Numerical determination of equivalent damping parameters for a finite element model to predict the underwater noise due to offshore pile driving

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Summary
Due to the massive construction of offshore wind parks in the German North Sea, an increasing attention has been directed to underwater noise. In particular, limiting values for the sound pressure level during construction have been introduced by the German authorities to protect marine life. State-of-the-art technology for the erection of the wind turbines is impact pile driving. Hence, a reliable prediction technique for the noise due to pile driving with an impact hammer becomes increasingly important. At present, different numerical methods are under development for these kinds of forecasts. The most common approach used to calculate the sound pressure in the area close the pile is the finite element method (FEM). In several publications, an equivalent damping in the embedded part of the pile is chosen to take the losses, e.g. the plasticity of the soil, into account. In this contribution, a method to determine the equivalent damping with the "Wave Equation Analysis of Pile Driving" (WEAP) is shown. During a drivability study performed with WEAP, the Rayleigh damping coefficients are extracted. Finally, these coefficients are validated by comparing predicted values calculated with the FEM to measured data.

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1. Introduction

Since the German government decided to substantially reduce greenhouse gas emission, the extension of renewable energy gains more and more of importance [1]. In this turnaround of the energy policy, offshore wind energy plays a key role. The fact that pile driving with an impact hammer is still the state-of-the-art technology for the erection of foundations for offshore wind turbines leads to a massive noise emission into the sea water. To protect marine wildlife, like the harbour porpoise, limiting values have been introduced by the German authorities. These were defined as 160 dB re 1 μPa for the sound exposure level SEL and 190 dB re 1 μPa for the peak sound pressure level L_{peak}. In most cases, it is hard to comply with these limits without applying a dedicated sound mitigation system [2]. To optimize such systems, numerical methods, as the finite element method (FEM), are an important tool to get a physical insight and a better understanding of the acoustic radiation and sound propagation during offshore pile driving. One of the most important input quantities for such a FEM model is the force applied to the pile, such that the input energy and the shape of the forcing function are represented realistically. Other important input parameter are the equivalent damping parameters, which are assigned to the embedded part of the pile to take the losses, e.g. the plasticity of the soil, into account[3], [4] . Trimoreau et al. presented an approach, in which they used a WEAP calculation to determine both the pile head force and the equivalent damping [5]. However, one of the major drawbacks of WEAP is the necessary discretization of the ram and the anvil of the impact hammer.

To avoid this drawback, first a numerical model to predict the pile head force for frequencies up to 10 kHz is presented in this contribution. This model features a FEM time domain approach, in which the ram and the anvil are discretized explicitly. The modelling requires the definition of two contacts: The contact of the ram to the anvil and the contact of the anvil to the pile. In both cases, the same problem occurs: The properties of the used contact model have to be well known to get proper results. In different previous contributions, the relevance of an accurate contact modelling is discussed (see for example [6] and [7]). A wrong contact stiffness in a numerical model, for example, may lead to wrong results or numerical instabilities, as convergence problems or even matrix singularity [6]. Within this contribution, the contact of the impact hammer model under highly loaded conditions is studied in detail with the presented numerical model. For a contact model, namely a bilinear relation between the contact pressure and the contact displacement, the contact properties are determined with a Design of Experiment (DOE). The estimation of the parameters is accomplished for a stroke with 1400 kJ. Afterwards, the results of this contact model are discussed. The chosen properties are cross-validated with two other strokes of the impact hammer.

With a second model, finally the equivalent damping parameters are determined. Therefore, WEAP is chosen, which was originally proposed by Smith and is here extended by the radial displacements [8], [9], [5]. To avoid the mentioned drawback of WEAP, the determined force of the FEM approach is defined as a boundary condition on top of the pile.

In a last step, the underwater sound pressure is determined with a separate model. For this model, FEM is used and the pile head force is assigned as a boundary condition in this model. Furthermore, the Rayleigh damping parameters are implemented at the embedded part of the pile. Here, a very good accordance of the model with respect to measurements is shown.

2. Numerical impact hammer model

2.1. Motivation and general numerical setup

For the proposed model, a 2D axis-symmetric formulation and explicit time integration scheme (central differences method) is chosen to reduce the computational time and to have the opportunity to describe brief transient dynamic events, like the impact of the hammer on the pile.

