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Underwater noise mitigation from pile driving using a tuneable resonator system

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Abstract

This paper covers the development of a tunable acoustic resonance-based underwater noise abatement system for use with marine pile driving, offshore energy production, seismic sources, and ships, among others. The system consists of arrays of underwater air-filled resonators, which surround the noise source and are tuned to optimally attenuate noise in a frequency band of interest. Based on the predictive models for the acoustic dispersion relation in bubbly liquids given by Church and Commander and Prosperetti, this system has been shown to attenuate sound by up to 50 dB near the resonance frequency of the resonators. In this investigation, modeling and laboratory tests were used to tune the system for pile driving applications with a spectral noise peak near 100 Hz. System demonstrations that were conducted at two offshore wind farm construction sites in the North Sea will be discussed. In these tests, peak sound pressure level reduction of nearly 40 dB was measured around the design frequency, and almost 20 dB sound exposure level reduction was measured in the 20 Hz to 20 kHz band. The method of deploying these resonator arrays in a simple collapsible framework, as well as the operational advantages of this system for pile driving, will be described and details on a fully constructed noise abatement system that will soon be tested will be shared.

Keywords: Pile driving noise, underwater noise abatement, Helmholtz resonance

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1 Introduction

An improved approach to underwater noise abatement for pile driving is described in this paper. This noise abatement system uses a simple collapsible framework containing arrays of acoustic resonators, tuned to absorb the broadband underwater acoustic noise radiated by marine pile driving. The system is fully customizable and shown to have predictable performance both in terms of the frequencies that are absorbed and the level of reduction that is demonstrated. Noise reduction of up to 37 dB was measured in a field demonstration test of the technology. The estimated installation time for a full-scale noise abatement system around an 8-meter-diameter pile in 40 meters of water is approximately 15 minutes while staying outside of the critical path of the installation procedure.

2 Background

The system uses arrays of resonators similar to Helmholtz resonators [1], but with two fluids—air and water. Single-fluid versions of these devices have been used for decades as sound attenuators in architectural acoustics, engineering acoustics, and other fields of airborne acoustics, but this is the first known application of Helmholtz resonators for underwater noise reduction. A modified Helmholtz resonator, having soft sides and an open bottom, is used in this application to broaden the range of frequencies that may be attenuated by a single device. Laboratory tests on these resonators were conducted previously [2,3], and demonstrations of a reduced-scale noise reduction system utilizing these open-bottom resonators were performed in the North Sea are reported here.

The resonator-based noise abatement system is derived from research and development conducted by the authors for underwater noise mitigation for offshore drilling by the oil and gas industry and other low-frequency (< 1000 Hz) noise sources including pile driving and seismic sources [4–6]. Earlier noise abatement strategies relied on screens of freely rising bubbles [7,8]; however, these are mainly effective at higher frequencies (> 1000 Hz) due to the order-millimetre bubble size. To exploit acoustic resonance phenomena at low frequencies, larger resonators are needed. The concept of attenuation of underwater sound using large fully encapsulated resonators is described in references [2–4].

The new two-fluid, open-ended, Helmholtz-like resonators differ from fully encapsulated resonators in that the resonance behaviour is dependent on a number of factors shown in Fig. 1: air volume *V*, neck length *L*, and aperture surface area *A*. There are a number of advantages to using open-ended resonators over fully encapsulated resonators:

- They are more customizable and their acoustic properties are better predicted using mathematical models than fully encapsulated resonators or balloons.
- Their acoustic performance is less sensitive to depth changes.

- More rigging and manufacturing options are available.
- The ballast requirement is reduced because resonator-based systems require less air than equivalent performance encapsulated bubble systems.

Laboratory and lake demonstration tests of open-ended, rubber-sided resonators were reported previously [2,3]. These resonators were incorporated into a small demonstration system, which was tested at an offshore wind farm construction site in the North Sea in 2014.

