Numerical modeling of radiated sound for impact pile driving in offshore environments

Daniel R. Wilkes, Tim Gourlay and Alexander N. Gavrilov

***Abstract*—A coupled near-to-far field numerical model for predicting the acoustic emissions from impact pile driving in offshore environments is presented. The near-field region of the pile is modelled via an axisymmetric finite element method (FEM) model which is solved in the frequency domain. The calculated radiated field at a chosen radial distance in the FEM model is then expanded into a series of local normal modes (NM) which are propagated into the far field, to predict the piling sound characteristics, such as the peak pressure and sound exposure levels, at large ranges. Numerical examples are presented for the same pile configuration adopted for the COMPILE 2014 benchmark workshop on predicting offshore pile driving noise, and these results are compared in both the near and far fields to those of several other research groups who presented results at the workshop. Results from the present FEM-NM near-to-far field model are shown to be generally in good agreement with those results from the other research groups. In the near field, similar signal waveforms are predicted by the various models which employ the same pile wall boundary conditions. In the far field, the selected models showed a variation of ±1dB at 1.5km, and ±4 dB at 50km for the predicted peak pressure levels, and a variation of ±1.5dB over the 50 km range for the predicted sound exposure levels.**[1]

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***Index Terms* – acoustic emission, numerical simulation, underwater acoustics, underwater structures.**

I. INTRODUCTION

Impact pile driving in marine environments results in the emission of high intensity impulsive underwater noise which may affect marine fauna in the surrounding area. This may manifest as a physiological impact at short distances from a driven pile (e.g. temporary or permanent shifts of the auditory threshold, or even physical trauma) or as a behavioral disturbance and sound masking at larger distances. A number of studies have determined underwater sound emission levels from pile driving operations which could be potentially harmful to marine life near to the piling location [1], [2], [3], [4]. With the increasing number of marine pile driving activity in offshore environments (e.g. for wind farms and other offshore infrastructure) there is a need to understand the sound radiation mechanisms of piling.

A pile driven into the seabed via an impact hammer is a physically complex source of sound. The impulsive hammer impact energy travels down the pile in the form of elastic waves, resulting in both radial expansion and flexural deformation of the pile wall due to the Poisson effect. The radial displacement of the pile wall results in sound radiating into the water column and seabed via a coupled fluid–structure interaction (FSI). The radial and axial displacements of the pile wall embedded in the seabed result in compressional and shear waves in the seabed material. The sound emission from offshore pile driving is strongly dependent on the type, geometry and construction material of the pile, the type and driving force (impact energy) of the pile hammer, and the marine environment (water depth, sound speed profile and geoacoustic properties of the seabed). Thus an accurate numerical model of sound emission from marine piling has to account for all these parameters.

Numerical modelling techniques, such as the finite difference method (FDM) and finite element method (FEM), allow for the pile geometry and the material properties of the pile, water column and seabed to be explicitly defined in the model. However the required resolution for these domain discretization methods is dictated by the highest frequency component that must be modelled for the radiated sound field (typically a few kHz for impact pile driving) and so this limits the range of applicability of these models to the near field (typically < 100 m). To model the sound radiation from pile driving over larger distances, coupled "near-to-far" field models have been developed, where the radiated field from the near-field model is input into an appropriate long-range underwater sound propagation model, such as normal mode (NM), parabolic equation (PE) and wave number integration (WI) models (see [5] for details). Reinhall and Dahl [4] coupled an FEM model of the near-field sound pressure to a long range PE model by matching the FEM field to a phased array of point sources distributed along the pile which were then used as input into the PE model. Lippert and Lippert [6] used a similar phased array technique to couple a near-field FEM model to a WI model for long range propagation of the pile radiated sound. This coupled FEM-WI model was subsequently used by Lippert and von Estorff [7] to conduct a parameter uncertainty analysis of the model inputs, and so provide some error bounds on the modelled sound pressure levels (SPLs). Zampolli *et al*. [8] coupled an FEM model of the near-field to an energy flux integration method to propagate the sound field to larger distances. Fricke and Rofles [9] directly couple a near-field FEM model which includes layered elastic seabeds to a range-dependent PE model (with a fluid seabed) for the long range propagation.

