

**Naval Information
Warfare Center**



PACIFIC

TECHNICAL REPORT 3307
OCTOBER 2022

Wave Tank Experimentation of Seafloor Pressure Waves Induced by Ocean Surface Wave Interactions

Doug J. Grimmett
P.F. Wang, Ph.D.
NIWC Pacific

Umesh Korde, Ph.D.
Johns Hopkins University

Michael McBeth
NIWC Atlantic

DISTRIBUTION STATEMENT A: Approved for public release.
Distribution is unlimited.

Naval Information Warfare Center (NIWC) Pacific
San Diego, CA 92152-5001

This page is intentionally blank.

TECHNICAL REPORT 3307
OCTOBER 2022

Wave Tank Experimentation of Seafloor Pressure Waves Induced by Ocean Surface Wave Interactions

Doug J. Grimmett
P.F. Wang, Ph.D.
NIWC Pacific

Umesh Korde, Ph.D.
Johns Hopkins University

Michael McBeth
NIWC Atlantic

DISTRIBUTION STATEMENT A: Approved for public release.
Distribution is unlimited.

Administrative Notes:

This report was authored in September 2022 approved through the Release of Scientific and Technical Information (RSTI) process in October 2022, and formally published in the Defense Technical Information Center (DTIC) in March 2023.



NIWC Pacific
San Diego, CA 92152-5001

NIWC Pacific
San Diego, California 92152-5001

A. D. Gainer, CAPT, USN
Commanding Officer

C. A. Jackson
Executive Director (acting)

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Technical Staff Branch (Code 56406) of the Autonomous Technologies Division, Naval Information Warfare Center Pacific (NIWC Pacific), San Diego, CA. The NIWC Pacific Naval Innovative Science and Engineering (NISE) Program provided funding for this Basic Research project. Further assistance was provided by NIWC Atlantic, Johns Hopkins University, and Naval Surface Warfare Center Carderock Division.

Released by
Todd N. Miller, Division Head
Autonomous Technologies

Under authority of
Michael McMillan, Department Head
Intelligence, Surveillance, and Reconnaissance

ACKNOWLEDGMENTS

We would like to acknowledge Miguel Quintero and Mathew Green, of Naval Surface Warfare Center Carderock Division, for their contributions in supporting the planning and execution of experimental work contained in this publication.

This is a work of the United States Government and therefore is not copyrighted. This work may be copied and disseminated without restriction.

The citation of trade names and names of manufacturers is not to be construed as official government endorsement or approval of commercial products or services referenced in this report.

Editor: LMG

EXECUTIVE SUMMARY

OBJECTIVE

The Naval Information Warfare Center's Naval Innovative Science and Engineering (NISE) program has funded the project "Assessing Longuet-Higgins double frequency pressure on the shallow (<200 m) seabed as an energy source (LHiPS)," during the period 2020–2022. The present study is part of an investigation to evaluate whether the Longuet-Higgins (*LH*) predicted pressure fields could be utilized for energy generation at the seafloor. If harvestable, this energy source could provide power to underwater sensors, communications nodes and undersea vehicles, etc.

The project has been investigating the basic properties of the *LH* effect, in order to better determine its ability to produce exploitable pressure fields at the seafloor, for energy harvesting purposes. In Fiscal Year 2020, an attempt was made to measure the phenomenon off the shore of southern California. In 2021, a high fidelity Finite Analytical model was employed to study the undersea pressure generation effects of the *LH* effect. And finally, as detailed in this technical report, we present the results of an experiment conducted in 2022, in a wave tank. The objectives of the experiment were to assess the sensitivity of the *LH* pressure field production effect with non-ideal conditions, i.e., the effect of mismatched wave frequencies and oblique (rather than perfectly opposed) wave encounter angles.

METHODS

The approach taken in this technical work was to conduct acoustic measurements on the bottom of a suitable wave tank. A wave tank facility with the capability to generate directly opposing waves was a key to the experimental method. It also needed to be able to generate various regular monochromatic and irregular surfaces waves over wide frequency range. Various comparison baselines were defined and multiple runs were executed to establish performance losses as various wave parameters were varied.

CONCLUSIONS AND RECOMMENDATIONS

The experiment was successfully executed, with 68 individual test cases conducted. The *LH* theory of seafloor pressure production was successfully demonstrated in the tank experiments by observation of the surface wave field and the underwater acoustic measurements. While absolute pressure levels were not obtained during experimentations, their relative levels were sufficient to characterize the *LH* performance dependencies. Through analysis of the experimental results, the sensitivity of (*LH*) pressure production criteria was determined. As expected and demonstrated from the study, as encountering waves become increasingly mismatched in wave frequency and/or when they collide with increasingly oblique angles, the produced bottom pressure was seen to be reduced.

Future recommendations are to continue studies of energy availability (feasible locations, required oceanographic conditions, and pressure field strength). Ultimately, we also recommend to conduct in-ocean acoustic measurements to assess actual in-situ pressure levels that may be harvestable by undersea technology yet to be developed.

This page is intentionally blank.

ACRONYMS

CTBTO	Comprehensive Test Ban Treaty Organization
CUI	Controlled Unclassified Information
DF	double frequency
<i>LH</i>	Longuet-Higgins (theory, effect, pressure, interaction)
MASK	Maneuvering and Seakeeping Basin
NAVWAR	Naval Information Warfare Systems Command
NIWC Pacific	Naval Information Warfare Center Pacific
NSWC	Naval Surface Warfare Center
<i>P-M</i>	Pierson-Moskowitz sea surface spectrum

This page is intentionally blank.

CONTENTS

EXECUTIVE SUMMARY	v
ACRONYMS	vii
1. INTRODUCTION	1
1.1 OBJECTIVES	1
1.2 BACKGROUND	2
2. EXPERIMENTAL SETUP	5
2.1 WAVE TANK FACILITY	5
2.2 WAVEMAKER CAPABILITIES	6
2.3 HARDWARE SETUP	9
3. EXPERIMENTAL DATA COLLECTION	11
4. EXPERIMENTAL DATA ANALYSES	13
4.1 LONGUET-HIGGINS (<i>LH</i>) BASELINE CASES	13
4.1.1 Regular (Monochromatic) Waves	13
4.1.2 Irregular (Pierson-Moskowitz) Waves	16
4.2 FREQUENCY AND WAVE AMPLITUDE DEPENDENCIES	21
4.2.1 Regular waves as a function of wave height	21
4.2.2 Regular waves as a function of frequency	22
4.2.3 Irregular <i>P-M</i> waves as a function of frequency	24
4.3 FREQUENCY-MISMATCHED CASES	25
4.3.1 Regular waves with frequency mismatch	25
4.3.2 Irregular <i>P-M</i> waves with frequency mismatch	26
4.4 OBLIQUE ANGLE CASES	27
4.4.1 Regular waves with oblique encounter angles	27
4.4.2 Irregular <i>P-M</i> waves with oblique encounter angle	29
4.5 CASES WITH BOTH FREQUENCY-MISMATCH AND OBLIQUENESS	30
4.5.1 Regular waves with frequency-mismatch and oblique angles	30
4.5.2 Irregular <i>P-M</i> waves with frequency-mismatch and oblique angles	31
5. CONCLUSIONS AND RECOMMENDATIONS	33
REFERENCES	35

FIGURES

1. Diagram of <i>LH</i> double frequency interaction.	2
2. The NSW Carderock MASK wave tank facility.	5
3. Diagram of the NSW Carderock MASK wave tank layout.	6

4. The NSW Carderock MASK wavemaker maximum wave heights vs. wave period.....	7
5. <i>LH</i> standing waves produced by the MASK wave tank facility.....	8
6. The NSW Carderock MASK wave facility showing four example wave encounter angles.	8
7. Regular monochromatic surface wave elevation timeseries (in inches) corresponding to unidirectional and <i>LH</i> wave cases.	14
8. Bottom pressure amplitudes of regular waves.	14
9. A zoomed view of the second minute of Figure 8.	15
10. Spectra of the bottom pressure timeseries of Figure 8.	16
11. Irregular (<i>P-M</i>) surface wave elevation timeseries corresponding to unidirectional and <i>LH</i> wave cases.	17
12. Bottom pressure amplitudes of irregular waves baseline case; no wave making vs. unidirectional waves vs. <i>LH</i> waves.	19
13. Zoomed view of the second minute of Figure 12.	19
14. Comparison of bottom pressure power spectra for irregular <i>P-M</i> waves; no wave making vs. unidirectional waves vs. <i>LH</i> waves.	20
15. Comparison of bottom pressure power spectra for <i>LH</i> waves; regular (monochromatic) waves and irregular <i>P-M</i> waves.	20
16. Comparison of bottom pressure spectra for regular (matched monochromatic) <i>LH</i> waves as a function of wave amplitude.	21
17. <i>LH</i> pressure production loss as a function of wave height for regular, matched, perfectly opposed waves.	22
18. Comparison of bottom pressure spectra for regular (matched monochromatic) <i>LH</i> waves as a function of wave frequency.	23
19. Comparison of bottom pressure spectral peaks for regular (matched monochromatic) <i>LH</i> waves as a function of wave frequency.	23
20. Comparison of bottom pressure spectra for irregular (<i>P-M</i>) <i>LH</i> waves as a function of wave frequency.....	24
21. Comparison of bottom pressure spectra for regular (mismatched monochromatic) <i>LH</i> waves with various amount of frequency mismatch.	25
22. Comparison of bottom pressure spectra for regular (mismatched monochromatic) <i>LH</i> waves with various amount of frequency mismatch.	26

23. Comparison of bottom pressure spectra for irregular <i>P-M LH</i> waves with various amount of frequency mismatch.	27
24. Comparison of bottom pressure spectra for regular (matched monochromatic) <i>LH</i> waves as a function of oblique encounter angle.	28
25. <i>LH</i> pressure losses as a function of the oblique angle, for matching wave frequencies.	28
26. Comparison of bottom pressure spectra for irregular (matched <i>P-M</i>) <i>LH</i> waves as a function of oblique encounter angle.	29
27. Comparison of bottom pressure spectra for regular (mismatched monochromatic) <i>LH</i> waves as a function of oblique encounter angle.	30
28. Comparison of bottom pressure spectra for regular (mismatched monochromatic) <i>LH</i> waves as a function of oblique encounter angle.	31
29. Comparison of bottom pressure spectra for irregular (mismatched Pierson-Moskowitz) <i>LH</i> waves as a function of oblique encounter angle.	32

TABLES

1. Energy harvesting potential, with estimates of second-order pressure-related power amounts per unit area, for (1) wave amplitudes of 1.0 m, (2) wave amplitudes of 1.41 m [9].	2
2. Main wave frequencies and associated parameters used in the experimentation.	8
3. Experimental runs and associated parameters.	12

This page is intentionally blank.

