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A small-scale pile impact test for demonstrating the coupling between structural vibration and underwater noise generation

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ABSTRACT

The performance improvement of renewable energy sources has become nowadays a crucial topic to boost the energy transition. With respect to offshore wind farms, larger wind turbines are currently being designed to increase their power capacity. To support such turbines into the seabed, monopile foundations are mainly used, due to their low-cost manufacturing and transportation. Because of the increased wind turbines' dimensions, larger monopiles are needed, which have shown to shift high

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sound waves to lower-frequency ranges during their installation. A precise prediction of the high noise level is necessary to properly design noise-cancelling devices, which prevent negative impacts on marine life. Because the evaluation of sound levels at a full-scale monopile installation is time-consuming and expensive, small-scale tests are being explored. Here we propose a small-scale test for investigating the high noise levels source. To that end, proper scaling laws and instrumentation have been adopted to assure the similarity between the small- and full-scale cases. The experimental results were also compared to a simplified numerical model. The findings of this work showed that investigating a priori the monopile's features provides an underwater noise prediction, which can be used to design the upcoming noise-cancelling devices.

1. INTRODUCTION

As renewable energy sources have nowadays become a crucial topic for green energy transition, improvements on efficiency of offshore wind farms have been widely discussed around offshore community. One notable aspect of that is the increase in wind farm's capacity with the manufacturing of bigger wind turbines – from the capacity of around 30 GW in 2022, the European Government predicts an addition of up to 160 GW of offshore wind by 2030 [1].

Currently, the most used wind turbine foundation is a monopile. In order to follow the growth trend of wind turbines, large-diameter monopiles are being designed. Such monopiles are driven into the soil through the impact of a hydraulic hammer. During the drivability process, energy is released to the underwater environment in the form of pressure waves, which travel for long distances that can reach the order of kilometers [2]. The high magnitude of such waves has caused negative impacts to marine life, such as hearing damage, changes in behavioral patterns and even death [3,4]. Therefore, understanding the underwater noise source during monopile installation is fundamental to design noise reduction devices for marine life protection.

Since the driving process of large-diameter monopiles is a complex process demanding operational time and cost, the investigation of noise propagation in such full-scale environment becomes a challenge. Furthermore, the number of variables involved in this system (such as, current, pile geometry variation, soil composition uncertainties, noise generated by other offshore processes, and other factors) increases the uncertainty regarding to the noise source. Therefore, the development of a small-scale setup is desirable to create a controlled domain, in which measurements are precisely executed.

Although the importance of small-scale tests in understanding the physics behind large-scale monopile installation, few works describing the scaling laws and the main design variables can be found. For instance, Woolfe [7] proposed a scaled setup for investigating the underwater propagation of partially submerged piles under impact load. Although the scaling laws are highlighted, the soil effect on noise propagation is not considered. A comparison between a semi-analytical variational formulation and measurements made in a mini offshore pile was presented by Deng et al. [8]. Since the author's aim consisted in demonstrating the reliability of the proposed formulation, the comparison study was performed in a non-scaled monopile. The driving process of monopiles is recently being explored in centrifuge tests, where stress fields in soil are comparable with the ones obtained in a full-scale prototype [9,10]. The noise propagation in such models, however, has not been evaluated. Jiang et al. [11] proposed a theoretical characterization of a fluid-pile-soil system and an experimental study of a noise reduction device. Even though the listed physical pile driving models have provided insights about scaling laws and noise prediction, the focus on noise generation has not been addressed.

This paper proposes a design of a small-scale test for offshore monopile to predict the underwater noise during the first hammer impact. Here, we describe the main assumptions and scaling laws used to study the sound emission in a small-scale monopile analysis. The experimental results are also compared to a simplified numerical model. The findings in this work will contribute to understand the noise generation phenomenon so that it can be applied for designing the upcoming noise reduction devices.

