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INFLUENCES OF NUMERICAL PARAMETERS ON SOUND PERCEPTION OF SIMULATED TRANSFER PATHS

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ABSTRACT

In many industrial applications, and especially in transport industry, sound perception is an important aspect manufacturers have to consider during the development phase of their products. At this step, numerical models are often used to solve the partial differential equations governing the problem. On one hand, a disadvantage of such numerical methods is the high computational cost to pay when a fine representation of the physics is necessary. On the other hand, the human hearing system has some limitations and cannot perceive all the details of the physical sound. It appears therefore reasonable to reduce the accuracy of simulations, though maintaining them "fine enough" to ensure that computed sounds can be used in sound quality experiments. This paper investigates the effect of several numerical parameters on the perception of sounds obtained by convolving a simulated transfer path (TP) with a recorded sound signal. The transfer path is simulated via a Finite Element (FE) model validated with a physical mockup and taken as reference. Then, the same transfer path is simulated using less accurate Finite Element models and a sensitivity analysis checks how those changes affect psychoacoustic metrics associated to sound quality. Finally, hearing tests are conducted to determine the effect of calculation parameters on the perceived similarity between sounds.

1. INTRODUCTION

The current automotive market is extremely competitive and dynamic, forcing enterprises to innovate and renew their portfolio at a quick pace. This pressure comes has multiple causes. On the one hand, due to concerns about public health and related issues, institutions are enforcing very stringent regulations. On the other hand, customers expect high-quality products. Consequently, besides regulations regarding the overall sound level, car manufacturers pay attention to the so-called sound quality of the car, namely how the potential customers perceive the emitted sound. Companies run in-depth studies to evaluate the sound-quality of their products, involving several kinds of test and requiring economic effort.

A common approach is to rely on CAE tools, which allow to get satisfactory results. Auralization techniques allow humans to hear and evaluate the simulated sounds [1]. Still, the computational cost associated with simulations is responsible for the elongation of the design phase, in terms of time. Not even the most recent software products manage to escape from this issue. The field of acoustics is notably delicate from this perspective, since numerical simulations are often computational costly.

How can scientists help in solving this issue? Many paths might pave the way to the solution but, as usual in applied science, these paths are often limited to a particular class of problems. So the first step is to identify a cluster of applications that share some peculiarities.

A particularly important set comprises all the problems in which sources, transfer paths (TP) and receivers act independently to a satisfactory degree. In this class, by associating a transfer function (TF) to each TP, the sound at the receiver results in a simple combination of the source signal and the TF itself. In such a way, engineers can analyze sources and TPs separately. The receivers can stay out of the simulations in most cases (e.g. when engineers want to perform jury tests without earphones and when they can rely on psychoacoustic metrics). The focus of this research is on the simulated TPs.

What about the TFs? An easy solution is to calculate them via frequency-domain approaches, so that the combination of TFs and sources becomes a simple convolution in time-domain. In detail, the inverse Fourier transform modifies these TFs into their equivalent IRFs, thus removing the constraint of time-harmonicity.

The main technical issue is that a unique simulation method able to tackle the typical engineering problem does not exist. Deterministic techniques such as the Finite Element Method (FEM, [2]) have proved to be very efficient in the low-frequency range. In order to increase the frequency range of their applicability, researchers tried several diverse approaches, developing techniques able to reduce the computational cost of simulations (see, for instance, [3]). Despite the effort, simulations continue to be time demanding in most applications.

An alternative approach to the mentioned techniques is in theory possible. In most applications, a certain degree of error is acceptable, and an accuracy higher than such error is meaningless. What could happen if less precise simulations would be satisfying for some applications? Engineers could diminish the quality of the simulations, thus saving significant amount of time, while still getting useful numbers. This idea makes sense especially in the case of sound quality applications, due to the variations in acoustic per-

ception of humans. As a first step in this direction, the relationship between the simulation error and human perception need to be understood. In this context, Pulvirenti et al. [4] analyzed the effects of finite element errors into perceptual similarities. In that work, the authors used different FE models to simulate the same TP. Since the considered TP was between a tire and a pedestrian, the resulting FE models were unbounded. Infinite elements (IE, [5]) were used to ensure the Sommerfeld radiation condition. In practical terms, the infinite volume was truncated at an artificial boundary Γ_A, the volume inside Γ_A, was discretized via FEM, and the IEs applied on Γ_A. The IE formulation is based on the decomposition of the outgoing waves into multipole expansion, and they take into account only the first $\mathfrak{p}_{IE}$ expansions. The models didn't include a full vehicle geometry, but an idealized quarter vehicle model with rigid surfaces.