1. INTRODUCTION

1.1 OBJECTIVES

In 1950, Longuet-Higgins (hereafter referred to as “*LH*”) developed a theory describing the non-linear interaction of opposing ocean surface gravity waves that produces a second-order pressure field that extends throughout the water column to the seafloor [1]. This second-order pressure field occurs at double the frequency of the two linear waves intersecting each other head-on at 180°. In contrast, normal unidirectional wave fronts (Airy waves), or multiple wave fronts that are not “oppositely interacting” will not produce the strong *LH* bottom pressure at the double frequency. Instead, they produce an underwater linear pressure at the actual wave frequency, and such pressure waves attenuate rapidly with depth. By the time they reach the seafloor, they are not detectable or are not of appreciable magnitude. However, the *LH* second-order pressure field is unattenuated in the water column, and extends to the ocean bottom, as depicted in Figure 1. With perfect *LH* conditions, the opposing waves share the same wave frequency, and when they collide with each other, a “standing wave” is generated, and the second-order pressure is generated. This pressure is unattenuated and detectable throughout the water column to the seafloor.

The basic aspects of the *LH* theory for the second-order pressure field have been validated in wave tank experimentation [2]. In the real world, its effect is commonly observed as so-called “microseism” signals [3,4] by monitoring stations worldwide like the Comprehensive Test Ban Treaty Organization (CTBTO) [5], having been produced by, and propagated from locations of *LH* wave interactions. Likewise, airborne infrasound signals can be produced by the *LH* mechanism and travel as “microbarom” pressure signals [6] to great distances through the atmosphere. A common *LH* source location has been observed in the mid-Pacific or North Atlantic [7,8]. The signals generated are very low frequency, due to interactions of prevalent long-period swells, and have typically been observed around 0.2 Hz. They may also occur in areas with sharp vertical coastlines, with opposing waves being reflected from the coast. Higher frequencies may also be possible, produced by shorter period waves. The phenomenon is depicted in Figure 1, and described in more detail in the next section.

Most existing wave energy harvesting approaches focus on energy produced by waves at or near the water surface. The present study is part of an investigation [9] to evaluate whether the *LH* pressure field could be utilized for energy generation at the seafloor. If harvestable, this energy source could provide electrical power to underwater sensors, communications nodes and undersea vehicles, etc. Preliminary calculations for energy extraction with reasonable efficiencies predict potential power output of several Watts per meter squared (W/m^2), as a function of wave period and amplitude as shown in Table 1 [9]. This energy could potentially be harvested via piezoelectric, elastomer, or other technology installed on the seafloor. The estimated potential energy density is significantly larger than other existing in-situ seafloor energy sources. As an example, estimates indicate that *LH* energy may be more than two orders of magnitude larger as that obtainable by current Microbial Fuel Cell (MFC) technologies, which are estimated to produce only $\sim 0.01 \text{ W/m}^2$ [10] at seafloor with suitable characteristics.

This report details the results of experimentation conducted in a wave tank, with a focus on getting a better understanding the sensitivity of *LH* energy production to non-ideal conditions. In addition to validation of the basic pressure production mechanism, we study the impact of mismatching wave frequencies, oblique rather than perfectly opposing interaction, and differences between random waves (sea surface spectrum) and regular monochromatic waves.

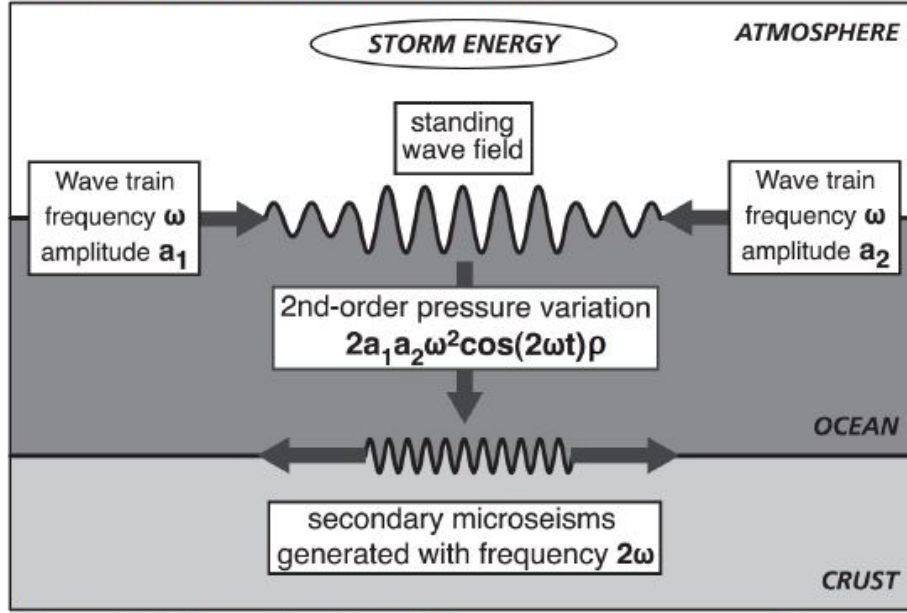


Figure 1. Diagram of *LH* double frequency interaction.

Table 1. Energy harvesting potential, with estimates of second-order pressure-related power amounts per unit area, for (1) wave amplitudes of 1.0 m, (2) wave amplitudes of 1.41 m [9].

Wave Period (s)	Angular Frequency ω (rad/sec)	P (W/m ²) (1)	P (W/m ²) (2)
5.0	1.257	1.781	7.12
8.0	0.785	1.040	4.16
10.5	0.598	140.9	563.54

1.2 BACKGROUND

Regular ocean surface waves propagating unidirectionally, without *LH* interactions, produce underwater pressure corresponding to the fluctuating wave amplitudes above/below the mean surface elevation. However, the underwater pressure of these so-called “Airy Waves” [11] attenuate significantly with depth according to:

$$p_{airy} = \rho g a_1 \cdot \frac{\cosh k(z+d)}{\cosh kd} \sin(\omega t), \quad (1)$$

where $k = 2\pi/\lambda$ (the wavenumber, where λ is the wavelength), d is the water depth, z is the measurement point from mean surface elevation (negative values underwater), and $\omega = 2\pi f$ (the

wave frequency). ρ is the water density, g is gravity, and a_1 is the wave amplitude. For deep water ($d \gg \lambda/2$) the formula simplifies to a decaying exponential as:

$$p_{airy} = \rho g a_1 \cdot e^{kz} \sin(\omega t) \quad (2)$$

With such attenuation, the amount of exploitable energy for harvesting at the seafloor is deemed to be insufficient. In contrast, the *LH* theory predicts a larger unattenuated pressure at the seafloor due to nonlinear effects, when sets of ocean waves interact appropriately.

LH theory predicts the amplitude of a resulting sub-surface second-order pressure field throughout the water column as [1]:

$$p_{LH} = 2\rho a_1 a_2 \omega^2 \cos(2\omega t), \quad (3)$$

where a_1 and a_2 are the wave amplitudes of perfectly directionally-opposed wave fields. The pressure amplitude increases with the product of wave amplitudes and the square of the wave frequency, although lower wave frequencies typically produce larger amplitudes, because of the larger wave heights characteristic of ocean swell produced from distant storm systems. Note that the equation indicates the second-order, non-linear pressure exhibits doubling of the incident waves' frequencies (the 2ω term).

Previous work on this concept has been focused on theoretical development [9], an in-ocean measurement campaign attempting to detect the *LH* effect from reflections from steep coastal cliffs off of southern California [12], an estimation of energy harvesting potential at various sites worldwide [13], and a high-fidelity Finite Analytical modeling study, focusing on the effect of wave frequency mismatch [14].

The *LH* occurrence conditions, their predictability, their energy production capacity, and reliability of this potential power source need to be better understood and evaluated. In particular, *LH* theory does not adequately describe the feasibility or sensitivity of the pressure generation mechanism for:

1. Mismatched wave frequencies for interacting ocean wave fronts
2. Obliquely interacting waves, with indirect, non-180° opposing wavefronts
3. Ocean conditions with 2-d wave surface spectra presenting wave energy over multiple (or a range of) frequencies and azimuths, i.e., combinations of 1 and 2 above

This report describes the results of wave tank experimentation done to validate the *LH* phenomenon and to better understand and estimate its energy harvesting potential. We focus on the effects of all the above conditions. The optimum case of directly opposing monochromatic waves (in a wave channel using reflected waves) was conducted by Longuet-Higgins at the time of the original theoretical development [2]. Here, we attempt to measure pressure signals in more complicated (non-ideal) scenarios, and to our knowledge, this is the first time such wave tank experimentation has been attempted.

The nonlinear wave theory dictates generation of steady state second-order waves with the sum and difference of the frequencies for two linear waves propagating into each other. When these two wave frequencies are identical (zero mismatch), the *LH* effects exist in the form of the analytical equation previously given in (3). When the mismatch of the two linear (monochromatic) wave frequencies increases, the second-order pressure field is still produced, but *LH* double frequency effects are expected to deviate or be reduced from the theoretical prediction of the *LH* equation. The effect of the mismatch of frequencies on the *LH* pressure is investigated in this experiment. A theoretical generalization for spectral wave descriptions has also been given by *LH* [1], which our model can be used to verify. The effect of realistic sea-surface wave spectra (irregular, non-

monochromatic), like the Pierson-Moskowitz spectra (hereafter referred to by “*P-M*”) [15], is also investigated.

The effects of obliquely colliding waves were also tested. We hypothesize a reduction in pressure from the optimum case, according to a modified version of equation 1, as derived in [13] based on the *LH* theory.

The experiment shows the behavior of the *LH* effect in a wave tank, and presents the results of mismatched wave frequencies compared to a baseline case meeting the precise *LH* pressure production criteria. Section 2 describes the experimental set up, including the wave tank facility, its capabilities, and the experimental hardware/apparatus and operations. Section 3 details the measurements collected during the experiment. Section 4 describes the processing and analyses of the measurements collected: the baseline *LH* cases, frequency mismatched cases, oblique encounter angle cases, and cases which combine frequency mismatch and obliqueness. For all these, there are results for both monochromatic regular waves and irregular waves with a *P-M* sea surface spectrum. Section 5 provides conclusions and recommendations.

