Design optimization in vibro-acoustic design of hearing instruments

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Abstract: In the design of hearing instruments it is important to achieve as high gain as possible without causing oscillation in the device, due to feedback between the microphones and the receiver (loudspeaker). More gain enables to fit a larger hearing loss and more users can benefit from the hearing instrument.

Since the feedback path is very complex with many variables it is difficult to make the right "guess" for optimal configuration (material parameters, geometry, contact properties) of the hearing instrument parts.

Different approaches have been used for optimization of a validated FE model of a BTE (Behind The Ear) hearing instrument. Manual optimization where best guesses, derived from experience, hypothesis and experiments, have been analyzed together with commercial software tools, which runs the optimization in a systematic process. Abaqus Standard from Simulia was used to build the model and to run the analyses.

The outcome of the optimization process has been analyzed and compared with physical experiments. The outcome also tells which parameters are governing the feedback path and which parameters could be relaxed.

Keywords: Acoustics, Structural-Acoustics, Design, Optimization, Hearing Aids, Vibro-Acoustic, Feedback, Microphones, Receiver, Loudspeaker, Sound Tube, Hook, Ear, Hearing, Life Science, Medical, Hearing Instrument.

1. Design optimization of a hearing instrument

1.1 Purpose of the optimizations

The purpose the optimization process is to minimize the feedback path between receiver (loudspeaker) and microphones so that the resulting gain in the hearing instrument is as high as possible.

The purpose is also to get an understanding for which parameters are the most important for achieving the highest gain possible.

1.2 Description of a hearing instrument

The amount of sold hearing instruments are about 6 millions pieces/year world wide, so the market is small compared to e.g. mobile phones (~800 millions/year and increasing). A hearing instrument consist of a microphone(s), amplifier/computer, receiver (=loudspeaker) as shown in figure 1.

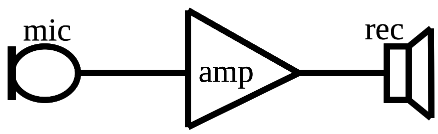

Figure 1, Simple hearing instrument

The amplifier/computer shapes and amplifies the sound picked up by the microphone. The computer works like a normal PC. There is an OS and different applications (feedback suppression, speech enhancement, directionality improvement, noise suppression etc.) running simultaneously.

Figure 2, Picture of hearing instrument, GN ReSound Azure71

Inside the shown device in figure 2, the sound pressure in the sound port of the receiver can be up to 170 dB sound pressure level (SPL). The loss through the long sound tube is approximately 25 dB before the sound reaches the eardrum of the user. The gain between the incoming sound pressure and the sound pressure at the eardrum is in this device 73 dB, but can be up to 80 dB.

1.3 Primary acoustic challenges in developing a hearing instrument

The primary challenges in developing a hearing instrument is to design for highest possible gain with smallest possible size of the hearing instrument. The trend for visual design is the smaller the better. But the closer the receiver (loudspeaker) is to the microphones the more difficult it is to obtain high gain without feedback. The decreased space inside the hearing instrument also demands for higher creativity to avoid feedback between microphones and receiver.

1.4 Description of the simulation model

A BTE (behind the ear) hearing instrument connected to a PVC tube and a 2cc coupler is simulated as a fully coupled structural-acoustics system using Abaqus. The input excitation to the model is obtained from a receiver. The analysis is started with a static step with shrink fit, then modal analysis and steady state dynamics response (linear perturbation) are performed on the model.

A simplified geometry is made for the housing of the device.

A physical model is made from the simplified model geometry to verify the simulation model.

All Parts are imported in using the Pro/ENGINEER Associative Interface and repaired for optimized meshing.

The parts consisting of air, both inside in tubes and outside the device are made from the imported geometries as Boolean cut’s in and hereafter adjusted to fit.

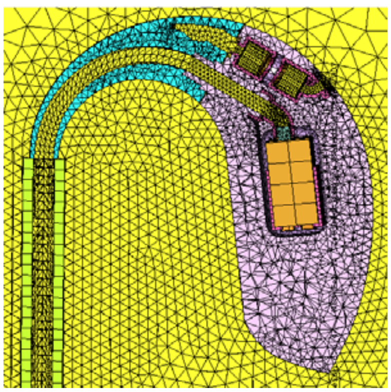

Figure 3, Picture of the simplified model

Standard available material data are used as a starting point. Then small beams/material pieces are produced and shaken. The velocity transfer function between end of beam and shaker is measured and compared to simulation of the same setup. If necessary then the material parameters are changed.