Near-field models have also been implemented using time-domain finite difference method (FDM) formulations based on the equations of motion for a thin cylindrical shell [10], which has been shown to be a good approximation for modelling vertical cylindrical piles with uniform cross-sections: see for example the work by MacGillivray [11] and Wilkes *et al.* [12]. The FDM formulations have the advantage that they are relatively straightforward to implement, and are typically much faster than FEM formulations to solve, but appear to suffer from stability issues when the pile and fluid equations are directly coupled to include the FSI effect [12]. An alternative approach to simulate the full FSI in the FDM models by including the radiation loading from the Mach cones to impede the radial motion of the pile [11] has been shown to provide good agreement with measured data in the near-field.

Semi-analytical models for predicting sound emissions from marine pile driving have also been developed by Hall [13] and Tsouvalas and Metrikine [14] (again based on the thin-shell theory representation of the pile), with the later model also extended to allow for a fully elastic seabed [15]. Finally, more recent research in the field has focused on the acoustic modelling of pile driving for more complex source/bathymetry configurations, for example to model sound radiation from vibratory piles [16], or to investigate the variations in modelled sound levels from impact pile driving for differing range-dependent profiles and sediment properties [17]. In all cases the near-field and far-field models are treated as axisymmetric for the offshore environments, while many of the long range sound propagation models are able to incorporate complex environmental features, such as range and azimuth dependent bathymetry, sound speed in water and geoacoustic properties of the seabed.

In this paper a coupled near-to-far field numerical model for predicting the underwater sound emission from pile driving is presented. A commercial FEM code is used to model the pile and near-field water/seabed region in the frequency domain, which is then coupled to a NM model for predicting the long range sound propagation. If the sound field at a certain reference distance in the near field can be sufficiently well approximated by a sum of local normal modes, then the FEM prediction at that distance can be readily expanded into a mode series which is then propagated in a range-dependent underwater sound channel using either adiabatic or coupled mode approximation. Thus no phased array of point sources is needed to couple the near and far field models. Numerical examples are presented for the generic pile driving scenario adopted for the recent COMPILE benchmark workshop [18] on predicting offshore pile driving noise, and results are compared to the coupled near-to-far field pile driving models of some of the other research groups who presented model results at the workshop. The paper is organized as follows: Section II presents the numerical methods for FEM near-field model, as well as the NM method for near-to-far field coupling, Section III describes the COMPILE benchmark test scenario and provides the corresponding numerical results for the present models, along with comparisons to some of the other near-to-far field models presented at the COMPILE workshop, and finally Section IV presents conclusions and recommendations for future work.

II. NUMERICAL METHODS

The general modeling approach adopted in much of the literature for predicting sound emission from marine piling via coupled near-to-far field models is depicted in Fig. 1. The near-field pile region, consisting of the pile, water column, and sediment, within a range of typically a few 10's of meters, is modeled using a domain discretization method such as the FEM or FDM method. These models can be computationally expensive for large model domains (particularly for the FEM) and so at a certain range from the vertical axis of symmetry the radiated field in the water column and sediment from the near-field model is used as the initial field in a suitable long range propagation model, such as the PE, WI or NM (pictured) models. Fig. 1 also depicts the main mechanisms of sound radiation from the pile. The axial displacement wave propagates down the pile faster than the sound speed in water and so radiates 'Mach cones' into the water column which propagate in alternating downward and upward directions as the axial displacement wave travels down and up the pile [4]. The displacement of the pile wall similarly excites compressional waves in the seabed and, in the case of an elastic seabed material, shear waves in the ground and Scholte waves at the seabed interface. For seabed materials which have low shear stiffness, an equivalent fluid seabed model is shown in many cases to provide a reasonable approximation for the sound propagation models [4], [7], [8]. In this work a fluid seabed model is employed for both near-field and far-field models, as specified in the COMPILE benchmark setup [18] and so only compressional waves/Mach cones are excited in the fluid sediment material. In the following sections, descriptions of the FEM model and its coupling to the NM model to yield the acoustic near-to-far field propagation model are presented.