2. EXPERIMENTAL SETUP

2.1 WAVE TANK FACILITY

In order to satisfy the objectives of the experiment, we required a wave tank facility that could support:

- 1) Regular (monochromatic) and irregular (random) wave generation, and
- 2) Wave fronts colliding against each other from opposite and oblique angles (opposing wavefronts from 90-180° of the incident wavefronts)

A survey of operating wave tank facilities was made. Only a few possessed the capability needed for this experimentation. The Naval Surface Warfare Center (NSWC), Carderock Division operates the Maneuvering and Seakeeping Basin (MASK) facility [16], which is a very large rectangular wave basin that was able to support these experimental requirements. The wave tank is shown in Figure 2. It has an overall length of 110 m, width of 73 m, and depth of 6.1 m. A diagram of the tank in plan-view is shown in Figure 3. A total of 216 individual wavemaker paddles contiguously line the north and west sides of the basin. These independent wavemakers may be programmed so that, working together, they can produce a wide variety of sea conditions in the basin, including the complex wave interactions of interest to our study. The large rectangular size of the basin, with wavemakers along orthogonal axes, allow for the generation of opposing waves. The south and east sides of the basin are lined with sloped beaches to minimize wave reflections back into the basin. An overwater bridge spans the basin, and was rotated to a suitable position to facilitate the execution of the experiment.

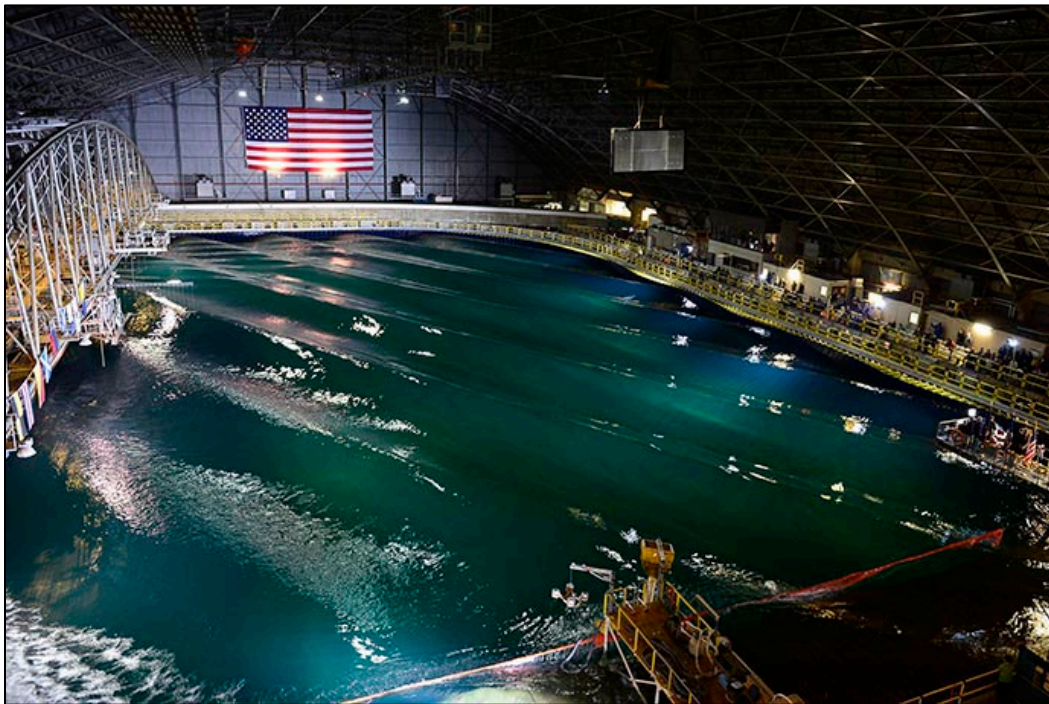


Figure 2. The NSWC Carderock MASK wave tank facility.

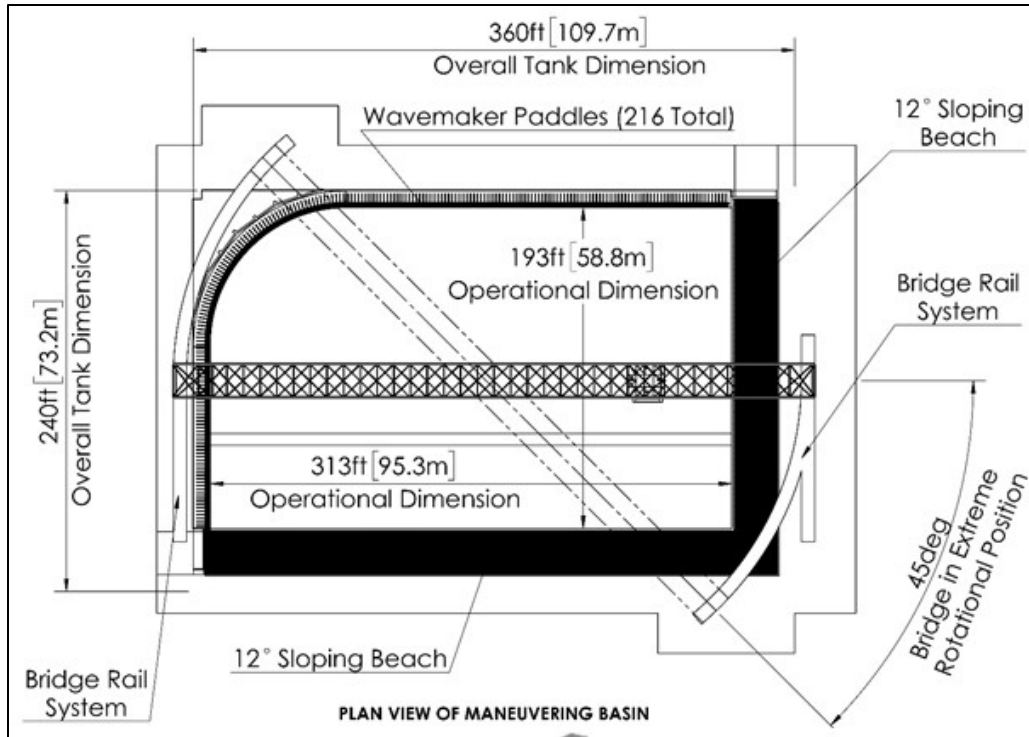


Figure 3. Diagram of the NSW Carderock MASK wave tank layout.

2.2 WAVEMAKER CAPABILITIES

The MASK facility's wave making capabilities are shown in Figure 4. Wave height generation as a function of wave period is shown. The wavemaker can produce waves with modal periods over a range of 0.5 to 5 seconds, which correspond to wave frequencies over the range of 0.2 to 2 Hz (the reciprocal of the modal period). The MASK maximum regular wave heights are shown in the figure, as well those that can be obtained for the peak of a Pierson-Moskowitz (*P-M*) sea surface spectrum [15]. The four main wave frequencies were selected for the experimentation, with their operating points as indicated. The frequencies are also listed in Table 2, which shows their corresponding wavelengths, wave speeds, and maximum wave heights. The underwater acoustic frequencies are expected to be twice the interacting wave frequencies, in accordance with *LH* theory.

For our experimentation, we required to generate opposing and obliquely opposing wave directions to study their subsequent *LH* interactions. When such waves collide, a "standing wave" is generated, and these resulting waves can be much larger in amplitude than their constituent interacting waves. Such conditions have rarely, if ever, been tested in the MASK facility. In order to ascertain if the MASK tank could effectively generate such waves, and, to determine what the safe limits for generated wave amplitudes would be, a preliminary test was conducted by the MASK facility.

After doing the test, it was decided to reduce the amplitudes of some of the regular waves. The large amplitudes of the resulting standing waves striking the wave gauges negatively impacted their ability to record quality ground-truth data. For wave frequencies of 0.40 and 0.46 Hz, the wave heights for some runs were changed from 19.7" and 15.4", respectively, to 13.4" as indicated in the figure and table. Later during the testing, we removed the wavegauges so that we could also make a few runs with regular waves of height 19.7".

Figure 5 shows a photograph of an example *LH* standing wave produced in the MASK tank, with the water surface captured at the precise moment of the wave maxima/minima. Overlaid onto the photograph is the approximate location of the standing wave nodes, indicated by the dotted white lines. At those locations, the surface water level is not undulating vertically over time. In between these nodal points, and at the precise time of the photo, the peaks (yellow arrows) and troughs (cyan arrows) of the standing wave are indicated, which then undulate vertically (trough-to-peak and peak-to-trough) over time. Although wave fronts are propagating directly toward each other, they are not discernable; instead the standing wave effect predominates.

The test was successful in generating the characteristic standing waves of *LH* theory, as shown. To achieve this, one set of wavefronts was generated by the wavemakers on the basin's north boundary from an angle of -55° . The other set of wavefronts was generated by the western wavemakers from an angle of $+125^\circ$, such that they would approach each other at 180° (i.e., "head-on"). The coordinate system is shown in Figure 6, which is a Cartesian coordinate system with +x-direction pointing north. Both sets of wavemakers simultaneously produced waves at 0.40 Hz. This configuration serves as a "BASELINE" case. It is a baseline because it has the most ideal conditions (matched frequency, perfectly opposing, waves) to measure the acoustic pressure of the *LH* phenomenon. Such a case can be used as a comparison baseline when less ideal *LH* conditions are present.