By changing the following numerical parameters:

1. size of the finite elements $\mathfrak{h}$ (0.11, 0.056 and 0.037 mm);
2. order of the polynomial shape function $\mathfrak{p}_{FE}$ (1 and 2);
3. order of the infinite element interpolation $\mathfrak{p}_{IE}$ (2, 5 and 7),

the authors obtained eighteen numerical models and, therefore, the same number of TFs (each representing the same TP). These simulated TFs were used to obtain several sounds by means of convolution, always using the same source signal. Because the source signal was constant, the differences among the auralized sounds could be imputed completely to the numerical errors. More precisely, since the surfaces were rigid, the error was only due to the changes in the three parameters previously mentioned ($\mathfrak{h}$, $\mathfrak{p}_{FE}$ and $\mathfrak{p}_{IE}$).

The sound auralized starting from the most accurate simulation was taken as a reference sound, and all the other sounds were compared to it. An analysis of loudness L (modeled according to Moore and Glasberg's model, [6]), revealed that changes were always equal or lower than 10%. Jury tests were conducted to have more significant results. A panel of people compared each of the auralized sounds with the reference one. A score between 0 and 10 was assigned to each auralized sound, depending on how similar it was to the reference. The minimum score, 0, meant that perception of the sound and the reference was equal; on the other hand, a score of 10 indicated an important difference. The reference sound itself was part of the jury test (that is, it was compared to itself). Jury tests revealed that the parameters inducing more changes was the order of interpolation of FE $\mathfrak{p}_{FE}$, followed by the average size of elements $\mathfrak{h}$. The order of interpolation of infinite elements did not play a significant role. These results are in accordance with theory, but further investigation is needed to generalize. Most importantly, two critical points were missing, and it is the purpose of the present work to discuss them.

First of all, although loudness plays a critical role in perception, it is not the only psychoacoustic metric that gives clues about the perception of a sound. In the case of FE simulations, accuracy decreases with the increase of frequency, and the most natural metric allowing to describe timbral differences in the high-frequency range is sharpness S (modeled according to Zwicker [7]). The change in sharpness is found to be more significant than the one in loudness, as expected. Even in this case, results suggest that the parameters inducing more changes is $\mathfrak{p}_{FE}$, followed by $\mathfrak{h}$. The considerable differences in sharpness are a further indication that human perception and numerical errors go together in the same direction.

The other critical point is related to the repeatability of these results. If they are not repeatable, they lose most of their significance for practical applications. However, the FEM accuracy cannot be precisely calculated. Common mathematical formula available only fix an upper bound to the error, like the one proposed by Ihlenburg [8]. Also, other factors can affect the precision. For instance, when using infinite elements, the more the distance between the artificial boundary Γ_A and the receiver, the better is the accuracy. This effect comes from the multipole expansion: each term of the infinite series is pondered by a factor $\frac{1}{r^n}$, where n is the order of the term. In the infinite element method, terms of order n higher than $\mathfrak{p}_{IE}$ are neglected, but when the distance increases, they become less important because of the pondering factor. Hence, the approximation quality increases. The use of an objective metric can help in overcoming these issues. In this research, the authors choose to use the response vector assurance criteria (RVAC). The RVAC compares two models with several TFs, not the TFs themselves, thus being a global metric. The comparison is in terms of correlations between the TFs, resulting in no information about amplitude available. In this case, the RVAC is calculated between each model and the reference model (namely, the more accurate one). It is found here that perception of sound similarities are strongly related to this metric. In particular, the lower the RVAC with respect to the reference model, the biggest the differences perceived between two sounds. More precisely, in this case the curve representing perceptual differences in function of the RVAC is monotonic; however, there was not a clear threshold of the RVAC below which sounds become statistically different. In details, four sounds were found to be statistically comparable to the reference sound (here statistically comparable means that the 95% confidence interval overlap). All of these sounds have a RVAC higher than 92%, while the first statistically different sound has an RVAC of 90%. Authors do not expect always to find a monotonic relation between objective metrics such as RVAC and similarity scores. Especially in the case of very similar numerical models, a monotonic $trend$ rather than a monotonic $function$ is more likely (and slightly different values of the RVAC threshold could be found). Further research is needed to make such a statement.

These results represent a confirmation of what previously found, and further prompt a possible exploitation of

psychoacoustic properties to define appropriate numerical settings that would lead to a diminishment of computational time.

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