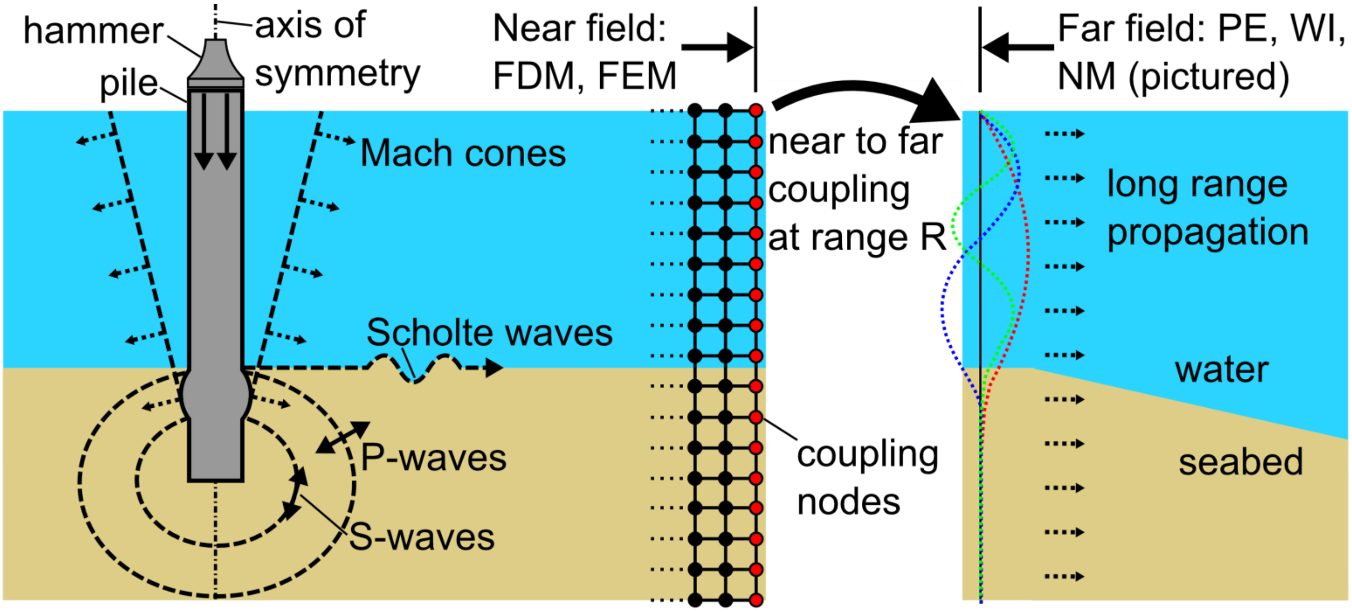

Fig. 1. Schematic of the general configuration for the coupled near-to-far field pile driving models in the published literature. A discretization-type numerical model such as the FEM or FDM is used to model the pile, water and sediment in the near-field region and the radiated field at a certain radial distance from the axis of symmetry is then used as the initial field in a suitable long range propagation model, such as the PE, WI or NM (pictured) models. The various waves excited by the pile deformation are also indicated for the case of an elastic seabed model (the secondary waves excited from the interface interactions are not shown). In the present work, the seabed is modeled as a fluid medium and so no shear waves or Scholte waves are included in the model.

A. *FEM Near-field Model*

An axisymmetric FEM model of the pile has been implemented using the PAFEC-FE software suite, developed by PACSYS [19]. The FEM applies the coupled FSI between the elastic steel pile and fluid media by enforcing continuity between the structural displacements and fluid particle velocities normal to the pile surface, while the normal stress on the pile surface must be equal and opposite to the fluid pressure. Thus the coupled FSI between the vectors of nodal structural displacements $\boldsymbol{u}$ and the nodal pressures $\boldsymbol{p}$ for the discretized near-field region of the pile may be written as a matrix equation:

$$\begin{bmatrix}\mathbf{K}_S & \mathbf{C}^T\\ \mathbf{0} & \mathbf{K}_f\end{bmatrix}\begin{bmatrix}\mathbf{u}\\ \mathbf{p}\end{bmatrix}+\begin{bmatrix}\mathbf{D}_S & \mathbf{0}\\ \mathbf{0} & \mathbf{D}_f\end{bmatrix}\begin{bmatrix}\dot{\mathbf{u}}\\ \dot{\mathbf{p}}\end{bmatrix}+\begin{bmatrix}\mathbf{M}_S & \mathbf{0}\\ -\mathbf{C} & \mathbf{M}_f\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{u}}\\ \ddot{\mathbf{p}}\end{bmatrix}=\begin{bmatrix}\mathbf{F}_S\\ \mathbf{0}\end{bmatrix} \tag{1}$$