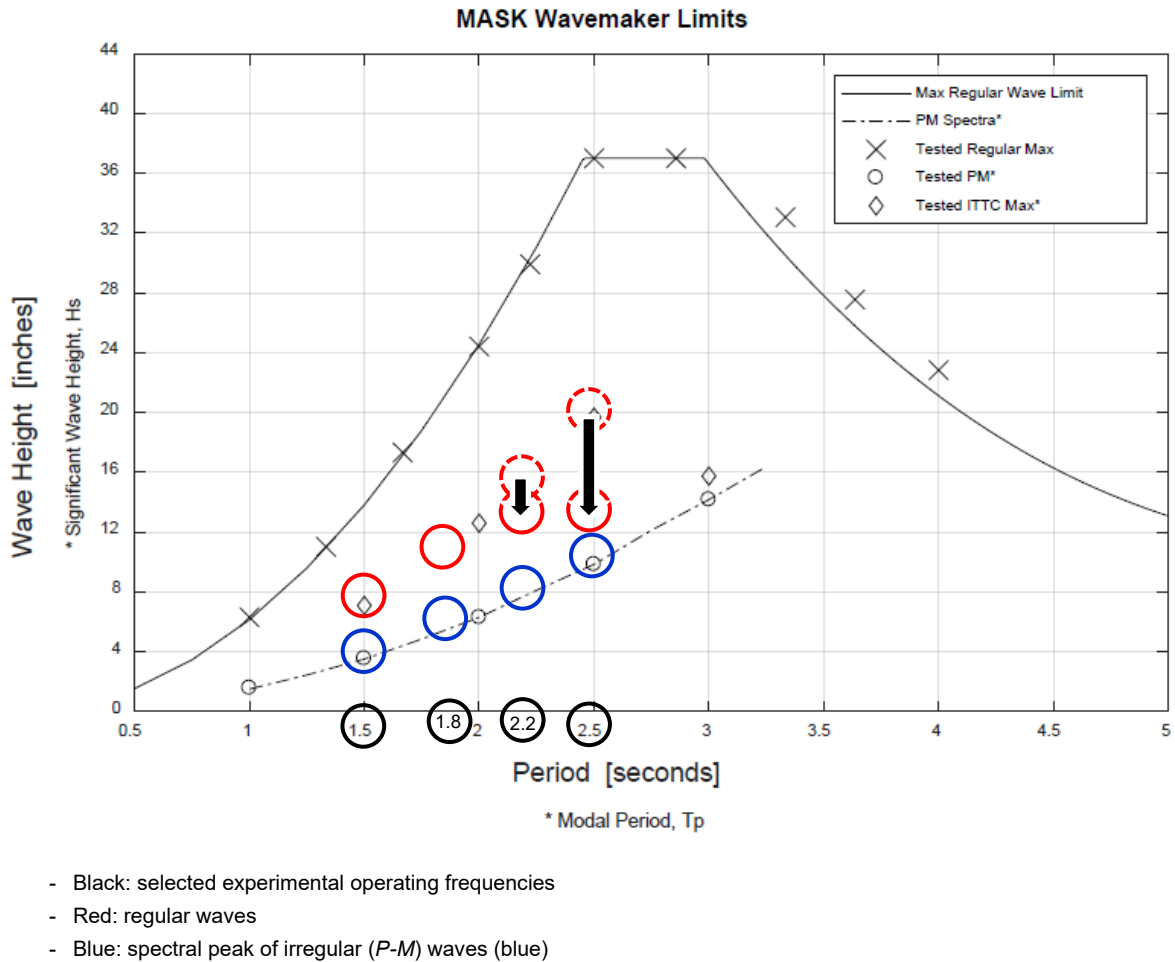
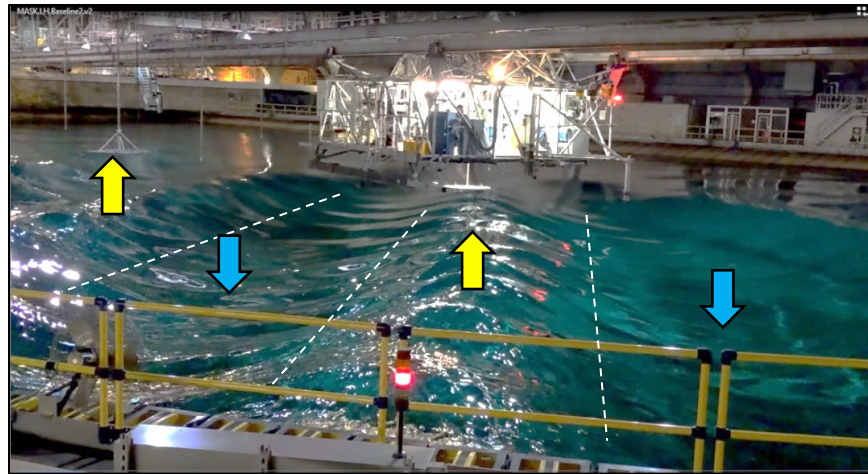


Figure 4. The NSWC Carderock MASK wavemaker maximum wave heights vs. wave period.

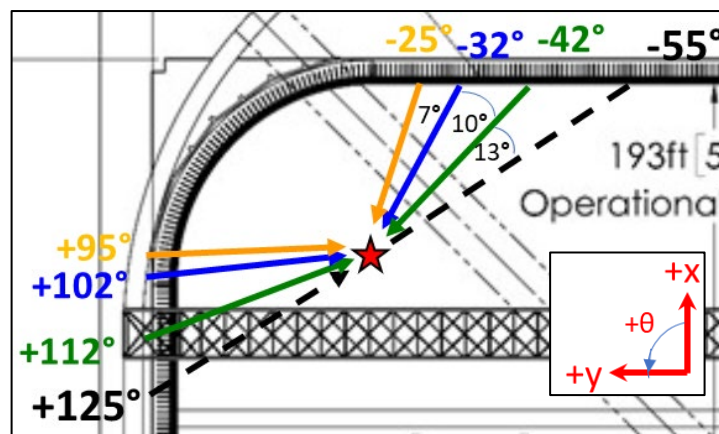
Table 2. Main wave frequencies and associated parameters used in the experimentation.

Wave Period (sec)	Wave Frequency (Hz)	λ (m)	Wave Speed (m/s)	Regular Wave Height (inches)	Irregular Wave Height (inches)	Acoustic Frequency (Hz)
2.50	0.40	9.75	3.9	19.7→13.4	10.0	0.80
2.17	0.46	7.37	3.4	15.4→13.4	7.9	0.92
1.82	0.55	5.16	2.8	10.9	5.6	1.10
1.49	0.67	3.47	2.3	7.0	3.5	1.34



- White lines: wave nodal points
- Yellow: peaks
- Blue: troughs

Figure 5. *LH* standing waves produced by the MASK wave tank facility.



- Black line: directly opposing baseline case
- Green, blue, yellow lines: increasingly oblique cases
- Red star: approximate location of the hydrophone in the MASK facility

Figure 6. The NSW Carderock MASK wave facility showing four example wave encounter angles.

2.3 HARDWARE SETUP

In order to measure pressure signals at the bottom of the MASK basin (6.1 m depth), a hydrophone was required. Because the pressure signals of interest are expected at twice the wave frequencies, they will be very low frequency. Generated wave frequencies in MASK can be between 0.2–2.0 Hz, with the *LH* double frequencies apparent at 0.4–4.0 Hz. Typically, hydrophones are not designed to capture such low-frequency signals very well; they are usually filtered out prior to digitization to remove the high levels of interfering low-frequency noise. This experiment utilized the OceanSonics icListen LF2549 hydrophone [17], which is specifically designed for such low-frequency data collections. Although the icListen hydrophone is low frequency, its sensitivity is not flat below about 10 Hz; i.e., there is a drop off in sensitivity at low frequency, and the hydrophone is not properly calibrated for those low frequencies.

However, we were able to compensate for this by equalizing the hydrophone's frequency response. These corrections are believed to be valid for spectral analyses, but not for timeseries analysis (i.e., time-domain timeseries will not provide correct calibrated pressure levels). Even then, it was found that our theoretically expected spectral levels were not well matched by the spectral measurements made in our experimentation. This issue is still to be understood and resolved, however, our subsequent analyses are based on comparative, relative acoustics levels, which are valid and do not require absolute calibration.

The hydrophone was placed in the tank's northwest quadrant, nearest to the curved wavemaker portion (Figure 6). Observation of the standing wave pattern obtained in preliminary testing was used to determine this installation location. This location was deemed to be best positioned to measure the *LH* "standing wave" effect under test. There may still be some dependence of the results to the choice of this operating position. The wave tank's carriage is also seen in the photo at the approximate location above where the hydrophone was positioned on the tank bottom at depth of 6.1 m. The hydrophone was mounted with vibration-isolating foam to a metal plate, and was weighted sufficiently to prevent movement/drift during our experimentation. A power and data cable were connected to an analysis computer on the bridge, where real-time data acquisition, processing and data display was provided. This real-time data analysis enabled quick decisions for the next best measurements to be made.

Two CR-1 hydrophones were also deployed, to provide additional pressure measurements. They were suspended in the water column at a depth of 4.5 m, and were separated horizontally north and south of the icListen position by about 4.3 m each. The sensors were cabled to a computer for digitization and real-time analysis. These hydrophones were placed to assess consistency of measurements and to better understand any underwater spatial variability in the produced *LH* pressure field.

In addition to the acoustic data collected by the hydrophones, wave surface elevation was also measured using MASK wavegauge sensors. Of the 22 wavegauge sensors that collected data, 4 were positioned directly above the operating point (above the icListen hydrophone position). The data collected by these sensors provided ground-truth of what the actual wave heights were during the executions of our runs.

Each experimental run in the wave tank was designed to be five minutes in duration, with the wavemakers operating. The first 30–60 seconds of each run allow the time required for the waves to propagate from the wavemakers at the basin edges toward each other and to establish a steady-state *LH* standing wave condition. The remaining 4 minutes of each run contained the data used in our analysis. In order to produce resolution in the pressure power spectra at the very low frequencies

expected, long durations were required. After each 5-minute data collection, we allowed 5 minutes for the waves in the tank to settle before launching another run.

3. EXPERIMENTAL DATA COLLECTION

For each individual run, the following control/input parameters had to be supplied for the operation:

- For opposing regular waves in two directions:
 - wave heights
 - wave monochromatic frequency
 - wave direction
- For opposing irregular waves in two directions:
 - wave heights
 - wave direction
 - frequency of peak of the P - M sea surface spectrum
 - wave azimuthal spreading (yes or no, with associated parameters)

We exclusively used Pierson-Moskowitz (P - M) sea surface spectrum for the experimentation when irregular waves were needed. For these, we executed them both with and without the azimuthal spreading, for comparisons.

Measurement runs were made over two days, with 68 total runs having been executed. The run types, along with their respective parameters, are listed in Table 3. The runs are grouped by types:

- Regular monochromatic wave BASELINES (no frequency mismatch, no obliqueness)
- Regular monochromatic waves with frequency-mismatch (no obliqueness)
- Regular monochromatic waves with obliqueness (no frequency mismatch)
- Regular monochromatic waves with both frequency-mismatch and oblique angles
- Irregular P - M wave (no frequency mismatch, no obliqueness)
- Irregular P - M waves with frequency-mismatch (no obliqueness)
- Irregular P - M waves with obliqueness (no frequency mismatch)
- Irregular P - M waves with both frequency-mismatch and oblique angles

Each run has a run ID# and details the day and time it was collected. In addition, the wavemaker control parameters and other properties are listed for the southwest and northeast waves. From this rich data set we could select certain runs to compare, usually against a baseline case, and with only one (or a few) other parameter variations. Doing this allows for us to analyze and evaluate the sensitivity of LH pressure production as a function of those parameters.

Table 3. Experimental runs and associated parameters.