2. PHYSICAL MODELLING

This section introduces the chosen methodology to design a small-scale experimental setup for evaluating the noise emission during hammering of an offshore monopile. The scaling laws, equipment description, and required instrumentation will be explained further.

For that end, it is important to initially define the scaling laws, which ensure a level of similitude between the full-scale and the small-scale setup. The geometric scale under normal gravity (1-g) conditions used in this work is expressed as

$$\frac{L_\mathrm{F}}{L_\mathrm{S}} = \frac{D_\mathrm{F}}{D_\mathrm{S}} = \frac{t_\mathrm{F}}{t_\mathrm{S}} = \lambda, \tag{1}$$

where the subscripts F and S indicate dimensions related to field and small-scale models, respectively; L indicates the pile length and λ is the chosen geometric scale. A traditional monopile used as offshore wind farm foundations is presented in Figure 1. The pile is made of Steel S355ML and is formed by sections with specific length, diameter, and thickness. The total pile length is $L_\mathrm{F} = 59.93$ m and the average diameter and thickness are $D_\mathrm{F} = 8.3$ m and $t_\mathrm{F} = 56.3$ mm, respectively. Steel sheets are commonly found in standard dimensions, which limits the choice of geometric scales. In this work, the small-scale monopile was made of a Steel S152-3N sheet of thickness $t_S = 2$ mm, whose material properties are Young's modulus $E_\mathrm{p} = 210$ GPa, density $\rho_\mathrm{p} = 7850$ kg/m^3, and Poisson's ratio $\nu_\mathrm{p} =$ 0.28. Replacing t_F and t_S into Equation 1 provides a geometric scale of 28. The total length and diameter of the scaled pile can then be determined, which gives that $L_\mathrm{S} = 2029$ mm and $D_\mathrm{S} = 295$ mm.

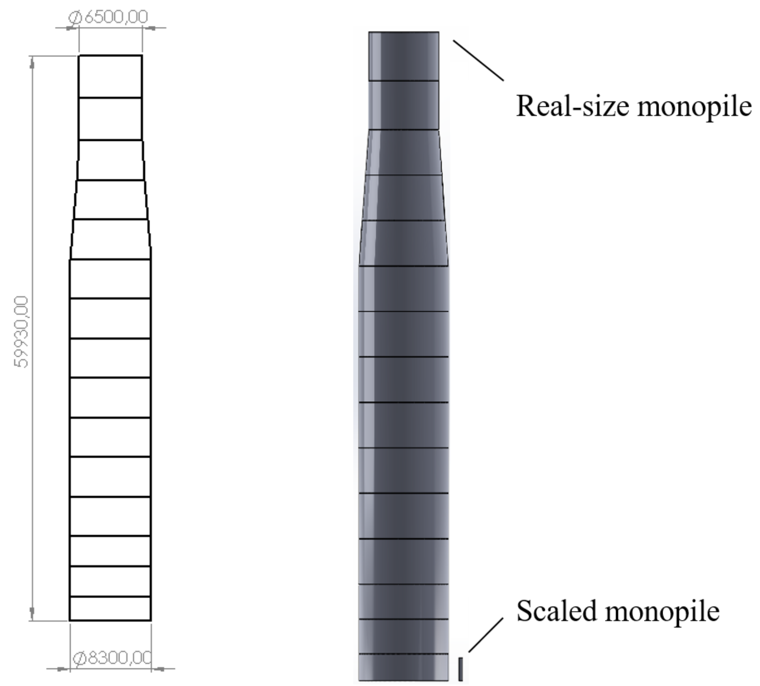

Figure 1: Perspective visualization of a real-size and a scaled monopile.