The friction in air (as volumetric drag) in narrow slits and thin tubes is also an adjustment from measured sound pressure results to the simulated response.

Surface impedances on the perimeter of the exterior air volume represents infinite air conditions. It couples the structure to air without the need to have matching meshes in air and structure and it can couple separately meshed air volumes together.

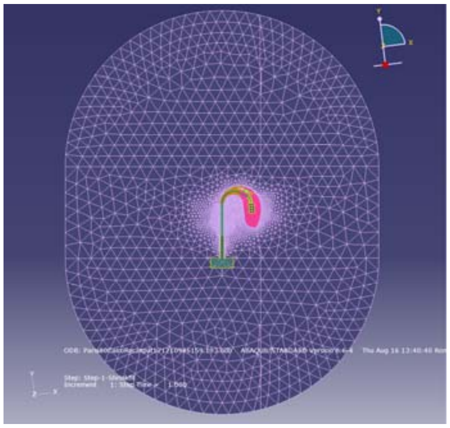

Figure 4, Picture of the model, with external air

Three major steps were performed:

- Shrink fit to make rubber parts slide over plastic parts with a final pretension of the rubber.
- Modal analysis was performed with Lanczos eigensolver Using structural-acoustic coupling were applicable when total modes analysis is done
- Steady state dynamics response (linear perturbation)

The model was validated with real physical prototypes made exactly like the parts used in the simulation. Validation started with comparing measured and simulated values of the input parameters to the model. The latter validation consisted of control measurements on surface vibrations of the model, measured with laser-vibrometry as seen in figure 5, where a measured and simulated curve is shown. The curves are not matched 100% but as long as the peaks and valleys in the response follow then it is sufficient.

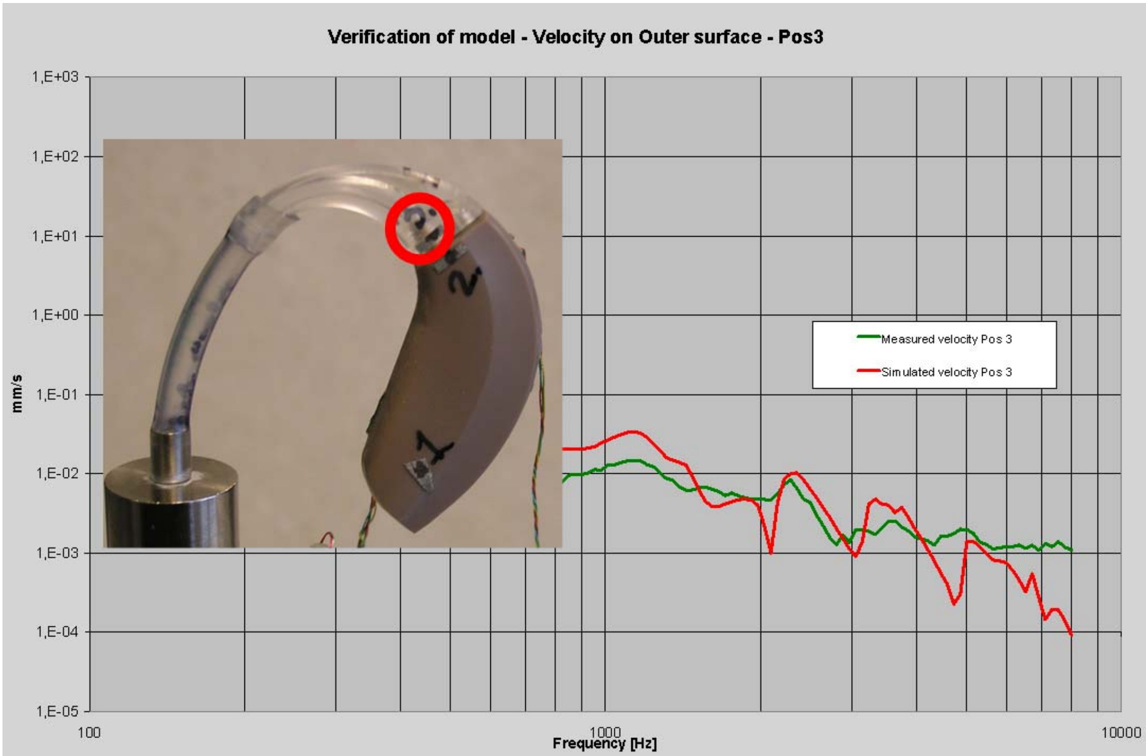

Figure 5, Validation of model with laservibrometry

3D acoustical holography was also used to validate the radiated sound pressure from the model as shown in figure 6.

