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Reducing offshore pile driving noise: Shape optimization of the impact hammer

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Abstract

Offshore wind energy is an emerging source of electricity generation and new offshore wind parks are under construction around the world. The foundation of offshore wind turbines is most often realized driving steel monopiles into the sea bed using impact hammers, a technique that causes high underwater sound pressure levels threatening to harm marine mammals and other sea life. In order to protect the marine fauna, limiting values have been introduced by several countries. Their fulfillment until now has been possible applying state-of-the-art sound mitigation systems. However, rapidly increasing dimensions of wind turbines with accordingly increasing pile diameters require an ongoing development of sound mitigation systems. Nowadays applied sound mitigations systems, e.g. bubble curtains, reduce the propagation of the emitted sound, but do not affect its generation. Therefore, modifying the sound source, i.e. the hammer and pile, to reduce the generation of the sound, has recently gained attention. This contribution focuses on the development of a hammer that causes less noise but is still capable of driving the pile. First results of optimizing the shape of the impact hammer regarding its acoustic characteristics are presented.

Keywords: offshore pile driving, impact hammer design, shape optimization, particle swarm optimization

1 INTRODUCTION

In order to construct an offshore wind park, piles are often driven into the sea bed to serve as foundations for wind energy turbines. In order to drive these piles, an impact hammer, usually consisting of two main components, namely an impact weight and an anvil, is used. During pile driving, the impact weight falls repeatedly on the anvil resting on the pile head. The anvil then transmits the impact to the pile, driving it into the sea bed but also deforming the pile. The pile deformation excites sound waves in the surrounding water as well as in the sea bed, often causing high underwater sound pressure levels. As these sound emission may harm marine mammals and fishes, several countries have defined official limits that the sound pressure levels must not exceed.

To comply with these regulations, several noise mitigation systems, e.g. bubble curtains, have been developed and successfully applied. However, the capacity of offshore wind turbines and with them the pile diameters are steadily increasing, causing even higher sound pressure levels. For this reason, in addition to existing approaches to hinder sound propagation, the development of an impact hammer with improved acoustic characteristics has been recently gained attention.

This contribution focuses on the optimization of the shape of the main hammer components, i.e., impact weight and anvil. Since no explicit analytical relationship of the hammer shape, defined as parameter vector θ, and sound pressure levels (SPL), i.e. SPL $= f(\theta)$ can be formulated, the optimization relies on numerical methods. Here, particle swarm optimization (PSO) is applied, an optimization method that only relies on the function evaluations $f(\theta)$, i.e. no gradients have to be computed numerically, and has been successfully applied in the context of shape optimization, [1].

2 NUMERICAL MODEL

Two axisymmetric finite element (FE) models are used to compute the sound excitation and propagation caused by the hammer impact on the pile. The first model includes only hammer and pile and serves to simulate the impact and to obtain the resulting deformation of the pile head. The pile head velocity $v_{\mathrm{p}}(t)$ is then passed to the second model, used to model the propagation of waves in pile, water, and soil. The described modeling approach is visualized in Figure 1. Further specifications of the FE models can be found in [2], [3].

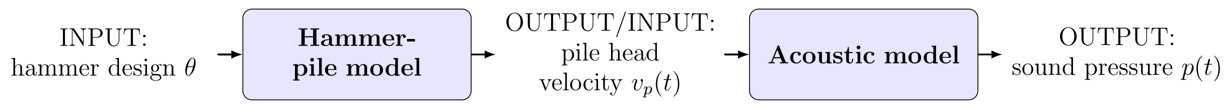

Figure 1. Modeling the underwater sound pressure as a result of pile driving.

For the present contribution, the second model covers the propagation in water and soil up to 30 m distance to the center of the pile. Although official limits include the SEL in 750 m and beyond, a relatively small model is applied here, to keep the simulation time short and therefore the model suitable to be used within an optimization. However, a larger model would also include sound waves traveling in the sea bed whose contribution to the SEL depends largely on the soil properties at the ram location. Therefore, a smaller model also serves as a model less dependent on the specific location of the driven pile and therefore might be beneficial for the purpose of defining a hammer design causing less sound emission independently of the specific site.