The experimental setup was built in the facilities of Huisman Equipment B.V.. The scaled monopile was placed in a steel tank with length $L_\mathrm{tank} = 6$ m, width $W_\mathrm{tank} = 2.44$ m, and height $H_\mathrm{tank} = 1.5$ m as shown in Figure 2. The tank bottom was covered with a 300 mm height layer of sand, whose density is 1500 kg/m^3. Since the sand has a low density, the self-weight penetration of the pile was high enough to result in the contact between the pile tip and the tank bottom. To prevent that (which could add extra noise to the measurements), four Styrene Butadiene Rubber with a thickness of 5 mm each were added between the pile tip and the tank. The tank has also been covered by foams in order to reduce the wave reflections.

Figure 2: Interior view of the tank showing the rubber plates used to keep the pile position, the soil layer profile, and the hydrophone location.

To measure the sound pressure in water, one hydrophone TC4013 was positioned at three different distances (500, 1000 and 2000 mm) from the pile wall and kept at the middle of the tank, as shown in Figure 2. Before identifying the noise due to the impact of a monopile, it is important to determine the natural frequencies of the tank, which may add background noise to the measure data. The following expression is used to calculate the natural frequencies,

$$f(l,m,n) = \frac{c_{water}\sqrt{k_x(l)^2 + k_y(m)^2 + k_z(n)^2}}{2\pi}, \tag{2}$$

where c_{water} is the speed of sound in water, which is equal to 1490 m/s; l, m and n are the mode numbers, and k_x, k_y and k_z are the wave numbers in the x, y and z directions, which are expressed as,

$$k_x(l) = l\pi/L_{tank}\,, \tag{3}$$
$$k_y(m) = m\pi/W_{tank}\,, \tag{4}$$
$$k_z(n) = (2n+1)\pi/(2H_{tank}), \tag{5}$$

The ten first natural frequencies of the tank are determined by replacing its dimensions into Equations 2-5. The calculated values are shown in Table 1.

Table 1: Ten first natural frequencies of the test tank predicted by Equation 2.

l,m,n	1,0,0	0,1,0	0,0,1	1,1,0	0,1,1	1,0,1	1,1,1	2,0,0	0,2,0	0,0,2
f_t(l,m,n) [Hz]	390	496	1110	511	1158	1116	1164	444	757	1850

The instrumentation used to investigate the dynamic behavior of the monopile is introduced in Figure 3. An Endevco 773-200-u accelerometer measures the wall motion in the three directions. Strain gauges are also used to measure the deformation of the wall. Both transducers were attached on the pile wall at a distance of 1.5× D_S from the pile top, as defined by the American Society for Testing and Materials (ASTM D4945) standard [5]. An impact hammer was used to provide the input load necessary to identify/induce the dynamic characteristics of the setup.