The model consists of the ram, the anvil, and the pile. The bottom of the pile is enclosed with infinite elements. This is well-founded by the fact, that the pile head force will be determined by this model. So, this forcing function should not include any reflections of the stress wave traveling through the pile. For the spatial discretization, four-noded bilinear quadrilateral elements with reduced integration scheme are used. The mesh size of this model is confirmed with a convergence study. This study leads to a mesh size of 0.01 m. To assign the energy of the impact hammer to the system, an initial velocity v_0 is defined to the ram mass.

2.2. Geometry of the model

To enable a comparison with measurement data, the model is set up according to an offshore measurement campaign carried out within the BORA project [10]. The pile has a length of 85 m, an inner diameter of 3.2 m, and an outer diameter of 3.35 m. The used impact hammer is of the type "MENCK MHU1900S" operated at a maximum blow energy of 1400 kJ. The material of the pile, the anvil, and the ram mass is steel. The weight of the ram mass is 92 t with a length of 9.6 m. The weight of the anvil is 45 t. For detailed information about the measurement campaign, see Reimann and Grabe [10]. The pile head velocity was measured in a distance of 6 m to the pile top during this campaign. The general setup of the FEM model including the impact hammer and the pile is shown in figure 1a) and 1b). In figure 1c), the discretization of the pile and the impact hammer is visualized.

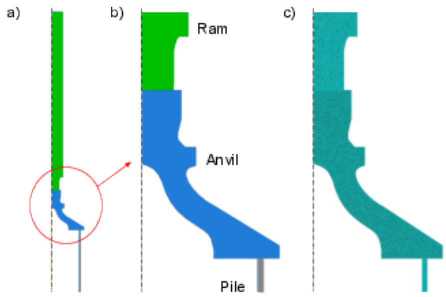

Figure 1. General setup of the model and discretization of the ram, the anvil, and the pile

2.3. Numerical implementation of the contacts

The modelling approach leads to the definition of two contacts: The contact of the ram to the anvil and the contact of the anvil to the pile. Both contacts are enforced with a penalty contact algorithm. This procedure can be interpreted as an introduction of several spring and damper systems representing the contacts. Afterwards, a normal and tangential behaviour is assigned to both of them. The tangential contact is related to a friction coefficient of 0.15 (steel-on-steel). However, more important is the normal contact property. Through this quantity, the energy transmission from the impact hammer to the pile is controlled. In the following, a contact model with a bilinear relation between the contact pressure and the contact displacement is studied.

The used bilinear relation between the contact pressure p and the contact displacement δ is

$$p(\delta) = \begin{cases} s \cdot \delta, & \text{for: } \delta \geq 0 \\ 0, & \text{for: } \delta < 0. \end{cases} \quad (1)$$

In this the relation, one parameter, the contact stiffness s, has to be defined, which is the gradient of the contact pressure p with respect to the contact displacement δ.

3. Determination of the contact properties

3.1. General proceeding

The used method to estimate the contact properties is the so-called response surface method [11]. For this, a response surface based on sampling points, which describe the shape of an objective function, has to be determined. Here, the sampling points, numerical calculations of the pile head velocity v_p with different contact properties in a defined search space, are determined by means of a latin hypercube sampling [12].

A suitable objective function for this problem is the frequency response assurance criterion (FRAC), which describes the correlation between a measured frequency response H_m and a numerically determined frequency response H_n [13]:

$$FRAC = \frac{(H_m^T H_n)^2}{(H_m^T H_m)(H_n^T H_n)}. \quad (2)$$

A FRAC value of 1 indicates a perfect correlation, while the correlation gets worse with decreasing FRAC value. In this study, the pile head velocity v_p of the measurement and of the calculation is transformed into the frequency domain by means of a discrete Fourier transformation leading to the required values H_m and H_n, respectively.

For the approximation function defining the response surface, a polynomial of fourth order is chosen. Using a least square regression, the coefficients of the polynomial are calculated. The last step of this procedure is a gradient-based optimization on the response surface. The used algorithm is the sequential quadratic programming [14]. The goal of the optimization is to find to highest possible FRAC value in a given search space.