An approach to increase the considered range and additionally decrease simulation time is to replace the second FE model by a transfer function. This approach is described in a publication by the same authors, in [4], but has not been applied for the present contribution.

Here, a cylindrical pile with 70 m length, 6.5 m diameter, and 80 mm wall thickness serves as an example. The embedded length of the pile is 35 m and the water depth is 30 m. Simulation time is set to 100 ms.

For the present contribution, the underwater sound pressure is evaluated based on the sound exposure level (SEL) according to

$$\mathrm{SEL} = 10 \log_{10} \left(\frac{1}{t_0} \int_{t_1}^{t_2} \frac{p(t)^2}{p_0^2} \, dt \right) \quad [\mathrm{dB}], \tag{1}$$

where p_0 refers to the reference sound pressure for underwater sound, i.e. $p_0 = 1\,\mu\mathrm{Pa}$, and t_0 to the reference time, i.e. $t_0 = t_2 - t_1 = 1\,s$.

3 ANALYSIS OF THE INFLUENCE OF THE HAMMER DESIGN ON THE SEL

Although this contribution focuses on optimizing the hammer shape, an analysis of the influence of the hammer material on the SEL is presented beforehand. The reason is that the material is rather easily described using the density ρ and the Young's modulus E, whereas the description of a realistic hammer shape requires several parameters. The effect of material and shape, however, is linked, since the mass is changed by either density or volume as is the stiffness by the Young's modul or the length and the cross section.

For the purpose of analyzing the influence of the material parameters on the SEL, several hammer models with different materials were generated to obtain the corresponding sound pressure levels. The shape was the same as of the existing hammer MHU3500S by the company MENCK. Its original density and mass were varied within a range of $\pm 50\%$. The impact energy was set to 2000 kJ. For the first analysis, the original material was used for one of the hammer components, while the material of the other were modified. 100 samples have been generated. The results are shown in Figure 2. For the second analysis, the material of both components were changed simultaneously, i.e, the parameter study was based on 4 parameters. 300 samples have been generated. The results are shown in Figure 3.

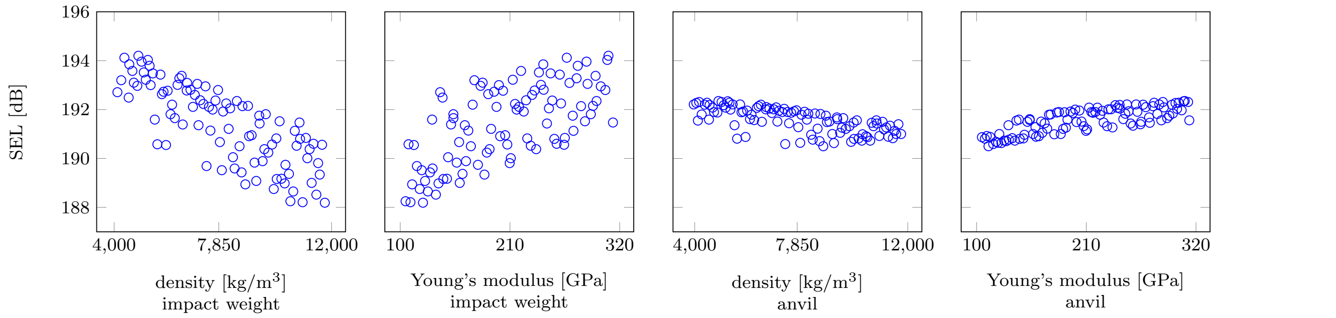

Figure 2. Parameter study hammer material for both hammer components individually.