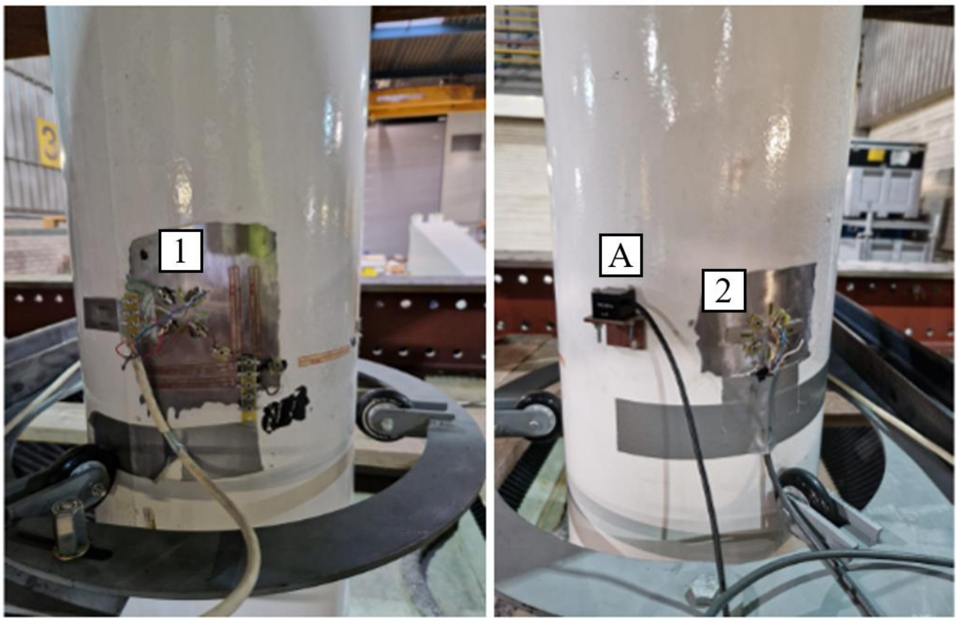

Figure 3: Instrumentation used to measure pile wall motion (A indicates the accelerometer; 1 and 2 represent the set of strain gauges).

The signal captured by the hydrophone is converted into sound pressure in time domain $p(t)$. In order to investigate the dynamic characteristics of the signal in the frequency domain, a Fast Fourier transform (FFT) is applied, which gives $P[k,x,y,z]$, being k the number of data points until the Nyquist frequency, and x, y, z the coordinates of the hydrophone position. The frequency domain pressure P is then used to calculate the sound pressure spectrum (SPS) defined as

$$SPS[k,x,y,z] = \sqrt{2}|P[k,x,y,z]|. \tag{6}$$

To measure the sound intensity in terms of decibels (dB), the zero-to-peak Sound Pressure Level (SPL_{peak}) will be determined, which is expressed as [6]

$$SPL_{peak}(k,x,y,z) \equiv 20\log_{10}\frac{SPS}{p_0}, \tag{7}$$

where p_0 is the pressure reference (for water $p_0 = 1\ \mu$Pa). The signal measured by the strain gauges and accelerometer are also analyzed by means of a linear spectrum, which states that

$$LS_A[k] = \sqrt{2}|A[k]|, \tag{8}$$
$$LS_S[k] = \sqrt{2}|S[k]|, \tag{9}$$

where A and S are the accelerometer and strain gauges data in the frequency domain.

3. NUMERICAL MODEL

A numerical model of the proposed test setup was developed in Comsol Multiphysics to compare the measured critical sound with the predicted values (Figure 4). Since the tank and the side foams have a complex geometry, which could increase significantly in the computational cost, some simplifications have been applied as described below:

- The water has been modeled as an acoustic domain. Its top surface is modeled as a soft boundary condition and the side boundaries were represented by a plane wave radiation, which states a non-reflective boundary. The interface between the pile and the water is modeled as an acoustic-structure interaction;

– Due to the addition of side foams and the sand layer, the tank influence can be neglected in the numerical model;
– Due to the symmetry of the problem, only one quarter of the domain is analyzed;
– The sand layer is represented by an elastic domain with fixed conditions at the exterior boundaries. The interface between the sand layer and the water is modeled as an acoustic-structure interaction;
– The pile is modeled as a linear solid domain with a free top surface and a fixed bottom.

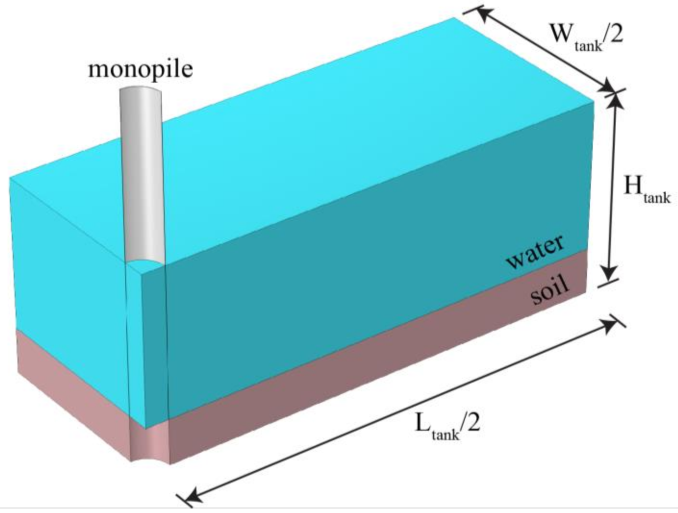

Figure 4: Simplified numerical model of the experimental test.