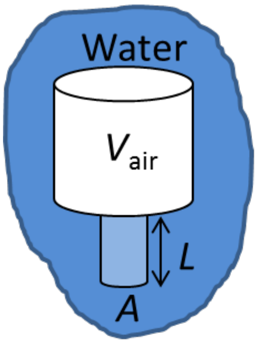

Figure 1: Diagram of underwater air-filled resonator. The upper portion (white) is filled with a volume V_{air}. The bottom of the resonator (light blue), called the neck, has length L, is filled with water, has cross-sectional area A, and is open to the water.

3 Offshore demonstration tests

A demonstration of the resonator-based noise abatement technology was conducted at the Butendiek Wind Farm in July 2014 in conjunction with the project developer, WPD, and the installation firm, Ballast Nedam. The diameter of the monopile was 6.8 m. Representatives from AdBm Technologies and the Applied Research Laboratories University of Texas at Austin (ARL:UT) conducted the demonstration with additional crew, vessels, and support provided by Ballast Nedam.

The demonstration system consisted of a modular, collapsible framework, which housed and deployed the submersible air-filled acoustic resonators. When fully deployed, the framework and acoustic resonators were designed to extend and cover the entire water column, but the collapsible nature of the framework allowed the system to be stored in a compact manner.

The demonstration noise abatement system consisted of a scaled-down, single collapsible framework populated with 240 acoustic resonators. The resonators were designed to have a resonance frequency of 100 Hz and were fabricated specifically for this demonstration. The framework consisted of eight horizontal slats, each housing 30 acoustic resonators that could be expanded to a height of 7 meters. When fully collapsed, the panel was less than 1.5 meters tall. A photograph of the demonstration panel in the fully collapsed state on deck of the Mena C, an anchor-handling tug boat subcontracting for Ballast Nedam, is shown in Fig. 2. A photograph of the fully extended panel at an ARL:UT test tank is shown in Fig. 3.

The purpose of the Butendiek demonstration was two-fold: 1) demonstrate deployment and retrieval of the panel in North Sea conditions, and 2) demonstrate our technology's sound reduction effectiveness on pile driving noise in protect-the-receiver configuration. To enable the acoustic tests of the demonstration panel, two hydrophone arrays were used – a baseline array that measured the untreated pile driving noise and an array embedded with the demonstration panel to measure the panel effects on the noise. The demonstration is described below, followed by the key acoustic results.

The demonstration panel was deployed from the Mena C during the driving of a monopile at the Butendiek offshore site. The demonstration panel was deployed approximately 285 m and 750 m away from the monopile, although most of the results will be based on the 285 m location. The Mena C's GPS system was used to determine the distance from its mooring location to the monopile. The panel, its embedded hydrophone array, and a baseline hydrophone array were deployed from the port side of the Mena C at each deployment location, and the Mena C was positioned such that its port side was facing the Svanen, the installation vessel. The Mena C's thrusters were turned off during acoustic data collection to minimize the ambient noise levels at each site; however, its generators were left on. The test configuration is summarized in Figure 4.

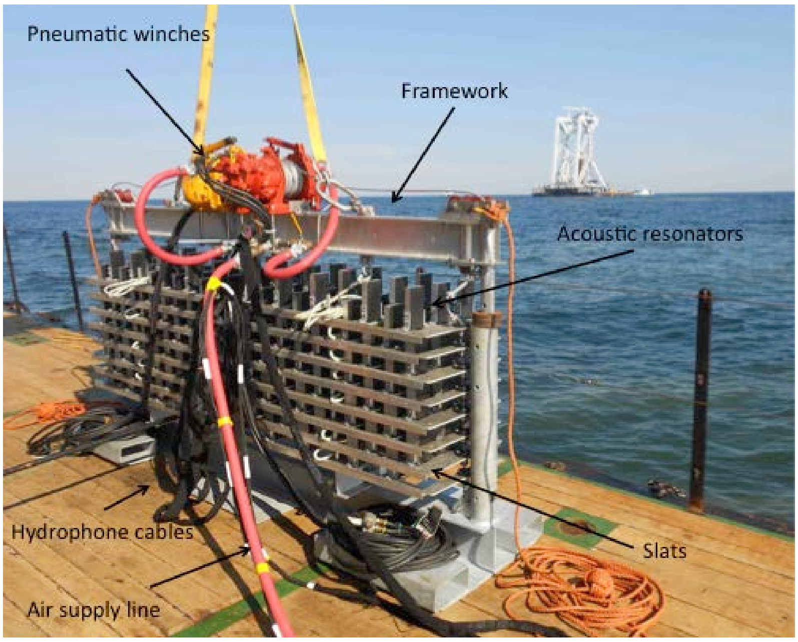

Figure 2: Photograph of demonstration panel in collapsed state on deck of the Mena C. The various components of the system are labelled. The Svanen is visible in the distance.