where **K**, **D** and **M** are respectively the global stiffness, damping and mass matrices for the steel pile (denoted by subscript *s*) and the combined water/fluid seabed (denoted by subscript *f*), ($\dot{\boldsymbol{u}}$, $\ddot{\boldsymbol{u}}$) and ($\dot{\boldsymbol{p}}$, $\ddot{\boldsymbol{p}}$) are the first and second time derivatives of the nodal displacements and nodal pressures respectively, **C** is the coupling matrix which relates the coincident displacement and pressure unknowns at the pile-fluid interface via the FSI, and $\mathbf{F}_S$ is the vector of nodal forces applied to the pile (i.e. related to the hammer impact force function *F* for the nodes defining the top of the pile, and defined as zero at the remaining pile nodes).

Solution of (1) in the frequency domain is straightforward: assuming harmonic time dependence denoted as $e^{-i\omega t}$, the time derivatives of the displacement/pressure unknowns become simple $-i\omega$ factors and so (1) constitutes an exactly solvable matrix equation.

To model the waveform of the emitted piling signal needed for calculating the peak pressure and sound exposure levels, (1) is solved on a frequency grid which spans the frequency band of the force function applied to the pile head; then the spectrum of the force function is used to calculate the waveform via Fourier synthesis. The frequency grid size has to be chosen small enough to model the full signal length at the reception point without wrapping effects.

B. Near-to-Far Field Coupling through Normal Mode Expansion

The vertical cross-section of the underwater sound pressure field $p(z, f)$ from an arbitrary sound source or a number of sources can be modeled as a sum of normal modes [20]. Omitting the harmonic time dependence $e^{-i\omega t}$, this can be expressed in the following generic form:

$$p(z, f) = A(f)\left[\sum_{n=1}^{N} B_n Z_n(z, f) + \int_{0}^{\xi_C} C(\xi) Z(z, f)\, d\xi\right] \tag{2}$$

where z is the receiver depth, f is the frequency, $A(f)$ is a constant coefficient defined by the signal source spectrum, $Z_n(z, r)$ and $Z(z, r)$ are the local normal modes of the acoustic channel, and ξ is the modal wave number. For a single sound source, the complex modal amplitudes B_n and C depend on source depth z_r, range r, modal wave numbers ξ_n and source directionality (if it is not omnidirectional), but do not depend on receiver depth z. For a number of sources, B_n and C are obtained by summation of the amplitudes corresponding to each source.

The first term in (2) is a sum of a discrete set of N modes, while the second term is an integral of a continuous spectrum of waves, often referred to as leaking modes, which are not trapped by the underwater sound channel. The leaking modes represent the sound energy radiated in the seabed and so attenuate with range much faster than the discrete modes $Z_n(z, r)$ trapped in the sound channel.

The normal modes are orthogonal to one another, so that:

$$\int_{z=0}^{\infty} \frac{Z_n Z_m}{\rho(z)}\, dz = \begin{cases} 1, & m = n \\ 0, & m \neq n. \end{cases} \tag{3}$$

Given a vertical cross-section of the sound field at certain radial distance r_0, and assuming that the contribution of the leaking modes is negligible at this distance, then the complex modal amplitudes $A(f)B_n(z_r, r, f, \xi_n)$ at r_0 can be found through mode filtering using (3):

$$A(f)B_n(z_s, r, f, \xi_n) = \int_{z=0}^{\infty} \frac{p(z) Z_m}{\rho(z)}\, dz \tag{4}$$

At short distances to the acoustic source (i.e. ranges comparable to the water depth) the contributions of the leaking modes in (2) cannot be ignored, and so the continuous spectrum of leaking modes must be approximated by a discrete set of rapidly attenuating normal modes. The ORCA NM algorithm [21] implements such an approximation by either introducing a false layer of high acoustic attenuation over a rigid basement at a suitably large depth from the seabed interface, or by introducing an infinite half-space with a positive sound speed gradient and high attenuation so that the energy of leaking modes returning to the sound channel in the water column is minimized.