A harmonic analysis of the pile-water-soil system is performed to identify the dynamic characteristics of the monopile and the noise levels. The strain and acceleration of the pile, as well as the pressure in water are measured at the same locations of the experimental model. Since the focus here is demonstrating the relation between the pile wall motion and the underwater pressure waves, a fictitious vertical harmonic load with amplitude of 1 N is applied on the pile top surface.

An eigenfrequency analysis of the monopile in vacuum conditions was also performed to compare with the resonant peaks predicted by the numerical harmonic analysis and the experimental test. The bottom boundary was fixed, while a free end condition was applied on its top surface. Table 2 shows the ten first natural frequencies of the monopile under such conditions.

Table 2: Ten first natural frequencies of the monopile in vacuum.

Eigenfrequency	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}
Value in Hz	398	637	1194	1903	1991	2788	3134	3584	4250	4381

4. RESULTS

The study of noise source from the driving process is performed by hammering a scaled monopile and collecting the data from the instrumentation described previously. The test is repeated five times to guarantee the accuracy of the output data. The test results are then normalized (with respect to the number of samples) and averaged, and finally used to determine the acoustic and mechanical indicators presented from Equations 6 to 9.

Figure 5 shows the typical time variation of pressure detected by the hydrophone located at 500 mm from the pile wall and 500 mm above the sand surface. Without loss of generality, the presented results will be associated with the hydrophone at such position.

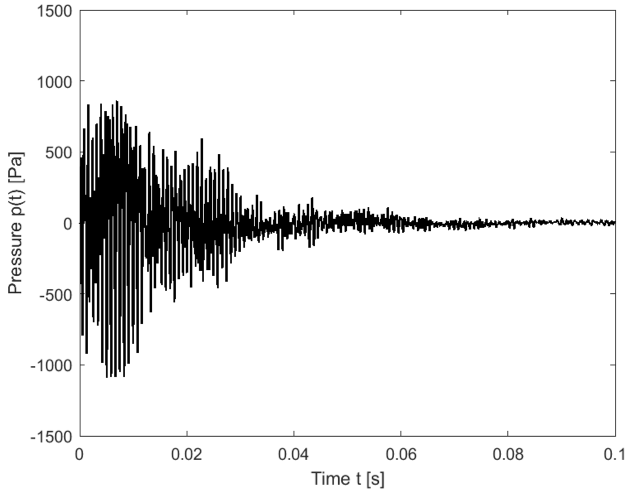

Figure 5: Pressure $p(t)$ detected by the hydrophone positioned at 500 mm from the pile wall and 500 mm above the sand surface after a hammer strike.

The measured pressure was used to determine the SPS (Equation 6) and the SPL (7), while the data collected by the strain gauge and accelerometer was applied into Equations 8 and 9. Figure 6 presents the comparison between the linear spectrum of the strain gauge and the sound pressure spectrum. The vertical blue lines highlight the natural frequencies of the monopile presented in Table 2. Notice that some peaks in the linear spectrum occur near the four lowest eigenfrequencies of the monopile, from which the third mode is more prominent. This difference can occur due to the difference in boundary conditions, once the experimental monopile is not fixed to the tank bottom, and due to the manufacturing of the monopile – in the numerical model, the monopile is uniform, while the tested pile is made of welded steel sheets. Furthermore, the interaction between the water column and the pile wall can act as added mass, which can bring the natural frequencies of the pile to lower frequencies [7]. For the SPS curve, however, only the peak associated to the third eigenmode is more emphasized, as we can also observe in the SPL curve presented in Figure 7, which can be attributed to a low sensitivity of the instrumentation at low frequency ranges. In the LS, SPS, and SPL curves, other peaks are also presented at frequencies close to the predicted tank's eigenmode (Table 1).