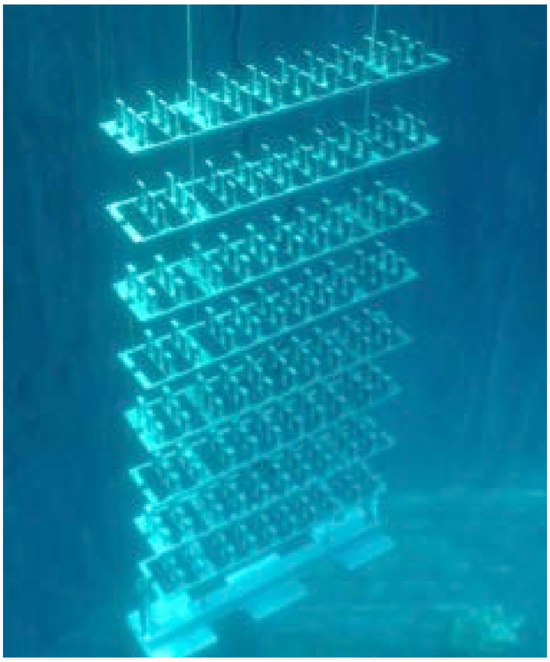

Figure 3: Photograph of the fully extended demonstration panel in the ARL:UT test tank.

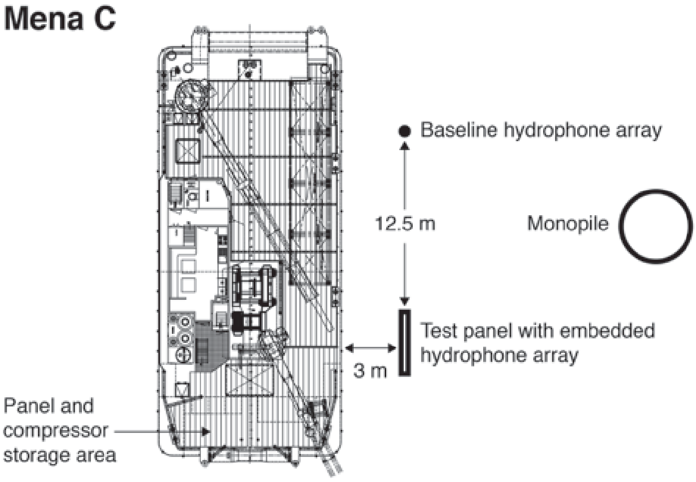

Figure 4: Plan-view diagram depicting the deployment and demonstration test configuration. Distance to pile depicted in the figure is not to scale.

At each test location the panel and baseline hydrophone array were deployed and left in the water during pile driving events until sufficient acoustic data were collected. Acoustic data were recorded simultaneously on three hydrophones from both arrays so that a direct comparison could be made between the signals recorded on the unshielded array and those recorded on the array embedded in the noise abatement panel. The individual hydrophones on each array were vertically spaced 0.6 meters apart. This comparison provided a measure of the amount of sound absorption provided by the demonstration panel.

All acoustic data were recorded using High Tech Inc. HTI-90-U hydrophones. The three hydrophones on each array were spaced at 1.2 m from each other at water depths ranging from 3.6 m to 6.0 m. The hydrophone signals were preamplified using a laboratory amplifier. Hydrophones signals were subsequently digitized at a sampling rate of 10 kHz in 24-bit resolution using a Data Translation DT9826 USB Data Acquisition Module and stored on a laptop computer.

