



Guided waves in a monopile of an offshore wind turbine

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ABSTRACT

We study the guided waves in a structure which consists of two overlapping steel plates, with the overlapping section grouted. This geometry is often encountered in support structures of large industrial offshore constructions, such as wind turbine monopiles. It has been recognized for some time that the guided wave technology offers distinctive advantages for the ultrasonic inspections and health monitoring of structures of this extent. It is demonstrated that there exist advantageous operational regimes of ultrasonic transducers guaranteeing a good inspection range, even when the structures are totally submerged in water, which is a consideration when the wind turbines are deployed off shore.

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1. Introduction

The paper addresses issues arising in ultrasonic inspection of offshore structures, such as wind turbine monopiles. These structures are subject to fatigue loading and corrosion, which can remain unnoticed and undetected until there is a catastrophic failure. It is thus desirable to monitor their structural integrity throughout the entire life cycle.

Ultrasonic guided waves are already widely used in nondestructive evaluation [1], in particular for inspection of iron pipes [2]. One of the challenges facing the technology is predicting whether and under what conditions enough wave energy is delivered to the area containing possible damage. Another important issue is the minimization of energy loss, that is increasing an inspection range.

The monopiles can be modeled as two-dimensional, because their diameter is much larger than its wall thickness. The relevant two-dimensional structure can be described as two overlapping grouted steel plates. The fundamental behavior of the guided waves known as Lamb waves, in homogeneous plates, has been intensively studied over the past century [3,4]. One of the most interesting problems of practical interest is the conversion of Lamb waves in structures with inhomogeneities (that is, defects, joints, etc.). Rokhlin [5] solved the problem of interaction of Lamb waves with adhesive metal lap joints using the Wiener–Hopf technique. A similar problem of Lamb waves transmission in adhesively bonded lap joints has been addressed in [6] by using a finite element code. The so-called “projection method” has been employed by Gregory

et al. [7] to study their reflection at the edge of a plate, and by Flores-López et al. [8] to investigate their scattering by a surface breaking crack. The interaction with the crack has been also studied by Castaings et al. [9], who used the modal decomposition to satisfy boundary conditions at a discrete set of points along the crack (a collocation method).

Recently, a number of hybrid approaches have been proposed. These are used to solve the problem using a finite element method [10] or boundary element method [11] in a finite region containing inhomogeneities and then utilizing the modal expansion in the regions where the waveguide is homogeneous. The general framework of this approach is described in [12]. The modal expansion can be performed using SAFE (the Semi-Analytical Finite Element) method [13]. It allows the authors to investigate modal conversion in waveguide of complex structure (i.e. three-dimensional, composite, etc.).

We present an alternative semi-analytical approach, which is similar to the one described in [14]. We split the construction into several simple waveguides and represent the displacement field inside each of them as a sum of Lamb modes. These are chosen to satisfy the appropriate boundary conditions. The solution of the resulting system of linear equations allows us to calculate the reflection and transmission coefficients on the waveguide boundaries. The technique leads to a straightforward estimation of modal amplitudes. It is applicable when the total displacement can be expanded in Lamb waves only, e.g. when working in two dimensions, it is applicable if all boundary segments are straight. The model allows for the energy losses caused by radiation into water.

The paper is organized as follows: in the next section we derive dispersion equations for Lamb waves in the waveguides of interest.

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Section 3 is devoted to the mode conversion coefficients. In Section 4 we discuss the amplitudes of modes present in the loaded overlapping grouted plates. The resulting approach is used to investigate response to loading in symmetric and asymmetric monopiles in Sections 5 and 6, respectively.

2. Dispersion equations in plates and composites immersed in water

The monopile structure is schematically shown in Fig. 1. To be specific, let us use realistic dimensions and assume the cylindrical pile to be approximately 30 m long, have a 5 m diameter and be driven approximately 20 m into the seabed. The top end of the pile is typically 2 m above the sea level. Let the tubular turbine superstructure be mounted on top of the pile, with an approximately 6 m overlap, which is filled with grout. Thus, the mid section is a composite consisting of steel/grout/steel layers. Throughout the paper, the parameters H_1 , H_2 and H_3 refer to the thicknesses of the bottom pile, grouted layer and top pile, respectively. The waves are excited by a transducer installed on the joint's butt-end.

As mentioned in the Introduction, the structure can be modeled as two overlapping grouted steel plates. The model can be decomposed into three simple waveguides I, II and III as illustrated in Fig. 2. The waveguides I and III are plain steel plates and the composite waveguide II consists of a grout layer sandwiched in between such plates. We assume that both steel and grout layers can be modeled as isotropic and homogeneous elastic solids. Then inside each layer the time harmonic displacement $\mathbf{u}$ of the circular frequency ω satisfies the elastodynamic equation

$$\nabla \times (\nabla \times \mathbf{u}) + \chi_l^2 \nabla \cdot (\nabla \cdot \mathbf{u}) + K_l^2 \mathbf{u} = 0, \quad l = 1, 2, 3, \quad (1)$$

where the index $l = 1, 3$ denotes the bottom and top plates, respectively, and the index $l = 2$ refers to the grouted section. The parameter $\chi_l = c_l^t/c_l^r$ stands for the ratio of the shear and compressional wave speeds and $K_l = \omega/c_l^r$ is the shear wave number.