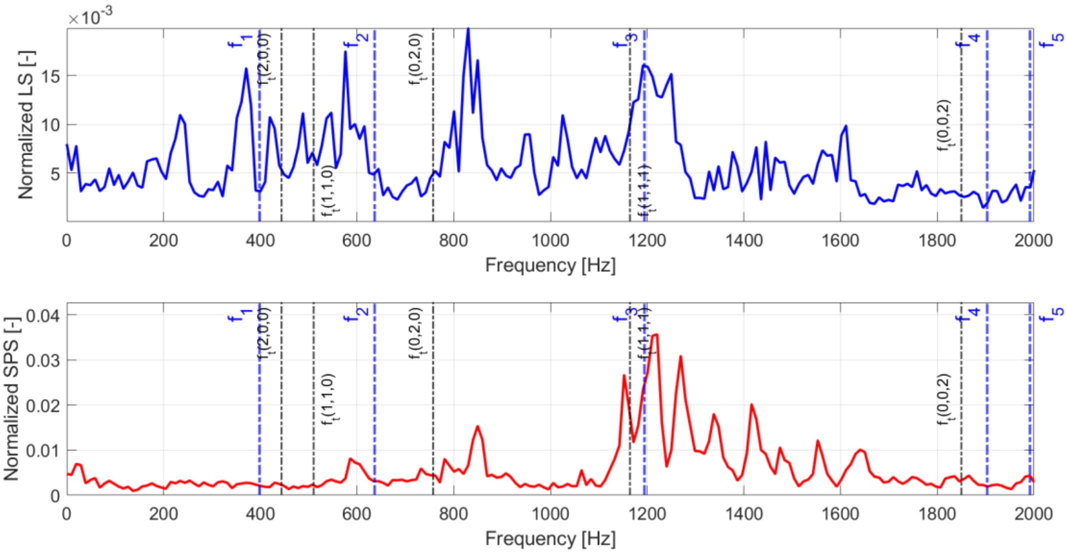

Figure 6: Normalized linear spectrum of strain gauge (top) and sound pressure spectrum of hydrophone (bottom) measurements obtained during monopile impact test. The vertical black and

blue lines highlight the numerically predicted eigenfrequencies of the tank (Table 1) and the monopile in vacuum (Table 2), respectively.