3.2. Determination of the contact properties for the bilinear model

As described in the previous chapter, one contact property has to be estimated for this relation. Konowalski determined a contact stiffness of $1.2 \cdot 10^{12}$ $Pa\ m^{-1}$ for a cycling load in his experiments [6]. Based on this finding, the search space for the DOE has been set to the interval from $1 \cdot 10^{10}$ $Pa\ m^{-1}$ to $5 \cdot 10^{12}$ $Pa\ m^{-1}$.

The influence of this property towards the pile head velocity v_p is visualized in figure 2. Here, the pile head velocity v_p is plotted over time for different contact stiffnesses s.

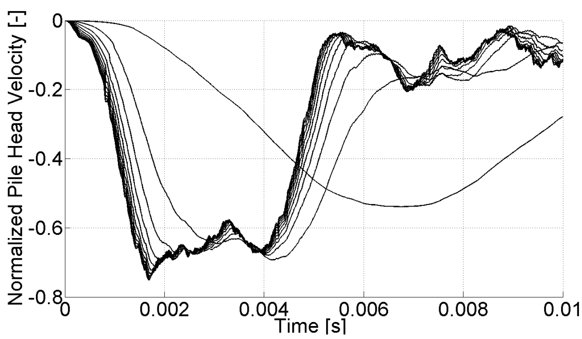

Figure 2. Resulting pile head velocity over time for an increasing gradient of the contact stiffness s

As it can be seen, the entire shape of the pile head velocity v_p changes with an increasing contact stiffness s. This may lead to a worse or also a better correlation between the measured and the calculated signal. To underline this even more, the determined response surface of the resulting FRAC values is visualized in figure 3.

The optimization on the response surface leads to a FRAC value of 0.994, which indicates a very good correlation between the measured and calculated results of the frequency response. The related optimized contact stiffness is $9.29 \cdot 10^{10}$ $Pa\ m^{-1}$.

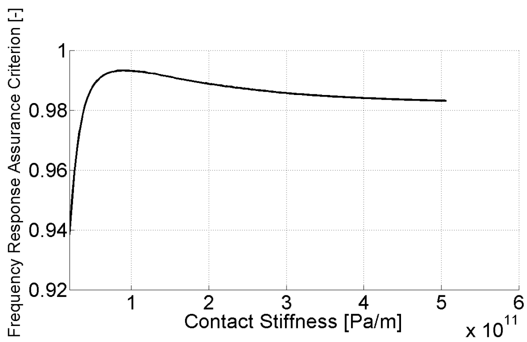

Figure 3. Plot of the FRAC value over the gradient of the contact stiffness

3.3. Resulting pile head velocity with the determined parameters

In this section, the resulting pile head velocity of the bilinear model is compared to the measurement data and visualized in figure 4. Both velocities are normalized by the initial velocity v_0.

The very good agreement of both the measurement data and the data of the numerical model can be observed. To underline this fact even more, the third octave band levels of the pile head velocity of the two signals are shown in figure 5. Here, again a very good accordance between the numerical and the measurement data can be seen up to 10 kHz. In the range

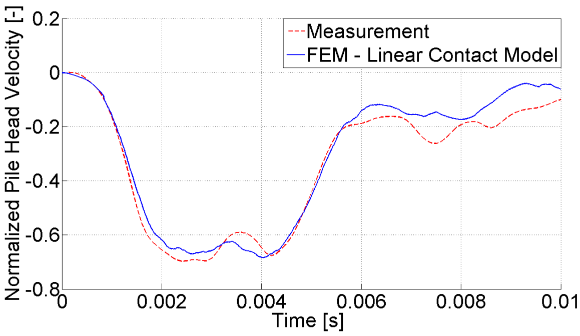

Figure 4. Normalized pile head velocity over time

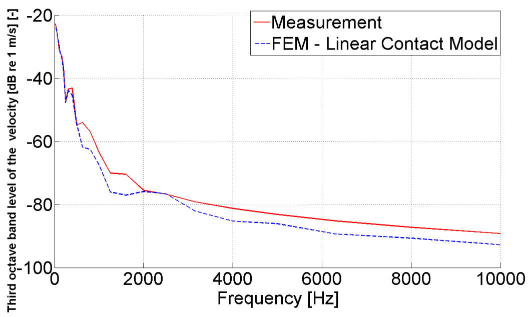

Figure 5. Comparison of the third octave band levels of the pile head velocity

from 3 kHz to 10 kHz, a difference of 3 to 4 dB is determined between the measurement and the numerical model. However, if the absolute error of the frequency response $e = abs(H_m - H_n)$ is studied, the error approaches zero (see figure 6).