													SouthWest WaveMakers						NorthEast WaveMakers									
													Freq (Hz)	Period (sec)	Speed (m/s)	Wavelength (m)	Angle (deg)	Height (in)	Freq (Hz)	Period (sec)	Speed (m/s)	Wavelength (m)	Angle (deg)	Height (in)	Expected Peak Pressure (α*Pa)	and in dB re 1μPa		
TEST TYPE	ID#	Day	UTC Time	index	Freq Matched	Freq Mismatched	Regular Waves	PM Uni-directional	PM Azi-Spread	Opposed	Oblique	Oblique Angle θ (deg)																
Non-LH // No Wavemakers	0A	13			N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A				
Non-LH // Single Wavefront	0B	13	11:10	1,3,5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.40	2.50	3.90	9.75	-55°	13.4"			
PM	0C	13	18:00	35	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.40	2.50	3.90	9.75	-55°	10.0"				
PM	0D	13	18:10	36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.46	2.17	3.39	7.37	-55°	7.9"				
PM	0E	14	14:15	55	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.40	2.50	3.90	9.75	-55°	10.0"				
PM	0F	14	14:25	56	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.46	2.17	3.39	7.37	-55°	7.9"				
Non-LH // Single Wavefront	10B	14	16:55	57	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.40	2.50	3.90	9.75	-55°	19.7"				
BASELINE Matched/Regular/Opposed	1A	13	11:20	2,4								0°	0.40	2.50	3.90	9.75	125°	13.4"	0.40	2.50	3.90	9.75	-55°	13.4"	373	171		
	1B	13	12:00	6								0°	0.46	2.17	3.39	7.37		13.4"	0.46	2.17	3.39	7.37		13.4"	493	174		
	1C	13	12:10	7								0°	0.55	1.82	2.84	5.16		10.9"	0.55	1.82	2.84	5.16		10.9"	466	173		
	1D	13	12:20	8								0°	0.67	1.49	2.33	3.47		7.0"	0.67	1.49	2.33	3.47		7.0"	285	169		
	11A	14	17:05	58								0°	0.40	2.50	3.90	9.75		19.7"	0.40	2.50	3.90	9.75		19.7"	805	178		
	11B	14	17:15	59								0°	0.46	2.50	3.90	9.75		15.4"	0.46	2.50	3.90	9.75		15.4"	651	176		
	9A	14	11:15	37								0°	0.40	2.50	3.90	9.75			0.40	2.50	3.90	9.75			75	157		
	9B	14	11:25	38								0°	0.46	2.17	3.39	7.37			0.46	2.17	3.39	7.37			99	160		
	9C	14	11:35	39								0°	0.55	1.82	2.84	5.16			0.55	1.82	2.84	5.16			141	163		
	9D	14	11:45	40								0°	0.67	1.49	2.33	3.47			0.67	1.49	2.33	3.47			210	166		
	9E	14	11:55	41								0°	0.33	3.03	4.72	14.3			0.33	3.03	4.72	14.3			51	154		
	9F	14	12:05	42								0°	0.50	2.00	3.12	6.24			0.50	2.00	3.12	6.24			117	161		
Mismatched/Regular/Opposed	2A	13	12:30	9								0°	0.46	2.17	3.39	7.37	125°	13.4"						429	173			
	2B	13	12:40	10								0°	0.55	1.82	2.84	5.16		10.9"						13.4"	417	172		
	2C	13	12:50	11								0°	0.67	1.49	2.33	3.47		7.0"	0.40	2.50	3.90	9.75	-55°		326	170		
	12A	14	17:25	60								0°	0.46	2.17	3.39	7.37		15.4"						724	177			
	12B	14	17:35	61								0°	0.55	1.82	2.84	5.16		10.9"						613	176			
	12C	14	17:55	62								0°	0.67	1.49	2.33	3.47		7.0"						19.7"	479	174		
Matched/Regular/Oblique	3A	13	14:30	21								26°	0.46	2.17	3.39	7.37	112°	13.4"	0.46	2.17	3.39	7.37	-42°	13.4"	443	173		
	3B	13	14:40	22								46°													102°	-32°	342	171
	3C	13	14:50	23								60°													95°	-25°	246	168
	3D	14	12:45	46								12.5°													119°	-48.5°	481	174
	3E	14	12:55	47								36°													107°	-37°	399	172
	3F	14	13:05	48								53°													98.5°	-28.5°	297	169
	3G	14	13:15	49								90°													80°	-10°	0	-150
	13A	14	18:05	63								26°													112°	-42°	585	175
	13B	14	18:15	64								46°													102°	-32°	452	173
	13C	14	18:25	65								60°													95°	-25°	325	170
Mismatched/Regular/Oblique	4A	13	16:10	24								26°	0.46	2.17	3.39	7.37	112°	13.4"	0.40	2.50	3.90	9.75	-42°	13.4"	385	172		
	4B	13	16:20	25								46°													102°	-32°	298	169
	4C	13	16:30	26								60°													95°	-25°	214	167
	4D	14	13:25	50								12.5°													119°	-48.5°	418	172
	4E	14	13:35	51								36°													107°	-37°	347	171
	4F	14	13:45	52								53°													98.5°	-28.5°	258	168
	4G	14	13:55	53								90°													80°	-10°	0	-152
	14A	14	18:35	66								26°													112°	-42°	651	176
	14B	14	18:45	67								46°													102°	-32°	503	174
	14C	14	18:55	68								60°													95°	-25°	362	171
Matched/PM/Opposed	5A	13	13:00	12								0°	0.40	2.50	3.90	9.75	125°	10"	0.40	2.50	3.90	9.75	-55°	10"	208	166		
	5B	13	13:10	13								0°	0.46	2.17	3.39	7.37		7.9"	0.46	2.17	3.39	7.37		7.9"	171	165		
	5C	13	13:20	14								0°	0.55	1.82	2.84	5.16		5.6"	0.55	1.82	2.84	5.16		5.6"	123	162		
	5D	13	13:30	15								0°	0.67	1.49	2.33	3.47		3.5"	0.67	1.49	2.33	3.47		3.5"	71	157		
	5E	13	13:40	16								0°	0.46	2.17	3.39	7.37		7.9"	0.46	2.17	3.39	7.37		7.9"	171	165		
	5F	14	14:05	54								0°	1.00	1.00	1.56	1.56		1.5"	1.00	1.00				1.5"	29	149		
Mismatched/PM/Opposed	6A	13	13:50	17								0°	0.46	2.17	3.39	7.37	125°	7.9"							189	166		
	6B	13	14:00	18								0°	0.55	1.82	2.84	5.16		5.6"	0.40	2.50	3.90	9.75	-55°	10"	160	164		
	6C	13	14:10	19								0°	0.67	1.49	2.33	3.47		3.5"						121	162			
	6D	13	14:20	20								0°	0.46	2.17	3.39	7.37		7.9"						189	166			
Matched/PM/Oblique	7A	13	16:40	27								26°	0.40	2.50	3.90	9.75	112°	10"	0.40	2.50	3.90	9.75	-42°	10"	187	165		
	7B	13	16:50	28								46°													102°	-32°	144	163
	7C	13	17:00	29								60°													95°	-25°	104	160
	7D	13	17:10	30								46°													102°	-32°	144	163
Mismatched/PM/Oblique	8A	13	17:20	31								26°	0.46	2.17	3.39	7.37	112°	7.9"	0.40	2.50	3.90	9.75	-42°	10"	169	165		
	8B	13	17:30	32								46°													102°	-32°	131	162
	8C	13	17:40	33								60°													95°	-25°	94	159
	8D	13	17:50	34								46°													102°	-25°	131	162

4. EXPERIMENTAL DATA ANALYSES

4.1 LONGUET-HIGGINS (*LH*) BASELINE CASES

4.1.1 Regular (Monochromatic) Waves

Initial measurements focused on understanding the underwater ambient background noise of the tank facility. This was important to know, so that we could determine if there would be any impact on the acoustic measurements when generating waves. The measurements were taken over about a 12-hour period prior to operating the wavemakers. The tank was quiet, and showed relative ambient noise levels during the day and even quieter conditions during the nighttime.

We chose as our regular *LH* wave baseline, Case 1A, with frequency-matched waves at 0.40 Hz, directly opposing (oblique angle of 0°) and with wave heights of 13.4" (corresponding to a wave amplitude of 6.7").

The first set of wavemaker runs were unidirectional "Airy" waves; i.e., non-*LH*, and propagating in only one direction. These runs provided a good baseline to measure and understand the underwater pressure due to the Airy waves only, without yet introducing any *LH* effects. Later when *LH* runs were executed, we could differentiate the respective contributions of the Airy waves and the *LH* interactions that contribute to the composite results. In agreement with theory, the Airy wave pressure fluctuation is seen precisely at the wave frequency, whereas the *LH* pressure effect is seen at double the waves' frequency.

Figure 7 shows the wave height timeseries at the surface above the hydrophone taken from one of the wavegauge sensors, for the unidirectional case (Run 0B, in red). Also shown is another run's results, overlaid, for the opposing baseline *LH* wave case (Run 1A, in blue) at the same wave frequency. There is a slight time offset between the two runs before steady-state is reached. We observe that the Airy wave height is very close to the 13.4" expected, and very regular with the correct frequency of 0.4 Hz. The surface wave height for the opposing *LH* waves case is seen to be similar, with same frequency, 0.4 Hz. From the wave height timeseries, there would be no apparent way to discern a *LH* effect is occurring. A doubling of the wave surface frequency is not observed (or expected) in the surface waves. The *LH* case exhibits slightly, but not significantly larger amplitude and is a bit more irregular than the unidirectional case.

Figure 8 shows the resulting pressure timeseries for these two runs, as measured by the underwater icListen hydrophone at the bottom of the basin. Their data are overlaid for their respective 5-minute run periods. At time zero, the wavemakers begin to generate waves, which then propagate toward the interaction point near the hydrophone's position. Run 1A (shown in blue) is the *LH* result, which is seen to have considerably more pressure amplitude than Run 0B (shown in red), which is due only to unidirectional (Airy) wave pressure. Also, another run of the ambient noise without the wavemaker operating at all, is shown to have negligible amplitude (shown in yellow) compared to those that do (Airy or *LH*).

Figure 9 zooms in on the second minute of the runs, and the *LH* pressure signal is clearly seen to be double the frequency of the Airy wave pressure signal. Note that the Airy wave pressure will attenuate exponentially with depth, as in equation (2). In this case, with the depth of the tank being only 6.1 m (equivalent to 0.62 wavelengths), it is still observable. However, in most real, deep ocean environments, the Airy wave pressure at the bottom will become small enough as to be unobservable above the local acoustic background noise, and not exploitable for energy harvesting purposes. As has been discussed previously, the absolute levels (in uPa) currently shown are not believed to be

accurate, however, their relative amplitude difference is nevertheless meaningful. Therefore, our subsequent analyses will exclusively use relative amplitude differences.