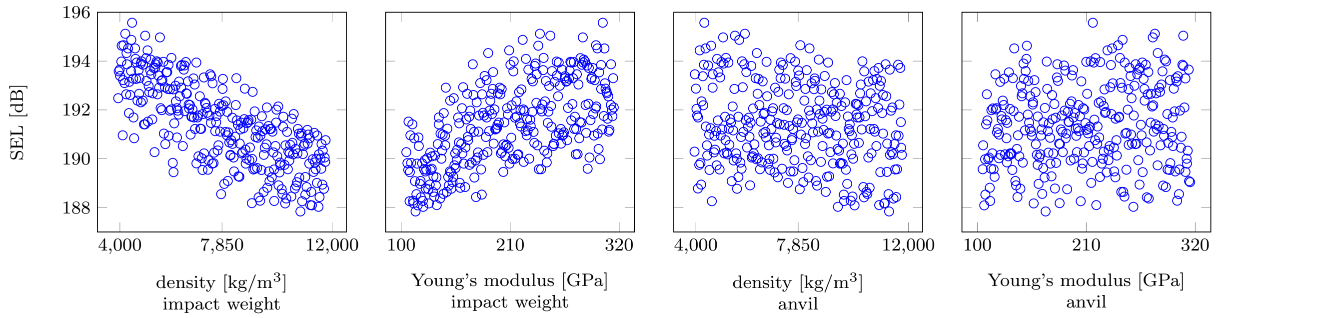

Figure 3. Parameter study hammer material for both hammer components simultaneously.

The results of the first analysis indicate that the SEL decreases with increasing mass and decreasing stiffness. Although this can be observed for both components, impact weight and anvil, the influence of the material of the impact weight seems to be stronger. Regarding the impact weight, a similar behavior of the SEL can be observed in the results for the second analysis. No clear relationship for the material of the anvil, however, can be established from the results shown in Figure 3. Furthermore, the corresponding correlation coefficients, shown in Table 1, support the above stated and indicate that especially the influence of the anvil design on the SEL depends strongly on the design of the impact weight.

Table 1. Correlation factors for material parameters and the SEL.

	density impact weight	**E-Modul impact weight**	**density anvil**	**E-Modul anvil**
Analysis 1	-0.79	0.67	-0.67	0.77
Analysis 2	-0.73	0.60	-0.16	0.13

Therefore, an optimization of the anvil should only be performed, if the design of the impact weight is already known, or in a joint optimization. The correlation coefficients regarding the material of the impact weight also decrease from analysis 1 to 2, indicating a low dependency on the shape of the anvil. In order to include all possible coupled effects, the optimization, presented in the following section, includes both hammer components.

4 OPTIMIZATION

The optimization problem considered here, i.e. defining the shape of the hammer components to minimize the sound emission caused by the hammer impact on the pile, is challenging. First, an integration of the FE model into the optimization is required since no explicit analytical relationship of the hammer shape and the sound pressure emission is known. Second, the hammer design underlies several restrictions, e.g, the size, mass, and manufacturability of the hammer components, but also the ram efficiency, drivability of the pile, and tensions of the material caused by the impact. Even more difficult to determine, but equally important, is the durability of the hammer.

The following sections present an optimization approach taking for now only relatively low restrictions in size, efficiency, and driveability into account.

4.1 Particle swarm optimization

The PSO is a method to optimize nonlinear functions, also applicable for black box problems as it is the case here, adapted from the behavior of animal swarms, e.g. birds or fish, originally proposed by [5]. Although the method does not guarantee to find the optimum, it is commonly referred to as an optimization method.

As proposed in [6], the position x of each particle d is updated every step k, using

$$x^d_{k+1} = x^d_k + v^d_{k+1}, \tag{2}$$

$$v^d_{k+1} = w\,v^d_k + c_1\,r_1\left(p^d - x^d_k\right) + c_2\,r_2\left(p_k - x^d_k\right), \tag{3}$$

where k refers to the current time step, $k+1$ subsequently to the next time step, v refers to the particle velocity, and p to the best position of either the current particle p^d considering all time steps or the current time step considering all particles p_k. The PSO parameters are the inertia w, the cognitive factor c_1, the social factor c_2, both equal two and two random factors $r_1,\ r_2 \in [0,1]$. Several extensions of the above definition have been proposed, however, this contribution focuses on this basic version of PSO.