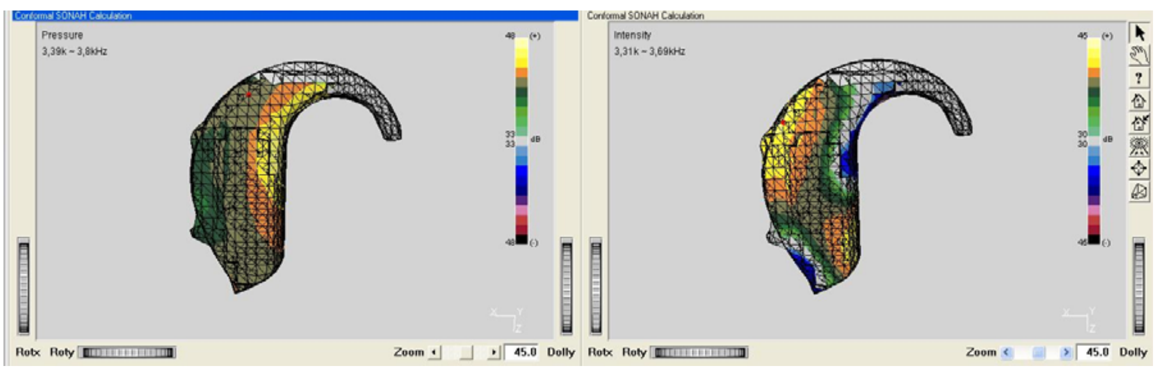

Figure 6, Picture of 3D acoustical holography

1.5 The optimization process

1.5.1 Validated simulation model

The simulation model used in the optimization process has been thoroughly validated and has proved it's reliability, so we have high fidelity in the results from the optimization.

When choosing the parameters for the investigation we only chose values which also could be realizable in practice.

1.5.2 Manual optimization

The manual optimization consisted of trying out all our hypotheses for minimizing feedback. This process resembled the trial and error approach we also do in parallel with the simulations. With manual optimization we already see savings in development time and can jump over several iterations and save on prototyping.

It was very time consuming due to the large amount of data and manual work. Another disadvantage was also that our "guessing" on best performance would not cover all combinations of the chosen parameters.

There is also an uncertainty factor for when you will make the right guess. This uncertainty seems much smaller with automatic optimization.

1.5.3 Automatic optimization

Different parametric optimization software (Isight and Modefrontier) were tried out with great help of the suppliers. The benefits of the optimization software were quickly discovered.

- better handling of the output results
- little manual work (when optimization flow is working)
- all combinations are systematically tried out
- good tools for analyzing the output data

The model was simplified mainly in the frequency resolution before the optimizations began.

Five different parameters were chosen as variables, whereas 2 parameters were changes between 3 different materials and the 3 others where changes in density and stiffness.

1.5.3.1 Optimization with Isight

To randomly spread the parameters within the design space and cover the different possible configurations in an optimum way, the Optimal Latin Hyper Cube is used. This is done to minimize the number of analyses and is defined in the DOE component (Design Of Experiments).

For best practice the number of runs were (n+1)(n+2) = 42 for 5 parameters.

The Data Exchanger component in Isight was used to rewrite the Abaqus input file for changing between the different materials.

The Abaqus component is used to vary density for 2 parts and stiffness for the last part.

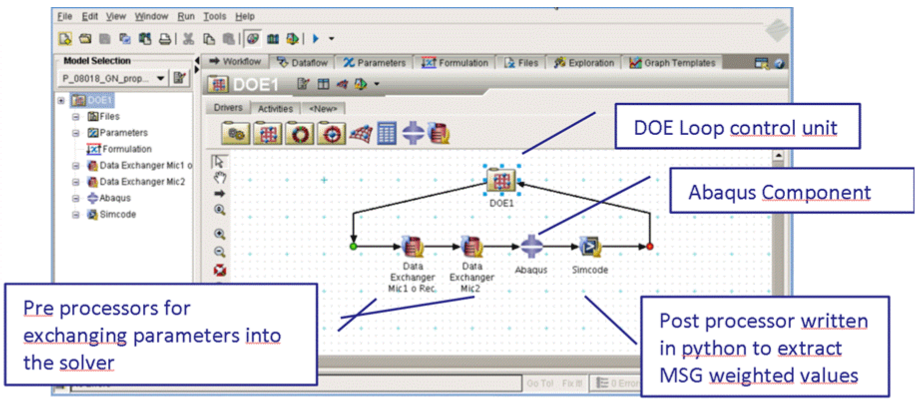

Figure 7, Setup in Isight

A Python script was used to evaluate the results and compare to a target curve. The target curve was defined as the maximum gain in the model without feedback as it was before the optimization. If the optimization process came up with higher possible gain then we have reduced feedback.