The acoustic data were analysed on a strike-by-strike basis. A computer algorithm was written to automatically detect and gate individual strikes in the data for further processing. The data were high pass filtered with a cut-off frequency of 20 Hz using a zero-phase forward and reverse digital filter to minimize the presence of low frequency pressure variation in the data due purely to surface water wave motion. Quiet gaps between strikes were used to obtain estimates of the ambient noise levels (non-pile-driving noise). Two metrics are used to quantify the demonstration panel's acoustic noise-reducing performance: peak sound pressure levels and third-octave band levels.

To determine the frequency-dependence of the sound attenuation provided by the panel, one-third-octave band levels were computed from the acoustic data for each pile strike. The hydrophone data was sent through a bank of digital filters each with one-third octave bandwidth and center frequencies specified by the most recent ANSI standard [9], and the peak pressure in each band was determined. Ambient noise bands levels were also computed from the quiet gaps in between the pile strikes. All of the third-octave band levels are plotted in Figure 5 to show the amount of variation in the recorded data. From the baseline data, the noise radiated from the monopile has a broad peak in approximately the 50 Hz to 300 Hz frequency range, with not much acoustic energy observed above the non-piling ambient noise levels at frequencies of 1 kHz and higher. As demonstrated at the 285 m measurement location, the panel reduced the sound levels at all frequencies above approximately 50 Hz.

Average band-level-reduction values were computed from the one-third-octave bands to further quantify the attenuation provided by the demonstration panel. These reduction values were calculated for the data taken at 285 m and also 750 m away from the monopile and were averaged over all pile strikes recorded at each location. Band level reduction was computed by subtracting the average band levels measured by the panel array from the average band levels measured by the baseline array, and it is plotted in Figure 6. Positive values of this quantity correspond to a reduction in sound by the demonstration panel. The peak reduction occurs in the band centred near 100 Hz, indicating that pile noise signals around this frequency were reduced on average by 36.8 dB at the 285 m measurement location. The peak reduction occurs at this frequency because the acoustic resonators used in the demonstration panel were designed to resonate near 100 Hz and provide the most attenuation at this frequency. As seen in Figure 6, the peak noise radiated by the pile also occurs near 100 Hz, coinciding by design with the highest reduction levels. The peak reduction calculated at the 750 m location was limited 29.6 dB; however, this is an artefact of the pile-driving signal being only that level above the ambient noise at these frequencies at this measurement location.

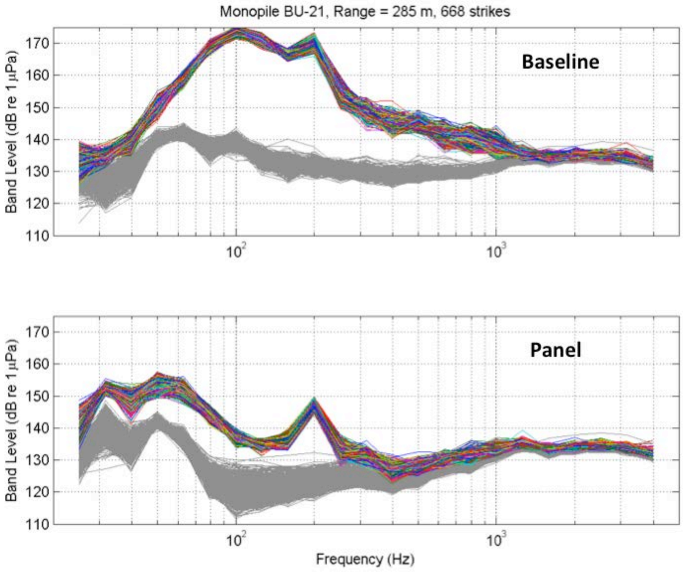

Figure 5: One-third-octave band levels for all monopile strikes recorded at the location 285 meters away from monopile. The coloured lines are the band levels corresponding to each pile strike. The grey lines are non-pile ambient noise band levels from the quiet sections of data between pile strikes. The horizontal axis is frequency on a log scale.