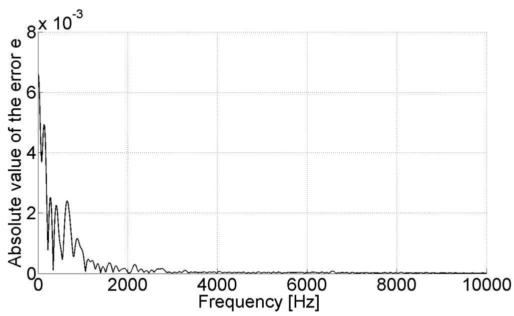

Figure 6. Plot of the absolute error over frequency

3.4. Cross-validation

Finally, the cross-validation technique will be used. Hereby, the contact properties assessed by the DOE will be generalized with two different data sets [15]. Here, the linear contact model is used. Therefore, two other strokes with different energy levels of the measurement will be compared with the results of the numerical model in the frequency and in the time domain, respectively. The energies of the two strokes are 145 kJ and 683 kJ, respectively. The results of both strokes are depicted in the figures 7 and 8. Here,

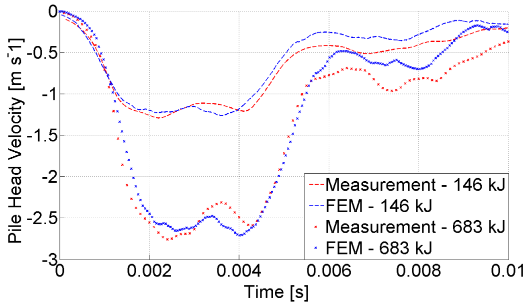

Figure 7. Pile head velocity over time for two strokes with 145 kJ and 683 kJ, respectively

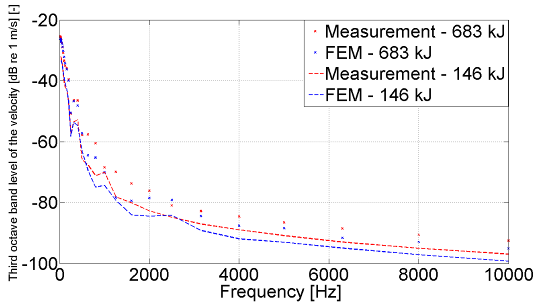

Figure 8. Comparison of the third octave band levels of the pile head velocity for two strokes with 145 kJ and 683 kJ, respectively

also a very good agreement can be seen. In the whole range of the possible energy of an impact hammer, the contact properties are validated. It can be stated, that these contact properties are generally valid for a steel-on-steel contact under highly loaded conditions.

4. Wave Equation Analysis of Pile Driving

The original WEAP as proposed by Smith is a 1D wave equation [8]:

$$\frac{\delta^2 D}{\delta t^2} = \frac{E}{\rho}\frac{\delta^2 D}{\delta x^2} \pm R, \tag{3}$$

where D are the longitudinal displacements of the pile and R is a term, which describes the damping due to the soil resistance. Smith assumed that this 1D wave equation is able to predict the stress wave, which propagates through the pile due to the hammer impact. WEAP is used for several geotechnical purposes, e.g. driveability studies.

As in the original work of Smith, a finite differences code with a lumped mass discretization is used. As discussed in the introduction, the force determined by the previous model is assigned to the top of the pile.

Furthermore, Wood and Humphrey presented an extension of the WEAP by implementing the radial displacements [9]. Therefore the relation of the lateral

Table I. Determined Rayleigh damping factors

Embedded length	Energy	α	β
18 m	1400 kJ	144.1	$3.0 \cdot 10^{-7}$

and longitudinal strains according to Poisson's ratio is used:

$$\mu = \frac{\epsilon_{lat}}{\epsilon_{long}}. \tag{4}$$

Hence, the following relation for the radial displacements x can be obtained:

$$x = \frac{\mu d C}{L}, \tag{5}$$

where d is the pile diameter, C is the compression due to the displacements D of the pile elements, and L is the element length of the discretization. With a system identification method Rayleigh damping parameters are extracted out of the radial displacements.