Two weighting functions were used to maximize the targets and make them more visible in the data. The weighting functions could also be used to let Isight search in the design space and price the solutions according to the weighting functions, but this was not done due to the small amount of solutions. The first weighting function weighs the solutions that have a value greater than 5 dB above a target value. The second weighting function then weighs the solutions which have high values compared to target in a specified frequency range.

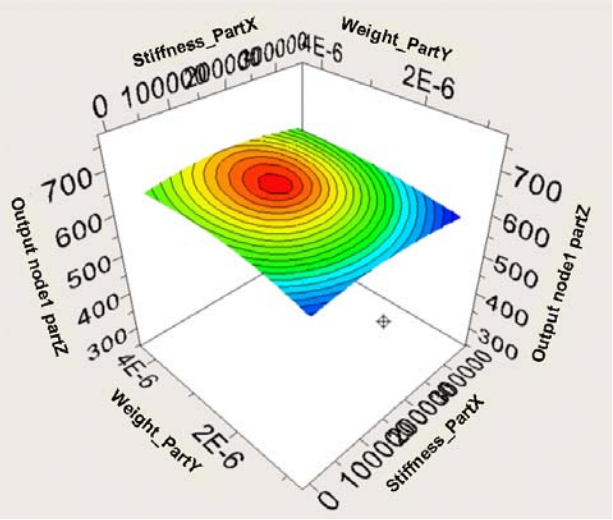

Figure 8, Response surface for part_Z using different parameters for Part_X and Part_Y

Figure 8 shows the optimal parameter for the 2 most dominating parameters for Part_Z. The highest spot (red area) for the surface gives the optimal properties for Part_X and Part_Y.

1.5.3.2 Optimization with Modefrontier

The same 5 parameters is also used in Modefrontier together with 2 targets. We had a target function that awarded the highest value in the frequency range and another function that awarded the highest average measure in the same frequency range.

In the DOE a SOBOL algorithm is used to spread and randomize the variables, so we use as few points as possible to build knowledge about our system.

10 SOBOL steps (designs) were used (thumb rule is 2 x input variables = 10 for 5 variables). If we knew more about how our model works and which parameters we should use, then we could also have included these together with the SOBOL to get a better starting point of the optimization process.

The real optimization is done with a MOGA-II (Multi Objective Generic Algorithm). MOGA works with generations, where 1 generation consist of number of starting points (designs) in the DOE (10 points), then MOGA picks out the best designs within the generation and continues with these. The designs are picked out by 3 operators: **Selection** (a "good" point from the old generation is copied to the new generation and the old ones are "forgotten"); **Recombination** (2 points from the old generation is paired to make new better designs); **Mutation** (some points are mutated (varied) a little to find a better design).

Every design is awarded a quality measure depending how well it fits the target functions.

A thumb rule is that 10 generations should be enough, but it depends if the response of the model is linear, non-linear or very unfeasible. We ran approx 14 generations.

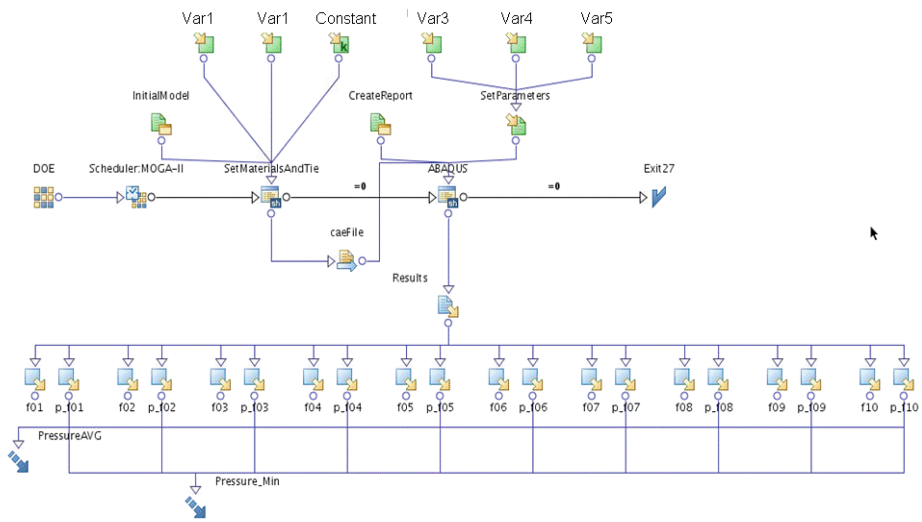

Figure 9, Setup in Modefrontier

Figure 9 show the flowchart setup in Modefrontier with the 5 variables and the 2 target functions Pressure_Min and PressureAVG.