C. *Acoustic Near-to-Far Field Propagation Model*

The algorithm for the acoustic near-to-far field propagation model proceeds as follows:

1) The near-field sound pressure from the pile is calculated with either the frequency domain FEM model using the pile geometry, material properties of the pile and surrounding media and the hammer forcing function as the model input.
2) A vertical slice of the sound field $p(r_0, z, f)$ at a short reference distance r_0 from the pile is taken from the near-field FEM solution to be used as input into the far-field NM model.
3) Shapes of the discrete modes Z_n and corresponding wave numbers ξ_n, are calculated for each frequency component of the near-field input $p(r_0, z, f)$ for the local acoustic environment at the coupling range (i.e. the water depth, sound speed profile and geoacoustic characteristics of the seabed).
4) The complex modal coefficients $A(f)B_n(f, \xi_n)$ are derived from the near-field modeling results at the reference distance r_0 via (4).
5) The sound field $p(r, z, f)$ as function of range, depth and frequency is then computed using the NM method:

$$p(r,z,f) = A(f)\sum_{n=1}^{N} B_n(r_0, f) Z_n(z, f) \frac{H_0^{(1)}(-\xi_n r)}{H_0^{(1)}(-\xi_n r_0)} \tag{5}$$

where $H_0^{(1)}$ is the zero-order Hankel function of the first kind. In the far field, where $\xi_n r >> 1$, (5) can be approximated by:

$$p(r,z,f) = \sum_{n=1}^{N} A(f) B_n(r_0, f) Z_n(z, f) \exp[-j\xi_n(r - r_0)]\sqrt{r_0/r} \tag{6}$$

III. NUMERICAL PREDICTION RESULTS

A. COMPILE Problem Configuration

The generic pile driving configuration adopted for the COMPILE workshop consists of a pile of 25 m in length, 1 m in radius and 0.05 m in wall thickness embedded 15 m into the sandy seabed in a 10 m water column, so that the top of the pile is flush with the sea surface. Shear stiffness in sand was ignored, so it was modeled as a fluid material. A schematic of the problem is shown in Fig. 2 and the pertinent material properties for the pile, water and fluid seabed are given in Table I.

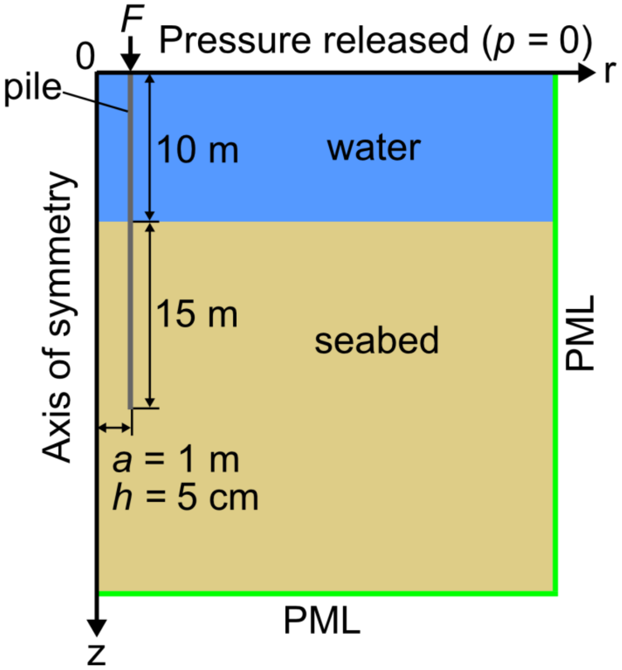

Fig. 2. Schematic of the COMPILE generic pile driving configuration. The axis of symmetry for the cylindrical coordinate system is defined as the centre axis of the pile (r = 0 m).

Table I. Material properties for the COMPILE benchmark model.

Parameter	Notation	Value	Unit
Density of steel	ρ_p	7850	kg/m^3
Young's modulus of steel	E_p	210	GPa
Poisson's ratio of steel	ν_p	0.3	-
Density of water	ρ_w	1025	kg/m^3
Sound speed in water	c_w	1500	m/s
Density of ground	ρ_g	2000	kg/m^3
Sound speed in ground	c_g	1800	m/s