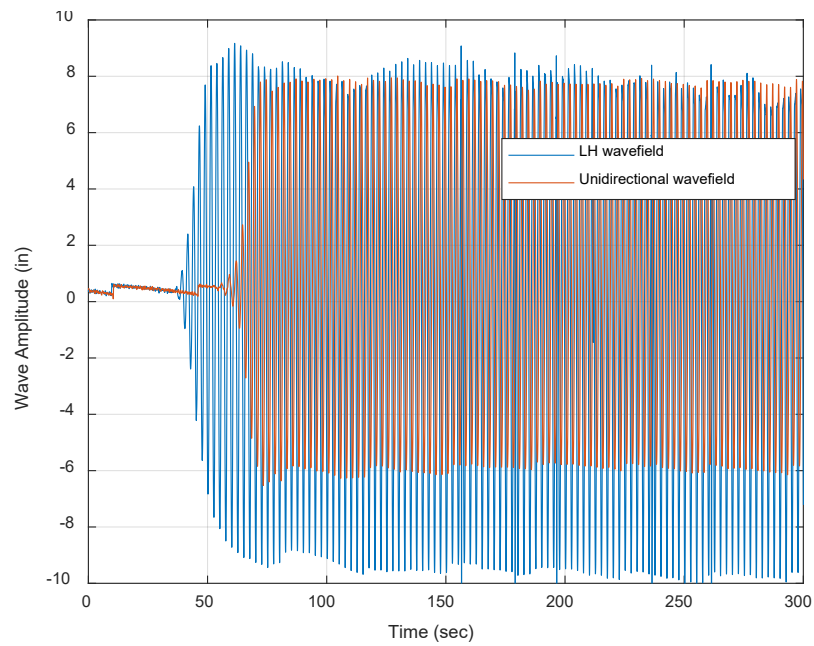
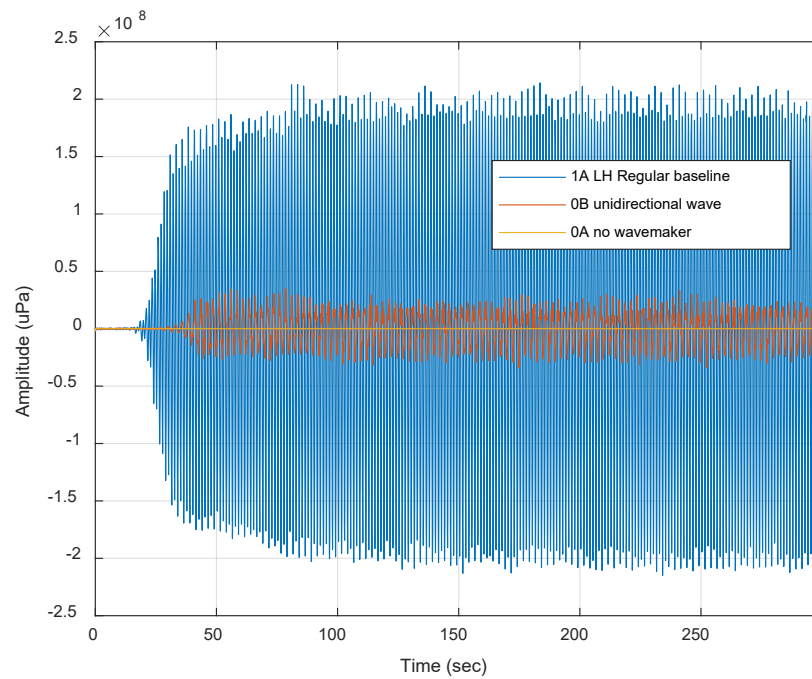


Figure 7. Regular monochromatic surface wave elevation timeseries (in inches) corresponding to unidirectional and *LH* wave cases.



- Yellow: no wave making
- Red: unidirectional waves
- Blue: *LH* waves

Figure 8. Bottom pressure amplitudes of regular waves.

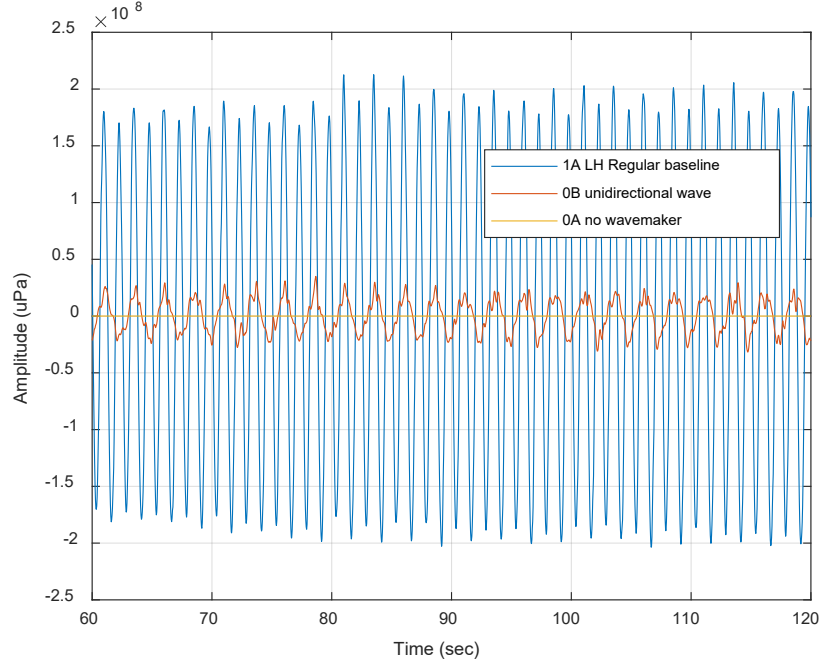


Figure 9. A zoomed view of the second minute of Figure 8.

Spectral processing for these runs was done to better observe the effects in the frequency domain. Figure 10 shows the equalized power spectrum for the same data (runs) shown previously in Figure 8. The equalization compensates for the reduced sensitivity at low frequency and makes the hydrophone response flat. We first observe that the pressure power spectrum for the ambient noise case is significantly lower than whenever any wavemakers are operating. This is a good result that confirms that the ambient acoustic self-noise of the wave tank does not have any negative impact on the experiment.

When we compare the *LH* and unidirectional (Airy) wave cases, we see that their spectra are similar around the fundamental wave frequency. They both observe the Airy wave pressure at the wave frequency of 0.40 Hz at the same pressure level as is expected. At higher frequency the curves diverge from one another, with the *LH* case showing a much larger spectral peak at double the wave frequency (0.80 Hz), whereas the Airy wave case shows a lower peak, which is a first harmonic of the Airy wave manifesting at the *LH* double frequency. It is not discernable in the *LH* case because the *LH* peak is so much stronger than this Airy wave harmonic. Here, the *LH* double frequency peak (at 0.80 Hz) is about 13 dB higher than the Airy wave fundamental. As stated previously, the Airy wave pressure (and its harmonics) in a real ocean environment will be more heavily attenuated, likely unobservable, and therefore not a significant contribution to energy harvesting at the seafloor.

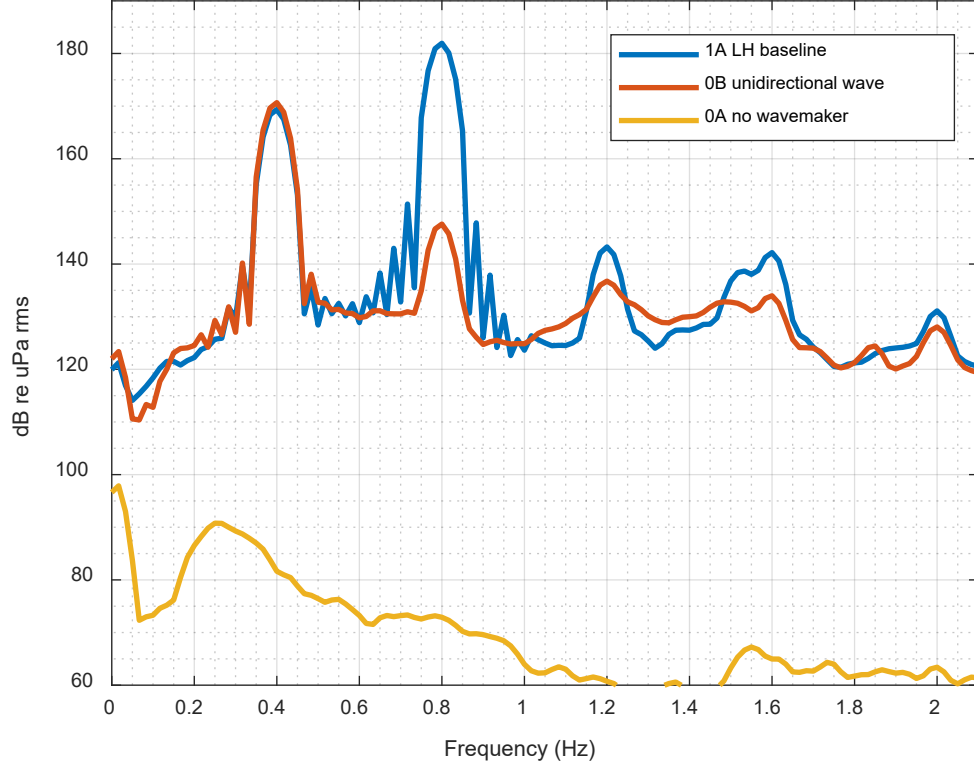


Figure 10. Spectra of the bottom pressure timeseries of Figure 8.

4.1.2 Irregular (Pierson-Moskowitz) Waves

In the previous results for regular (monochromatic) waves the *LH* effect is clearly identifiable and quantifiable. Now we consider non-chromatic, irregular waves. In the MASK facility, we chose to make waves that follow a Pierson-Moskowitz (*P-M*) sea surface spectrum.

Sea surface roughness can be characterized as a superposition of many waves with different periods (frequencies), heights, and directions. There may be more than a single source contributing to the generation of waves at any given location. Oceanographers typically use sea surface spectra to characterize the wave energy in the ocean as a function of frequency (and sometimes direction). The frequencies of the sea surface roughness (waves) are inversely related to the period of the swell. “Seas” often refer to localized, chaotic waves with many periods (broad frequency spectra), and can be distinguished from “swell,” which is a well-behaved undulation (narrow spectral peak) that has propagated from longer distances. Oceanographic wave buoy instruments are commercially available which produce sea surface spectra by direct measurement of ocean heave. Predictions of sea surface spectra can be made using models, for assumed (sustained) wind speeds. The *P-M* model is a simple, effective model that provides insight into the effects of sea surface roughness as a function of wind speed [15]. *P-M* models a fully developed sea with a sea surface spectrum of the form:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\beta(\omega_0/\omega)^4}, \quad (4)$$

where α and β are dimensionless constants given by 7.79×10^{-3} and 0.74, respectively, and g is gravitational acceleration. The reference frequency is given by $\omega_0 = g/U$, where U is the wind speed at a reference height of 19.5 meters (often a reference of 10 meters is also used). The peaks of the P - M spectrum in the MASK tank were selected to be at the same set of frequencies as used for the regular waves: 0.40, 0.46, 0.55, and 0.67 Hz. The corresponding wave heights and windspeeds for the P - M spectrum were 10.0", 7.9", 5.6", and 3.5", and windspeeds of 3.5, 3.1, 2.6, and 2.0 m/s, respectively. Note that the peak of the irregular wave heights is significantly lower than what is possible for monochromatic waves in the MASK facility.