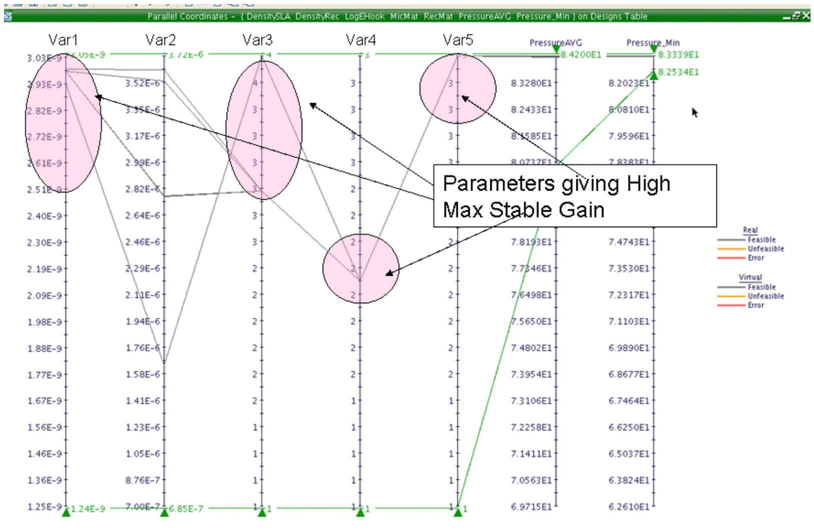

Figure 10, Parallel coordinates show the best designs for a given target function

1.5.4 Outcome of optimization process

The outcome of the process is used to understand which parameters are controlling the complex transmission.

With the manual optimization it was only possible to make 2 - 3 dB improvement in the desired frequency range. The largest effects were seen at lower frequencies where no improvements were needed. There were no clear dominant parameter.

With both Isight and Modefrontier it was possible to make approximately 6 dB improvement in the desired frequency range, which is significantly enough to plan a business case where the economics for making changes are included. The most dominating parameter along with 2 other minor dominating parameters were found. These results will directly be implemented and used in the next hearing instrument projects.

1.5.5 Validating of the results

Prototypes with the new optimized parameters are currently built and measured for comparison of the results from the simulations. The prototypes are built under microscopes since they are very small and the adjustments to first prototype are with a precision of 0.05 gram. Assembling is also critical since the smallest leakage can ruin all improvements and the contacts between the different parts must also be done precisely as in the simulation model.

1.6 Conclusion

The feedback path between receiver (loudspeaker) and microphones were minimized by approximately 6 dB by using automatic optimization compared to 2 - 3 dB with manual "trial and error" optimization.

The most dominating parameter and 2 other minor dominating parameters were found for achieving the highest gain possible.

It is important to remember that the so-called automatic optimization is not automatic in the sense that you manually have to choose the parameters you want to include in the process. The hearing instrument simulation model is still so complex so we cannot include all parameters in the model due to computation time.

The reason for trying 2 different optimization programs was not to benchmark the 2. They were also not having identical setup.

We have seen that the optimization programs are superior to manual optimization. They will more quickly investigate the design space and we can faster jump over iterations and save prototyping time.

1.7 FEA in GN Resound

We have used Abaqus since 2002. The first years were used to "validate" the program and build confidence around the simulation approach compared to trial and error approach. There were several barriers before it succeeded. The first barrier was that the software and license is an expensive investment compared to other software and also in the first place more expensive than to build more prototypes. The second barrier was the cost of engineering hours. Should the engineer hours be spent on the "safe" trial and error approach or on the (at that time) uncertain simulation approach? The uncertainty and doubt arose because hearing instruments are very small compared to other products where simulations were widely used (automotives etc.). The next barrier was to make changes in the project plan and add time for simulations in the beginning of the project and then cut down on trial and error time later on. In the beginning it took relatively long time to build the models and was therefore not appreciated when doing the project plan. But that building time has been greatly reduced.

We are now at a stage where FEA is a trusted tool, and we have several times proven the benefits from simulation. FEA is now a natural part of the project plan and implemented in many technology projects and we are striving to minimize the time for a simulation job to make the results more valuable.

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