4.2 Setup of the optimization problem

The hammer design with best acoustic properties within a certain design space can be identified as it causes the lowest underwater sound pressure levels. Here, it is important to compare sound pressure levels that result from the same amount of energy transmitted to the pile. The impact energy, in the model defined by the drop height of the impact weight, however, is usually not fully transmitted to the hammer. Since less energy transmitted to the pile would also cause less sound emission, using the SEL as the objection value could lead particles to move towards less efficient hammer designs. To avoid the above, the ram efficiency, defined as $\eta = \mathrm{E_P}/\mathrm{E_0}$, i.e. the relation of the energy transmitted during the impact to the pile $\mathrm{E_P}$ to the energy of the impact weight $\mathrm{E_0}$ before the contact of impact weight and anvil, is part of the objective function. The applied objective function is therefore defined as

$$\min\left\{\mathrm{SEL}_\eta = \mathrm{SEL} - 10\,\log_{10}(\eta)\right\}, \tag{4}$$

where

$$\eta \geq 0.5, \tag{5}$$

$$\max(v_\mathrm{p}(t)) \leq 0.5\,\mathrm{m/s}. \tag{6}$$

The constraints in Equation (5) and (6) were introduced to avoid particles moving towards very unrealistic hammer designs regarding their ram efficiency and ability to drive the pile into the sea bed.

If Equation (5) or (6) is not fulfilled, the inertia factor in Equation 3 is set to zero for the corresponding optimization step and particle. If the stated conditions are fulfilled, the inertia factor w is set to 0.8. The social and cognitive factor are chosen to be $c_1 = c_2 = 2$.

The parameters for the hammer design were chosen to be interpretable, to be able to get insights of their influence from the optimization. The definition of the parameters is shown in Figure 4. One example of a possible hammer design defined by the presented parameterization can be found in Figure 5. Parameters include height, radius, and inclination of the components. Additionally, curvatures of the outer surfaces are defined. Restrictions of the parameter space are stated in Table 2. The initial particle positions were chosen to have valid shapes and $\eta > 0.5$, but are otherwise randomly placed.

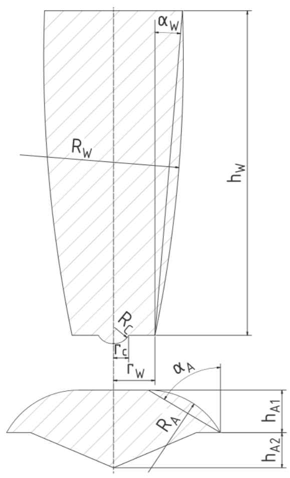

Figure 4. Parameterization.

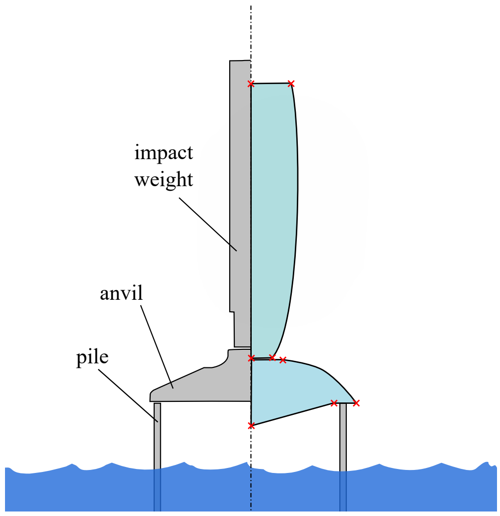

Figure 5. A simplified axis symmetric illustration of an existing hammer (left) in comparison to a possible hammer design for the proposed parameterization.

Table 2. Parameter bounds.

	$h_\mathbf{W}$	$h_\mathbf{A1}$	$h_\mathbf{A2}$	$r_\mathbf{W}$	$\alpha_\mathbf{W}$	$\alpha_\mathbf{A}$	$r_\mathbf{C}$	$R_\mathbf{C}$	$\lvert\mathbf{R_W}\rvert$, $\lvert\mathbf{R_A}\rvert$
min	1 m	0.5 m	-h_{A1} + 0.5 m	0.2 m	$-\cot\left(\frac{r_W}{h_W}\right)$	$-\cot\left(\frac{3.45\,\mathrm{m}}{h_{A1}}\right)$	0.2 m	5 m	60 m
max	15 m	4 m	3 m	4 m	$+\cot\left(\frac{r_{W,\,max}-r_W}{h_W}\right)$	$+\cot\left(\frac{0.55\,\mathrm{m}}{h_{A1}}\right)$	r_W	50 m	300 m