4.1. Determination and validation of the damping parameters

For the determination of the damping parameters, a stroke at an embedded length of 18 m of the mentioned measurement campaign is used. The impact hammer energy of this stroke is 1400 kJ. The determined damping factors for this experimental setup are summarized in table I.

The validation of these parameters is carried out with a comparison of the results of a FEM model with the measurement data. As in the first FEM model, an explicit time integration scheme is chosen. In addition, a 2D axis-symmetric formulation is used for the spatial discretization. This model contains the pile, the water, and the soil. The determined pile head force is prescribed as boundary condition to the top of the pile. Furthermore, the computational domain is enclosed with suitable non-reflecting boundary conditions. To decrease the computational effort, the air above the sea surface is replaced by an impedance boundary condition. Regarding the soil, the detailed layering at the construction site is taken into account, and a detailed contact modelling between the soil and the pile is accomplished. A more detailed description of this modelling approach can be found in [16].

A comparison of the underwater sound pressure of the computational model and the measurement in a distance of 27 m to pile is shown in figure 9 in the time domain and in figure 10 in frequency domain.

In both, a very good accordance between the predicted and measured underwater sound pressure can be observed. The measured and computed SEL and L_{peak} are summarized in table II By a comparison of the values in this table, a good accordance of both the measured and computed SEL and L_{peak} can be seen. The delta between SEL values is in this case 1.7 dB and for the L_{peak} the delta is 0.8 dB.

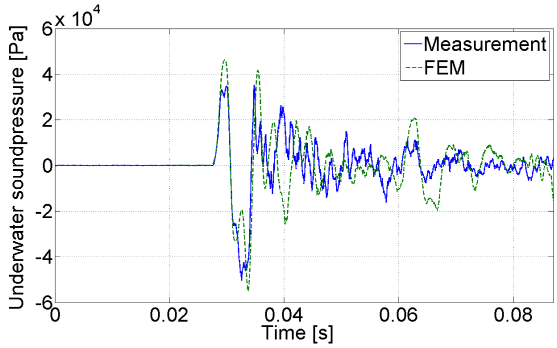

Figure 9. Comparison of simulated and measured underwater sound pressure over time

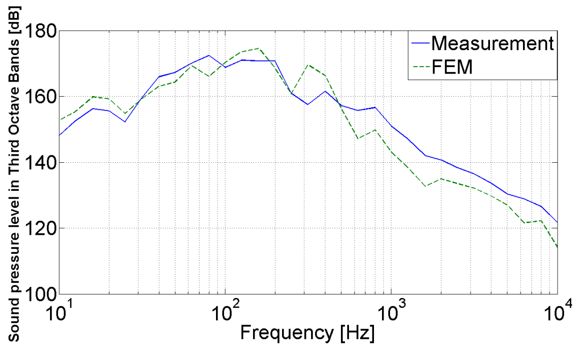

Figure 10. Comparison of simulated and measured underwater sound pressure over frequency

Table II. Measured and computed sound pressure levels

Measured SEL [dB]	Computed SEL [dB]	Measured L_{peak} [dB]	Computed L_{peak} [dB]
189.6	191.3	214.0	214.8

5. Conclusion

In this contribution, a model to determine the equivalent damping factors, which are commonly used in numerical pile driving models to predict the underwater sound pressure, was presented. Therefore, the WEAP approach was used and modified by an additional calculation of the radial displacements. Furthermore, one of the major drawbacks of WEAP was resolved by defining a pre-calculated forcing function of an impact hammer as a boundary condition to the pile top. To determine the forcing function of the impact hammer, a detailed study of the contacts within the impact hammer was accomplished and checked by cross validation. Out of the radial displacement of the WEAP approach, the equivalent damping parameters were estimated by a system identification method. In a last step, the equivalent damping parameters were validated with a comparison of the underwater sound pressure predicted by a FEM model and the measured data. Here, a very good agreement was found.

The advantage of this modelling approach is that all quantities required for a typical FEM model can be estimated with two different numerical pre-investigation with a high accuracy. These quantities then can be implemented as a boundary condition or a material property in the FEM model.

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