The hammer impact is modeled as a time-dependent force F which is applied at the top of the pile and acts axially downward. The forcing function consists of a steep linear increase followed by an exponential decay and is described by the following function:

$$F(t) = \begin{cases} F_p \dfrac{t}{t_r}, & for\ t \le t_r \\ F_p \exp\left(-\dfrac{t - t_r}{t_d} \right), & for\ t > t_r \end{cases} \tag{7}$$

where F_p = 20 MN is the peak force, t_r = 0.2 ms is the rise time and t_d = 1.5 ms is the relaxation time. The frequency band of the signal modeling is limited to 2.5 kHz. In the COMPILE problem configuration the effect of energy loss due to the pile-sediment friction is simulated by introducing excessive frequency-dependent damping coefficients for both the shear and compressional waves in the section of the pile which is embedded in the seabed, while the waves propagating in the pile section above the seabed remain undamped. The absorption coefficients are defined for the shear and compressional waves as $\alpha_{ps} = 11\times10^{-5}f$ Np/m and $\alpha_{pp} = 3\times10^{-5}f$ Np/m respectively, where f is the frequency. In this implementation, the α_{ps} and α_{pp} coefficients and the elastic material equations are used to derive complex material properties, which results in a complex Poisson's ratio and Young's modulus of 0.301-0.015i and $(2.085-0.210i)\times10^{11}$ Pa respectively for the damped section of the pile, while the pile density ρ_p remains unchanged. Finally, frequency-dependent material absorption is also defined in the fluid seabed, as $\alpha_s = 3\times10^{-5}f$ Np/m. In the present near-to-far field models, the absorption in the fluid seabed is only included in the long range NM model, as the effect of the absorption is negligible at the short ranges and frequency band of the near-field FEM model.

The FEM model of the near-field for the present near-to-far field model was solved in the frequency domain using triangular quadratic finite elements for the pile, fluid and seabed, and the average element size was interpolated from 2.5×10^{-2} m for the pile and contacting fluid to 0.2 m at the maximum radial distance of 36 m and axial depth of 95 m, totaling approximately 3×10^{5} elements. The maximum radial/axial edges of the mesh were attached to perfectly matched layers (PMLs, see Fig. 2) to absorb the outward propagating waves at the mesh boundaries and the model was solved for 800 equally spaced frequencies from 3.125 Hz to 2500 Hz. The large axial depth of the FEM model (compared to the radial dimension) was chosen to make sure that the contribution of highly attenuating high-order modes was adequately represented in the near-field FEM modeling result at the chosen near-to-far field coupling range of 11 m.

B. *Verification of Near-to-Far Field Coupling*

The near-to-far field coupling model can be verified by applying the NM expansion to the sound field modeled by FEM at a short radial distance and then propagating the NM field to a larger distance where the near-field FEM results are still available for comparison. Such a comparison is presented in Fig. 3, where the FEM signal waveform at a radial distance of 31 m and depth of 5 m is compared to the near-to-far field model results obtained at the same range and depth from the NM expansion of the FEM field calculated at a radial distance of 11 m. The agreement between the directly modeled and extrapolated waveforms is generally good, except for a small divergence seen mainly in the signal tail. This divergence results primarily from the approximation of the continuous part of the modal spectrum containing leaking modes by a finite set of highly attenuating discrete modes. However, such a difference did not noticeably affect the peak pressure and energy of the modeled signal as shown in Fig. 3. Good agreement between the FEM and near-to-far field coupled models was also observed in the simulated waveforms at other receiver depths.

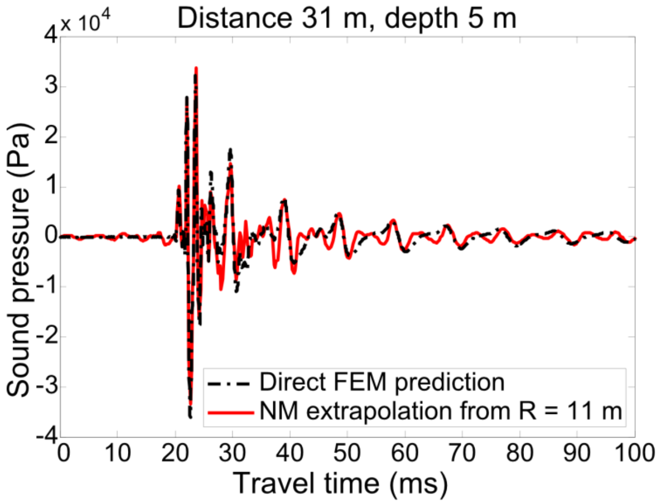

Fig. 3. Comparison of numerical predictions for the signal waveform at 31 m from the pile axis made by direct FEM calculations (blue) and extrapolated from the FEM solution at 11 m via modal decomposition and propagation (red). The SELs of the FEM and extrapolated near-to-far field signals are 182.4 and 182.3 dB re 1 μPa^2 s respectively.