4.3 Results and analysis

36 optimizations steps, i.e. 540 hammer evaluations, were performed until the process was stopped due to no improvement in the SEL_η within the last 8 steps. The development of the objective value SEL_η, the efficiency and the design parameters over the optimization steps are shown in Figure 7. The objective value SEL_η decreased successfully from 177 dB for the lowest value for the initial designs to the overall lowest value of 170.6 dB. At the same time, the efficiency increased, staying over 0.8 after only ten steps and over 0.9 after 23 steps. The latter observation demonstrates that an unrealistic decrease in the SEL_η due to less energy transmitted to the pile was avoided using the modified objective value SEL_η defined in Equation (4). However, the development of the efficiency η also indicates that the penalization of the efficiency η might be too high, as efficiencies between 0.8 to 0.9 may also be acceptable.

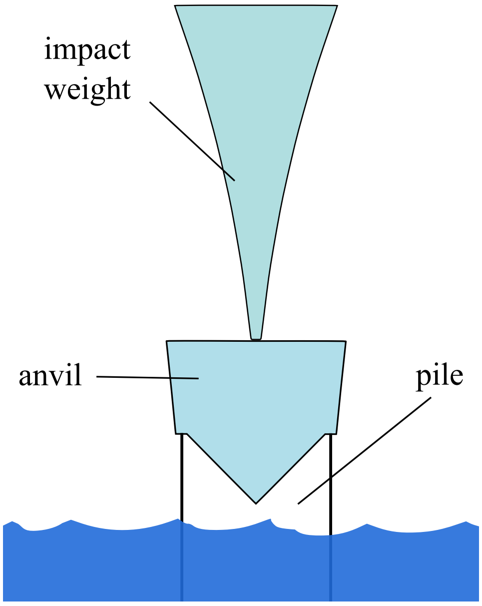

Figure 6. Simplified illustration of the hammer design with lowest SEL_η. The corresponding values are SEL_η=170.6 dB, SEL=170.3 dB, η=0.94.

The development of the design parameters for this example shows that most parameters converge to their given limits. The hammer design with lowest SEL_η is shown in Figure 6. Here, the PSO moves to a long impact weight with low radius at the bottom but increasing radius at the top (indicated by the parameters h_W, r_W, and α_W) with a pronounced curvature at the bottom (indicated by r_C and R_W). The pronounced curvature and the low radius at the bottom of the impact weight cause a low stiffness that increases due to the positive value of the angle α_W towards the top. The angle α_W converges here to the allowed maximum in case of the maximum value for h_W and the minimum value for r_W. The radius R_W, however, does not converge, eventually due to small to no influence on the SEL_η for, at least, the defined range in this case.

In contrast, the design parameters of the anvil move to a especially heavy anvil, as the parameters h_{A1}, h_{A2}, and α_W all move towards the maximum values. Especially the development of the parameter h_{A2} towards high positive values is noteworthy, since negative values would have caused lower stiffness. The radius R_A converges to its minimum value, i.e. the curvature practically vanishes.

In summary, the presented optimization results in an impact weight with increasing stiffness from the bottom to the top and a heavy anvil, while the introduced curvatures R_W and R_A appear to have zero or negative influence on the objective value SEL_η. These results, however, should be viewed cautiously, as some limitations of the hammer design, i.e. maximum mass and maximum tension, have not been taken into account. Results are also based on one optimization run with 15 particles and may therefore change with a different initial distribution of particles, i.e. hammer designs.