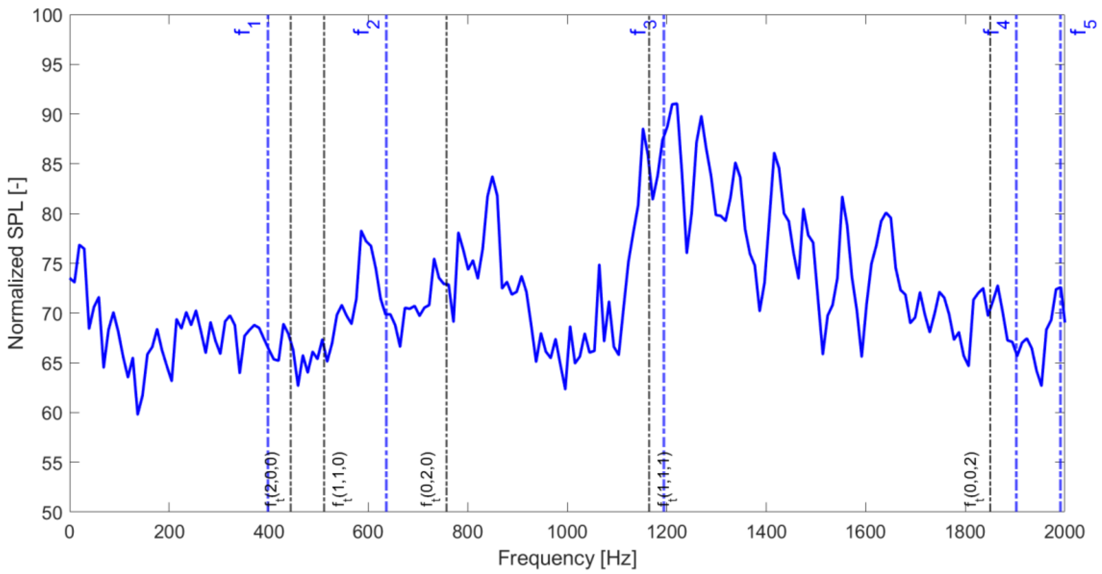

Figure 7: Normalized SPL obtained during monopile impact test. The vertical black and blue lines highlight the numerically predicted eigenfrequencies of the tank (Table 1) and the monopile in vacuum (Table 2), respectively.

Figure 8 shows the linear spectrum of the accelerometer data, which was smoothed by using a Gaussian-weighted moving average filter with a window of length 8. Notice the presence of a peak close to the second natural frequency of the monopile in vacuum, which was also highlighted in Figures 6 and 7. Through such analyses, we can emphasize the influence of the monopile's eigenmode on the sound pressure level at the same frequency.

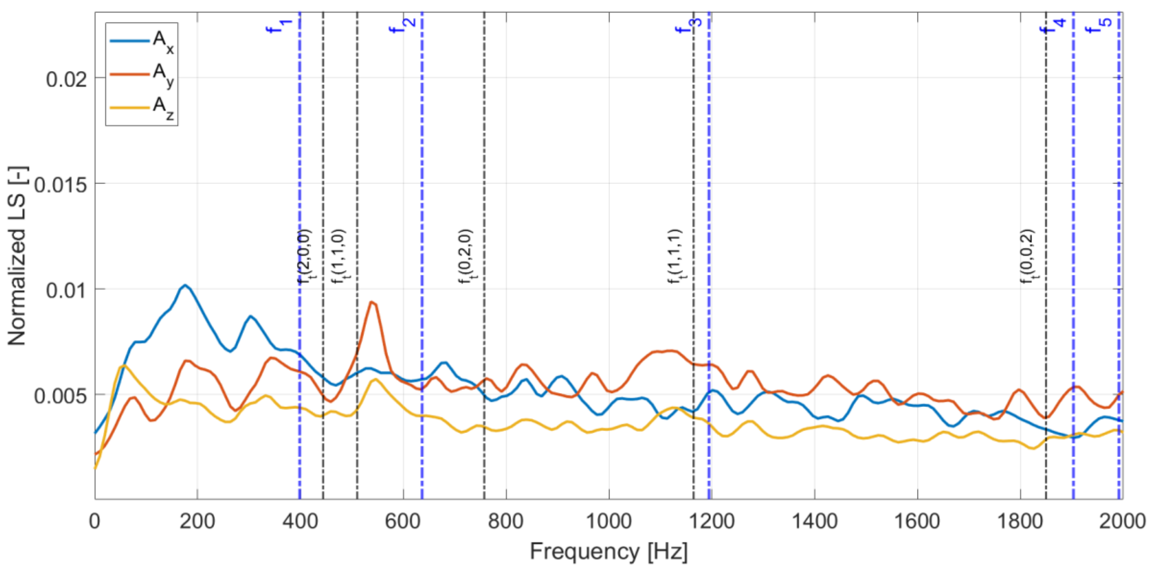

Figure 8: Normalized linear spectrum of the accelerometer (top) in the three directions. The vertical blue lines highlight the numerically predicted eigenfrequencies of the monopile in vacuum (Table 2).

The relation between the monopile vibration and the underwater noise was also investigated in the frequency response of the numerical model presented in Figure 4. The strain, acceleration and

SPL measurements are displayed in Figure 9. The numerical analysis also shows a strong coupling between the second eigenfrequency of the monopile and the highest peak in the SPL spectrum.