C. Validation of Results with Other Near-to-Far Field Models

Numerical results from the presented model were compared in both the near and far fields to the results provided by several other research groups that participated in the COMPILE workshop. All models include excessive damping in the pile material of the embedded pile section, except for the FDM model developed by JASCO where additional damping was introduced at the pile foot.

Predictions of the signal waveforms at a receiver depth of 5 m and radial distances of 1 m (pile wall) and 31 m from the axisymmetric origin are shown in Fig. 4 and Fig**.** 5 respectively. Corresponding results for the predicted signal waveforms are also presented in the figures for three other research groups which were in attendance at the COMPILE workshop: JASCO Applied Sciences Canada (JASCO), Bundeswehr Technical Center for Ships and Naval Weapons, Maritime Technology and Research (WTD 71), and the Technical University of Hamburg-Harburg (TUHH). The agreement between the numerical predictions by the different models is very good at both radial distances, except for the JASCO results, which are only consistent with the other models for the primary signal emitted from the pile for the first downward propagating wave. This difference is primarily due to the energy damping in the pile being treated in a different way to that described in the COMPILE problem configuration. Good agreement between the other models (WTD 71, TUHH) and the present near-to-far field model is not surprising, as all of these models employed an FEM solution to model the near-field region.

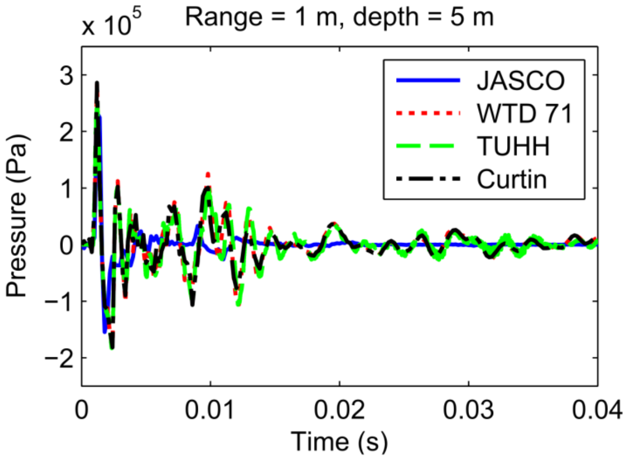

Fig. 4. Comparison of the signal waveform predicted at a range of 1 m and depth of 5 m for the COMPILE configuration. Results from the present coupled near-to-far field model are compared to those from three other research groups that were in attendance at the COMPILE workshop.

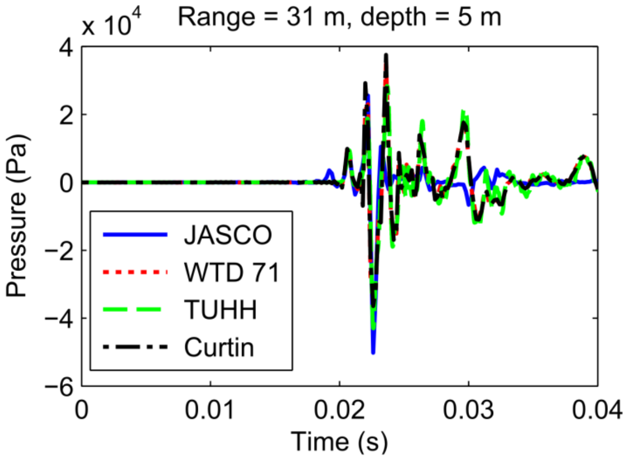

Fig. 5. Comparison of the signal waveform predicted at a range of 31 m and depth of 5 m for the COMPILE configuration. Results from the present coupled near-to-far field model are compared to those from three other research groups that were in attendance at the COMPILE workshop.

The variation of sound exposure and peak pressure levels with range in the far-field was calculated from the signal waveforms predicted for the COMPILE problem configuration. The predictions at a receiver depth of 5 m are compared to the results of the other three models in Fig. 6 and Fig**.** 7 for the levels of sound exposure and peak pressure respectively. Two of the models (JASCO and TUHH) use a WI method applied to a vertical array of point sources (simulating the driven pile) for the far-field model, WTD 71 use a PE method applied directly to the near-field prediction, and the present near-to-far field model employs a NM expansion of the near-field. The agreement between the models is good in general, but there is a deviation of the predicted peak pressure levels with increasing range, which varies from ±1dB at 1.5 km to nearly ±4 dB at 50 km, while the sound exposure levels exhibit a variation of ±1.5dB over the 50 km. Clearly the combinations of the different near-field and far-field models yield slightly different decay rates of the signals with increasing range.