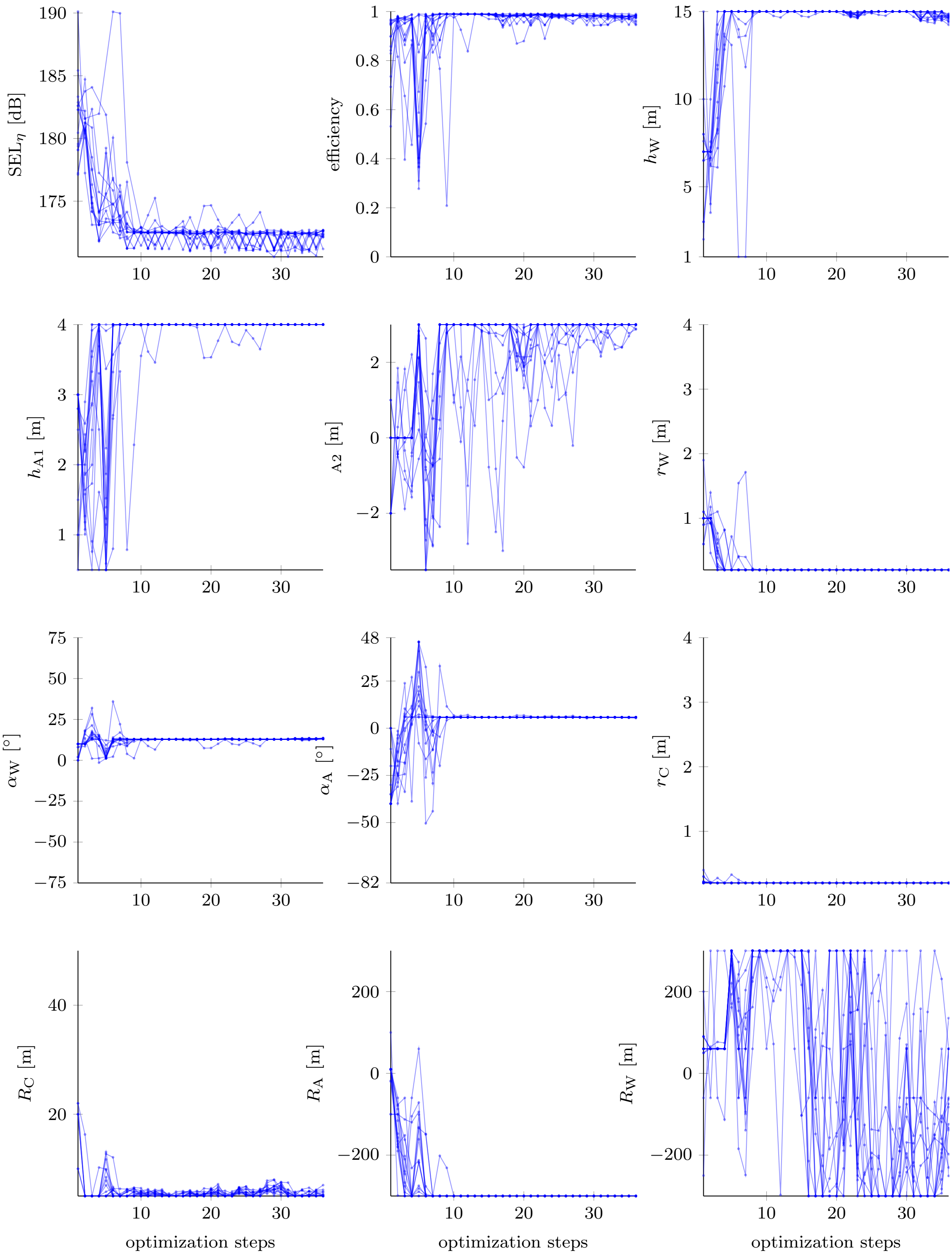

Figure 7. Development of the objective value SELη, the ram efficiency and the design parameters over the optimization steps. The limits of the plots are the optimization constraints (see Table 2) as far as these are constant, i.e. do not depend on other parameters.

5 CONCLUSIONS

An approach to optimize the shape of an impact hammer for offshore pile driving regarding its acoustic properties has been presented. The characteristics of the hammer design with low SEL_η are a heavy anvil and an impact weight with increasing stiffness from the bottom to the top. The SEL could be reduced by more than 6 dB while a high ram efficiency of 0.94 was maintaned. However, several constraints, e.g. regarding manufacturability were not taken into account. Future work will therefore include a more realistic parameter space. Future work will be also directed towards a PSO using a more detailed parameterization that allows for different shapes and therefore might uncover additional potential of the hammer shape to decrease sound pressure levels.

ACKNOWLEDGEMENTS

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