Let $\sigma_l = \{\sigma_{lij}\}_{i,j=1}^2$ denote the stress tensor. The displacement field $\mathbf{u}$ and the stress tensor σ_l are related by the following formula:

$$\sigma_{lij}(\mathbf{u}) = \lambda_l \delta_{ij} \nabla \cdot \mathbf{u} + \mu_l (u_{ij} + u_{ji}), \quad i, j = 1, 2,$$

where λ_l and μ_l are the Lamé constants. On the surface Γ with the outer normal vector $\mathbf{n} = (n_1, n_2)$, the components of the normal stress vector $\mathbf{S}_l(\mathbf{u})$ are given by

$$S_{li}|_{\Gamma} = \sigma_{lij}(\mathbf{u})n_j, \quad i = 1, 2. \quad (2)$$

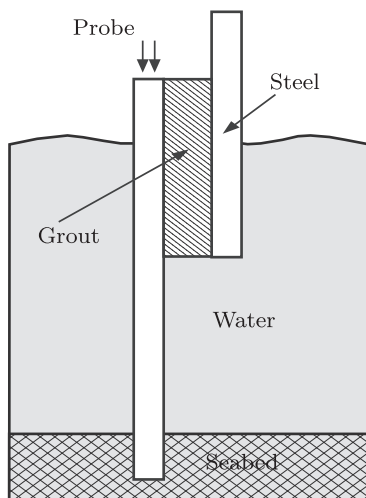


Fig. 1. A schematic of a monopile.

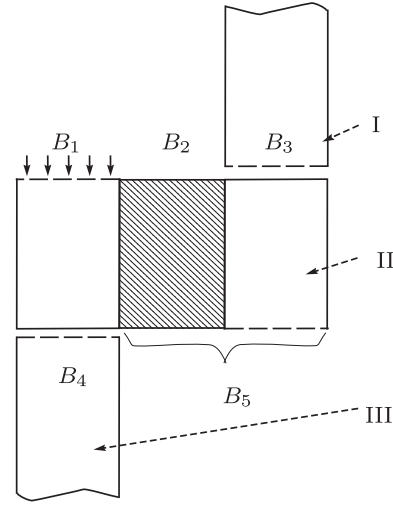


Fig. 2. Decomposition of the overlapping grouted plates into waveguides I, II and III. The vertical arrows indicate the position of the transducer.

The waveguides II and III can be partially submerged in water, where the motion is described by the potential ϕ satisfying the Helmholtz equation

$$\Delta \phi + K_W^2 \phi = 0, \quad (3)$$

with $K_W = \omega/c^W$ – the compressional wave number in water and c^W – its speed. The corresponding displacement $\mathbf{u}$ and pressure p are related to the potential ϕ by

$$\mathbf{u} = \nabla \phi, \quad p = -\rho_W \omega^2 \phi, \quad (4)$$

where ρ_W is the water density.

Let us consider the guided waves in the steel plate, which is submerged in water and has the half width $h_1 = H_1/2$. At the plate's boundaries $x_2 = \pm h_1$, the normal displacement coincides with the normal displacement in water, normal stress is compensated by the pressure field and plate's boundary is free of tangent loading. Therefore, the boundary conditions on the plate's sides $x_2 = \pm h_1$ can be written as

$$\begin{aligned} (u_{1,1} - u_{W,1})|_{x_2=\pm h_1} &= 0, & (\sigma_{1,11} + p_W)|_{x_2=\pm h_1} &= 0, \\ \sigma_{1,12}|_{x_2=\pm h_1} &= 0, \end{aligned} \quad (5)$$

where $\mathbf{u}_l$ and $\mathbf{u}_W$ refer to the displacement in the layer l and water, respectively. Also, as $x_2 \rightarrow \pm\infty$ we impose the standard radiation conditions at infinity, that is, request that the waves in water either decay exponentially or carry the energy away from the plate. We look for the guided waves of the form $\mathbf{u}(x_1, x_2) = \mathbf{U}(x_2) \exp(i\alpha x_1)$. The problem can be decomposed into symmetric and antisymmetric. The resulting symmetric secular equation for a plate, known as dispersion equation, is

$$\Phi_1^+(\alpha, \omega) = \begin{vmatrix} S_1^T \theta_1^2 & G_1^L & 0 \\ C_1^T \alpha_1^2 & C_1^L \theta_1^2 & K_1^2 h_1^2 \rho^* \\ S_1^T \alpha_1^2 & G_1^L & 2\gamma^W \end{vmatrix} = 0, \quad (6)$$

where we have

$$\begin{aligned} \gamma_l^T &= \sqrt{\alpha^2 - K_l^2} h_l, & \gamma_l^L &= \sqrt{\alpha^2 - \frac{K_l^2}{\chi_l^2}} h_l, & \gamma^W &= \sqrt{\alpha^2 - K_W^2} h_1, \\ \theta_l &= \sqrt{\alpha^2 - \frac{K_l^2}{2}} h_l, & \rho^* &= \frac{\rho_W}{\rho_1}, & \alpha_l &= \alpha h_l \end{aligned} \quad (7)$$

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