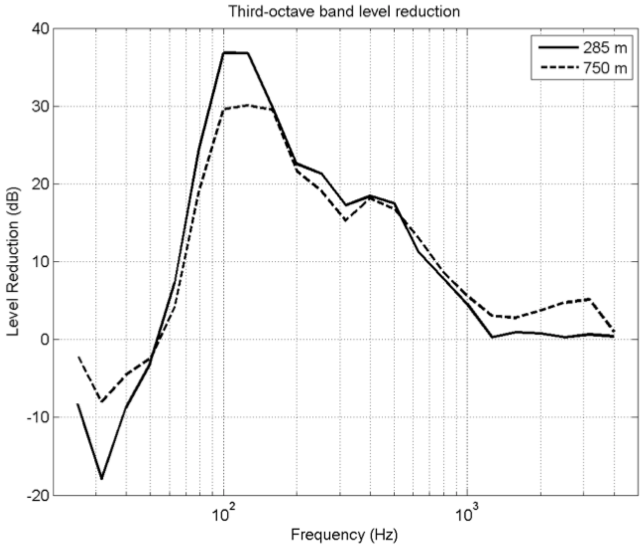

Figure 6: Average one-third-octave band level reduction measured at each of the test locations for monopile.

At the lowest frequencies the calculated band level reduction becomes negative, indicating a level increase. Below the resonance frequency of the individual acoustic resonators in the demonstration panel, a collective resonance of the entire panel is excited and the incoming sound wave can be coherently scattered, resulting in a net increase in sound pressure. This is a well-known phenomenon from the field of bubble acoustics [10,11]. Fortunately, there is not much sound energy in the pile driving noise spectrum below 50 Hz so there is very little noise at low frequencies to be amplified. Furthermore, a full-sized panel would be much larger than the demonstration panel, and since the collective panel resonance scales inversely with panel size, that mode would be shifted to much lower frequencies where no sound energy would be present to excite it.

4 New developments and future work

Recent research and development has led to a modified version of these resonators allowing them to be constructed from a single material, such as steel, aluminium, or plastic. These new resonators have several advantages:

- They are more rugged than the previous resonators.
- They have an increased acoustic response exhibited as a higher quality factor.
- 25% less air is required than the resonators used in the 2014 tests.
- They are easier to manufacture and customize, and their acoustic behavior is more predictable with the use of well-tested mathematical models.

New demonstrations are currently in the planning stages to validate this new approach. A schematic diagram of the full-scale demonstration system planned for these tests is shown in Figure 7.

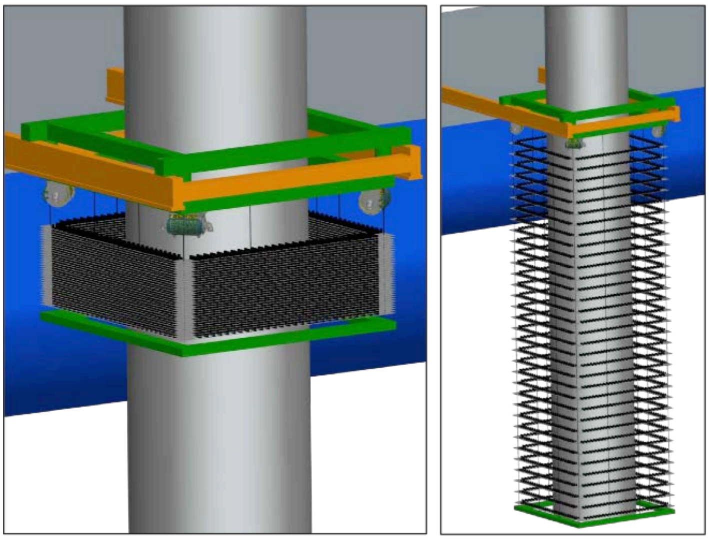

Figure 7: Schematic diagram of the planned full-scale pile-driving noise abatement system in compressed state (left) and fully expanded state (right).

5 Conclusions

Underwater noise is a significant issue for the offshore wind industry. Our approach has yielded the only system known to the authors with fully predictable performance that is customized for a particular application, significantly decreasing the risk of regulatory issues. In addition, being outside of the critical path, the system can be installed without any effect on installation cycle times, reducing operating costs and risk. In addition, the system requires no deck space if attached to a pile gripper or template, it requires no additional vessel support, is completely passive and silent and does not consume energy during operation (compared to compressor-driven freely-rising bubble curtains). It is a major advancement for the industry.

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