Using a random seed, the wavemaker generates a specific realization of wave height vs. time that is consistent with the desired P - M sea surface spectrum. When running P - M waves in opposite directions toward each other, different random seeds are chosen for each of the opposing wave trains. If the experiment needs to be repeated, the same selected random seeds can be reused. In addition, MASK provides an option to spread the generated random waves across an azimuthal sector, to further increase the realism that may be encountered in the real ocean environment. Cases both with and without this azimuthally spreading were conducted in our experimentation.

Figure 11 shows the irregular P - M wave amplitude timeseries at the surface above the hydrophone position for the unidirectional wavefield (Run 0C) and the baseline irregular LH wavefield (Run 5A). There is no frequency mismatching or obliqueness introduced yet. We observe that the Airy wave height is close to the 10" (+/- 5") wave heights expected, but with more random variations than the regular wave baseline case. The surface wave height for the opposing LH case is observed to be only slightly higher than the unidirectional case, and it shares a similar randomness.

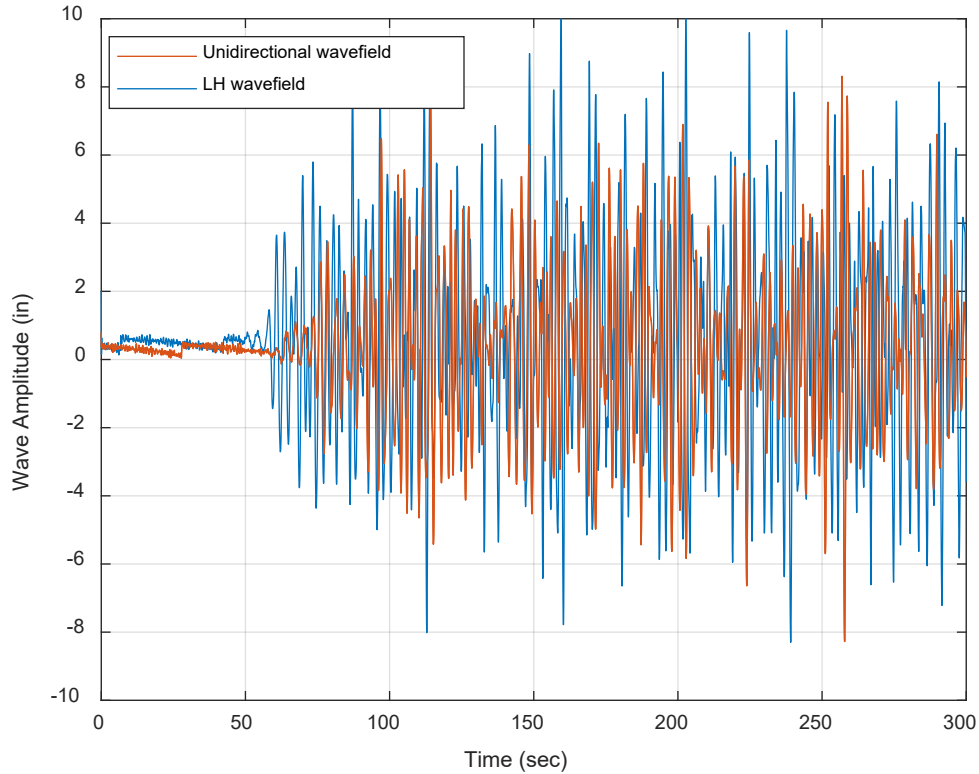


Figure 11. Irregular (P - M) surface wave elevation timeseries corresponding to unidirectional and LH wave cases.

Figure 12 shows irregular P - M pressure timeseries, as measured by the icListen hydrophone, overlaid for their respective 5-minute run periods. Run 5A (shown in blue) is the LH result, which is seen to have considerably more pressure amplitude than unidirectional Airy wave cases (Run 0C and 0E, without and with azimuthal spreading, respectively). An example run without the wavemaker running is shown to have negligible amplitude, in comparison. Figure 13 shows a zoomed view of the run's second minute. Because of the random nature of the P - M waves in the timeseries, it is more difficult to observe precise frequencies, but it is still apparent that the LH wavefield produces higher (double) frequencies of the P - M wave.

As was done previously, spectral processing for these runs was done to better observe the frequency effects. Figure 14 shows the pressure power spectra for the same data (runs) shown previously. We first observe that the power spectrum for the ambient noise case is significantly lower than whenever any wavemakers are operating. For the irregular unidirectional cases, we clearly observe the wave energy is spread over a very wide frequency range, unlike the regular LH waves, which showed strong energy only at the monochromatic wave frequencies.

There are peaks for both unidirectional cases (with and without azimuthal spreading) that occur at frequencies slightly lower than the specified P - M sea surface spectra peak of 0.40 Hz. The energy then reduces with increased frequency. Here, the effect of the P - M azimuthal spreading appears small, producing results similar to that of the unspread case.

For the LH waves, the pressure increase is easily observed, and its spectral peaks occur at slightly higher frequency, with the peak slightly higher than the expected double frequency of 0.80 Hz. The LH power spectrum is spread over a large frequency band with larger energy than the unidirectional wavefield pressure at those higher frequencies. However, for these irregular waves, the peak of the Airy wave pressure is slightly larger than the peak LH pressure. Again, it is important to remember that in a realistic ocean environment, the Airy pressure energy will attenuate with increased depth, whereas the LH pressure will not.

Figure 15 compares the LH pressure for the irregular P - M wave case (5A) with the regular wave case (1A). The regular LH waves show much higher pressure obtained, about 25 dB more than the P - M case, but only at the precise double frequency of the interacting waves. The difference is driven mainly by the reduced wave amplitudes of the P - M case available in MASK (which is likely also to be the case in real ocean conditions). Hence, the more regular (and matched) the waves are, the more they can produce energy for harvesting, compared to irregular waves. On the contrary, while irregular P - M frequency-spread waves may not produce as much energy, they may be more capable of finding matching between wide-bandwidth spectrally-spread components for energy production.

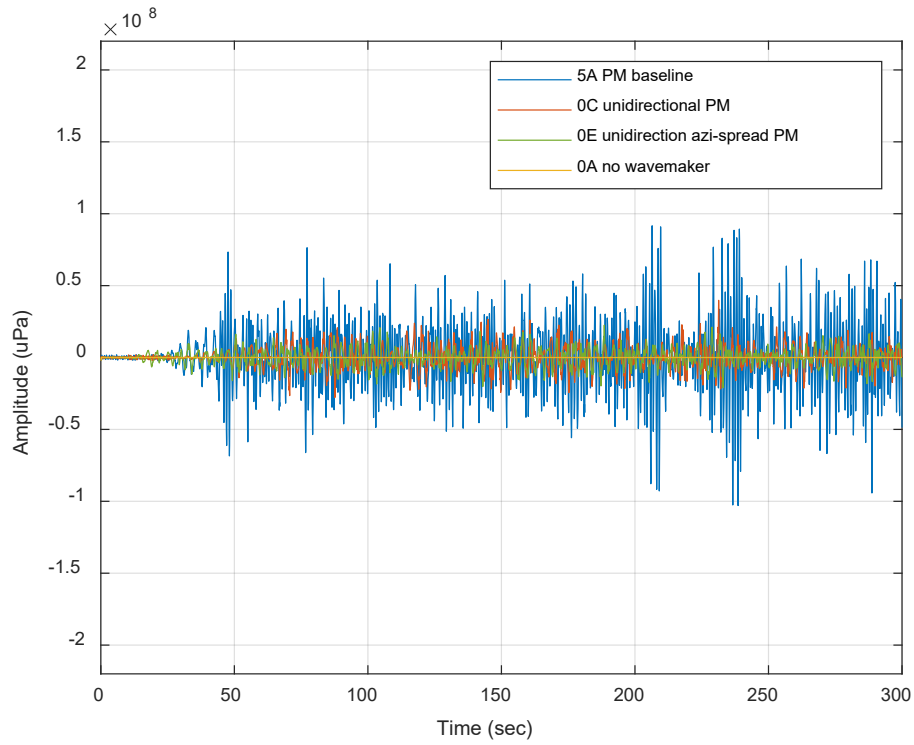


Figure 12. Bottom pressure amplitudes of irregular waves baseline case; no wave making vs. unidirectional waves vs. *LH* waves.

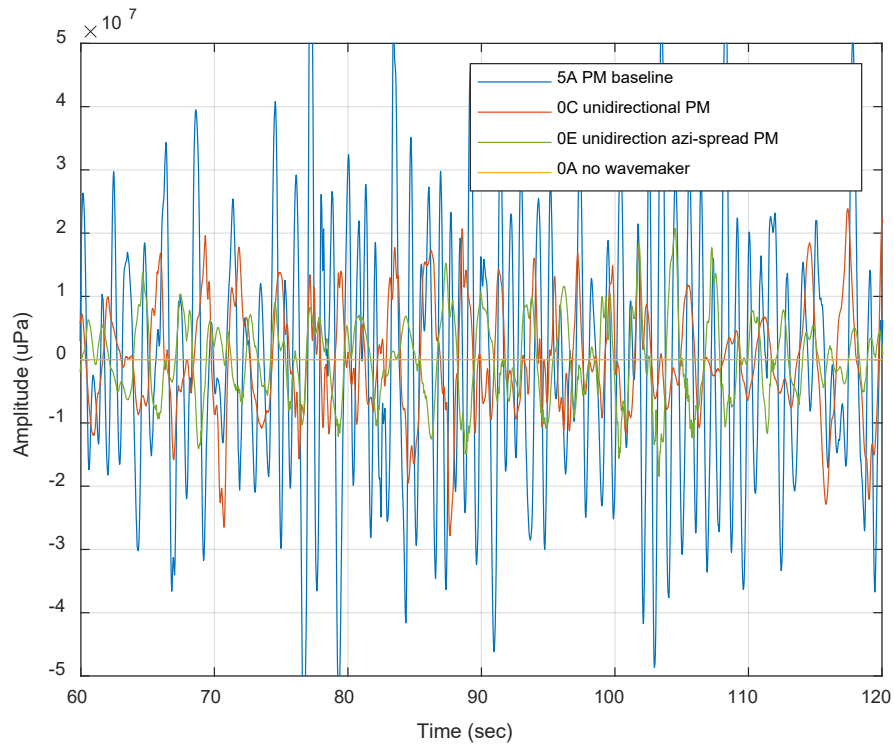


Figure 13. Zoomed view of the second minute of Figure 12.