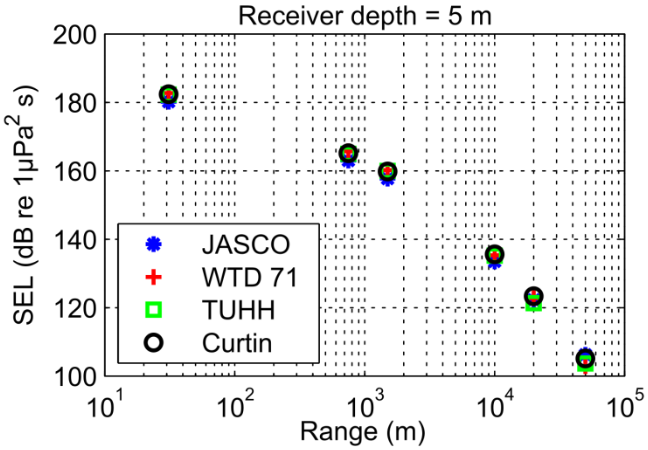

Fig. 6. Prediction of the SEL with increasing range for a depth of 5 m. Results from the present coupled near-to-far field model are compared to those from three other research groups that were in attendance at the COMPILE workshop.

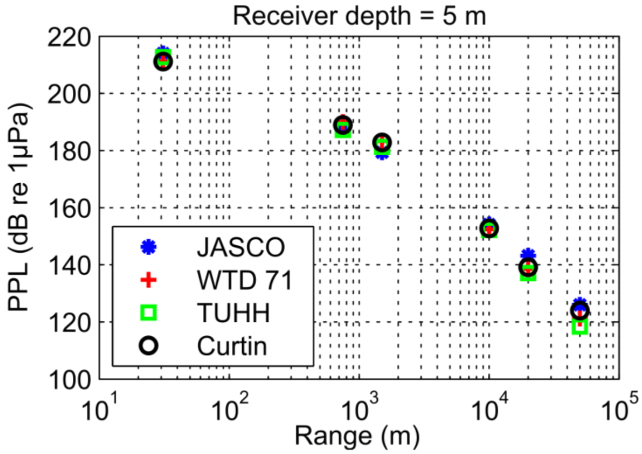

Fig. 7. Prediction of the PPL with increasing range for a depth of 5 m. Results from the present coupled near-to-far field model are compared to those from three other research groups that were in attendance at the COMPILE workshop.

IV. CONCLUSIONS

This paper has presented a coupled near-to-far field model for the numerical prediction of sound emission from impact pile driving in offshore environments. An axisymmetric finite element model of the near-field region is coupled to a normal mode model for the sound propagation into the far-field. Numerical results from the presented coupled near-to-far field model have been compared to those results from several other research groups who presented their models at the COMPILE workshop on predicting offshore pile driving noise. The predicted signal waveforms in the near-field and the sound exposure levels and peak pressure levels in the far-field were shown to be in good agreement between the different models, despite the different approaches employed to model and/or couple the near-field and far-field regions.

Future work on the coupled near-to-far field pile driving model will focus on the development of near-field models which incorporate elastic seabeds (as has been done in [9] and [15] using FEM and analytic near-field models respectively) and so allow for the excitation of shear waves in the seabed, as well as Scholte waves which propagate along the water-seabed interface. This is expected to be particularly important for pile driving modelling in Australian coastal waters, where the seabed typically consist of cemented-sediment materials which have a much higher shear speed than the sandy seabeds, and so the treatment of the seabed as a fluid medium becomes a poor approximation in these environments. Furthermore, the modelling of long range sound propagation from marine pile driving over the cemented-sediment seabeds will require coupling between near-field and far-field models which both incorporate elastic seabeds. A key question that still remains is how to adequately treat the slip of a driven pile in the ground and the resulting energy loss due to the pile-sediment friction in the acoustic model. Some preliminary results from modelling the effects of the pile-sediment friction in elastic and hypoplastic seabed materials have recently been presented in [22].

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