case study on a real compression driver showed that the tool is effective in improving the quality of existing drivers, according to some specific frequency response evaluation indexes, and that it can be a useful tool to support the engineer on the design of new compression drivers.

Some new techniques for the identification of nonlinear behaviours have been presented in this thesis. The proposed methods allow to efficiently model a nonlinear device behaviour, according to different structures. In the first method, an extension of the classic convolution operation, the dynamic convolution, has been improved by decomposing the signal into its principal components. This allows to significantly increase the algorithm efficiency and to reduce its computational cost. Moreover, some new adaptive structures for nonlinear identification has been proposed. In particular, the orthogonality properties of the Legendre polynomials has been exploited in order to improve the convergence of a parallel nonlinear adaptive filter. It has been proven, by comparing the algorithm with other techniques already present in the literature, that orthogonality of the input signals is a convenient condition for parallel filters adaptation.

In addition, a new adaptive structure based on the use of a cubic spline has been presented to identify a nonlinear model. The linear part of the system has been implemented with a FIR or IIR digital filter, while the nonlinear part has been modelled through a parametric curve, namely the Catmull-Rom spline, because of its advantageous properties. Several tests has been performed, showing that the proposed method is effective in modelling nonlinear devices, especially when severe or asymmetrical distortion are present.

6 References

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