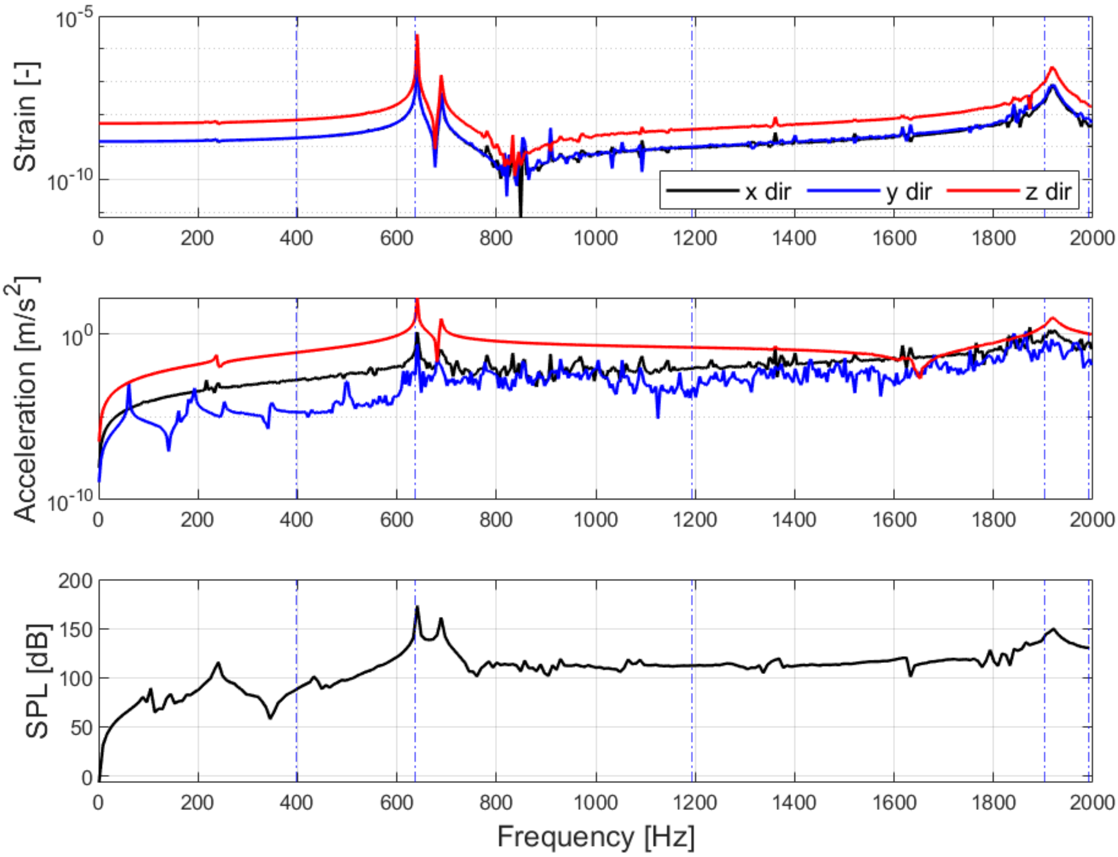

Figure 9: Strain (top) and acceleration (middle) obtained in the numerical monopile, and SPL (bottom) measured at the water domain. The vertical blue lines highlight the numerically predicted eigenfrequencies of the monopile in vacuum (Table 2).

4. CONCLUSIONS

This paper proposes a small-scale pile driving test to investigate the underwater noise source when the monopile is installed into the seabed. To guarantee some similarity with a full-scale system, proper scaling laws were applied. Both numerical and experimental results showed the strong influence of the monopile's natural frequencies on the SPL levels, with some distinctions due to the simplifications of the numerical model. We also demonstrated the importance of a controlled environment for the identification of the variables influencing the highest peaks in the SPL becomes accurate. Finally, selecting transducers that operate at the expected frequency range is essential to enhance the dynamic characterization of the setup. Considering such key aspects is necessary for a precise prediction of underwater noise, which can be further implemented at the design of new noise-reduction devices.

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