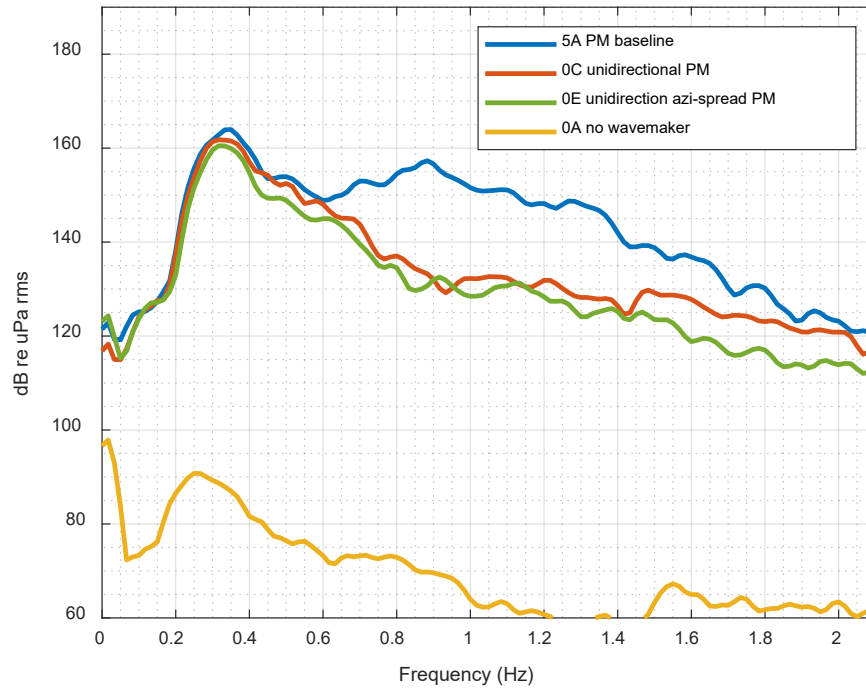


Figure 14. Comparison of bottom pressure power spectra for irregular *P-M* waves; no wave making vs. unidirectional waves vs. *LH* waves.

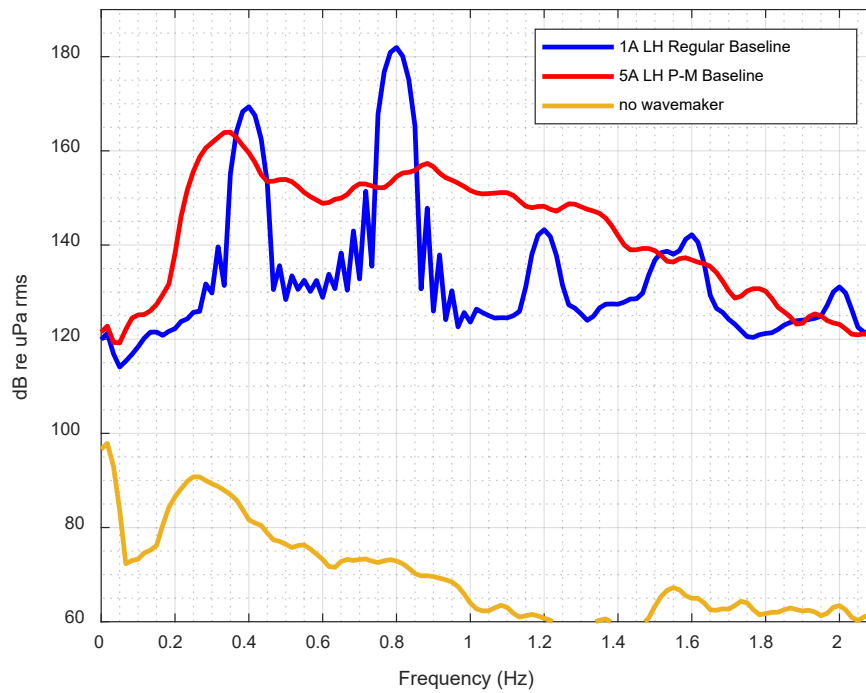


Figure 15. Comparison of bottom pressure power spectra for *LH* waves; regular (monochromatic) waves and irregular *P-M* waves.

4.2 FREQUENCY AND WAVE AMPLITUDE DEPENDENCIES

4.2.1 Regular waves as a function of wave height

It was not possible to run the MASK wavemakers to produce the same wave heights for all frequencies, without the waves and subsequent *LH* pressure being too low. As a result, many of the measurements desired for comparison had different wave heights, and this becomes another variable in pressure production that must be considered.

As the wave height increases, the *LH* pressure should increase. Here we compare the baseline regular *LH* waves against higher and lower wave heights. For this comparison, the wave frequency was 0.40 Hz, and the wave heights were 12", 13.4" (baseline), and 19.7". There was no frequency-mismatch and no obliqueness. Figure 16 shows the pressure power spectra for these cases and shows both the Airy wave pressure peaks and the *LH* pressure peaks increasing with wave height.

Figure 17 shows the comparison of relative values of the *LH* pressure production loss (in dB) obtained in the experimentation with theoretically predicted (relative) values for these cases. It is computed by taking the differences between the sets of measurements and their maximum value, which occurs here for the largest wave amplitude of 19.7". There is excellent agreement between the losses expected theoretically and the losses seen in the data analysis, and showing that reduced wave amplitude will also reduce the *LH* pressure produced.

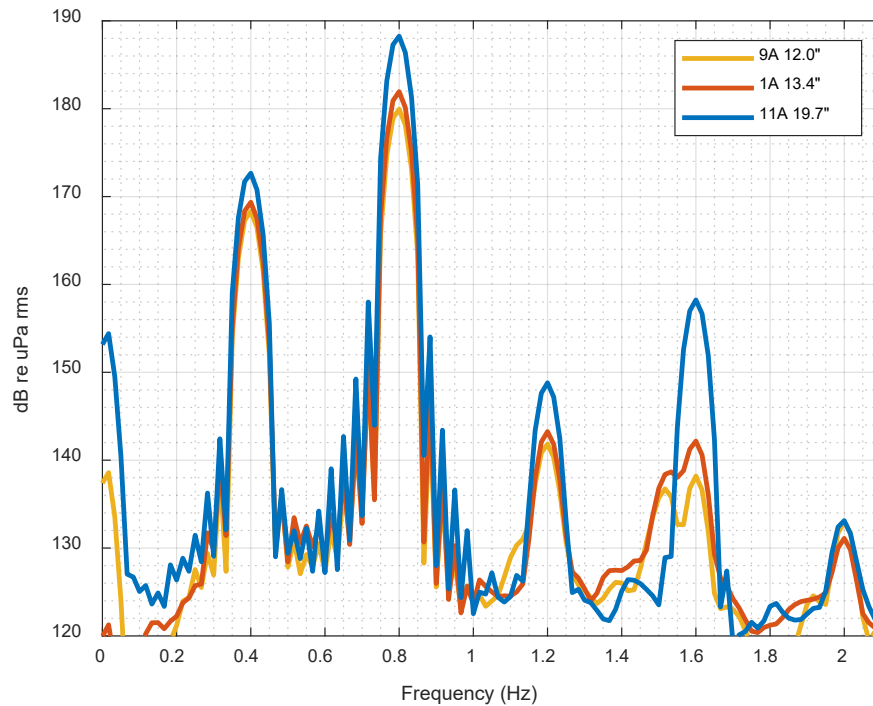


Figure 16. Comparison of bottom pressure spectra for regular (matched monochromatic) *LH* waves as a function of wave amplitude.

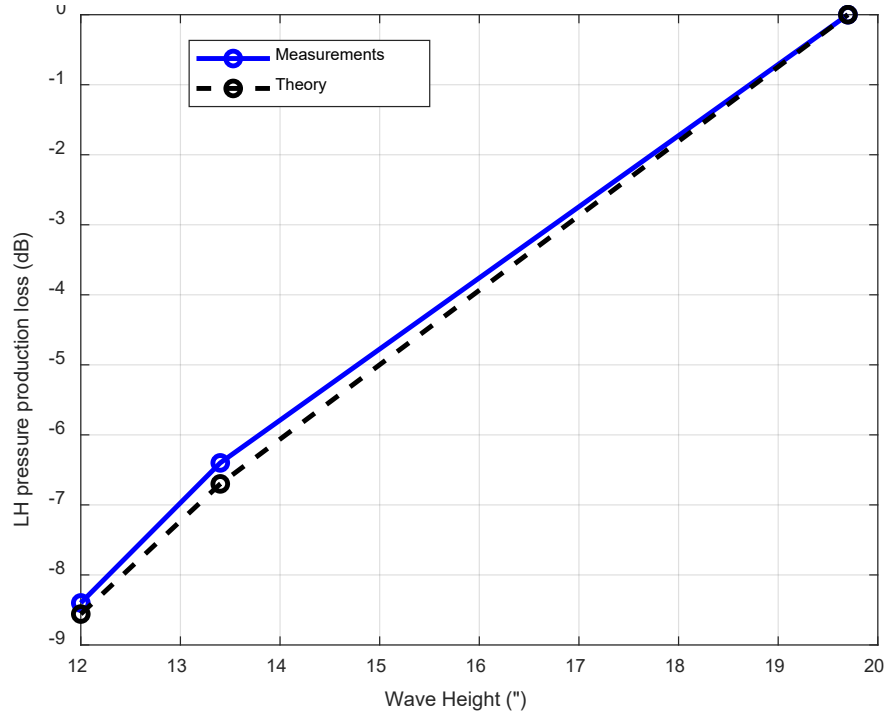


Figure 17. *LH* pressure production loss as a function of wave height for regular, matched, perfectly opposed waves.

4.2.2 Regular waves as a function of frequency

Before we consider frequency-mismatched cases, we characterize the *LH* baseline performance as a function of frequency, for matched-frequency, regular opposed waves. Here we compare cases 1A, 1B, 1C, and 1D. The wave frequencies were 0.40, 0.46, 0.55, 0.67 Hz and the wave heights were 13.4", 13.4", 10.9", 7.0", respectively. The results for 0.40 Hz are the same as for the baseline case previously shown. Figure 18 shows the bottom pressure power spectrum after equalization to flatten the sensitivity across all frequencies. The Airy wave pressures are seen at the wave frequencies at lower pressure levels. As expected, they decrease in amplitude with frequency as the wavelength decreases (or wavenumber increases) as predicted by equation (2). The *LH* peaks are also seen as expected at the double frequencies of 0.80, 0.92, 1.10, and 1.34 Hz, respectively.

Figure 19 shows the *LH* pressure production loss as a function of frequency, relative to the expected maximum at 0.46 Hz. Here, the comparison of theory and measurements show some differences. In this case, the theoretical curve considers both of the variables of frequencies and wave height. We were not successful to conduct an experiment where all the wave heights were equal over frequency. The differences between 0.40 and the 0.46 reference are not large (only about 2 dB). The differences between the last two frequencies (0.55 and 0.67 Hz) for both theory and measurements are similar, about 5 dB difference. However, between 0.55 and 0.46, there is about an 8 dB difference, which is currently unexplained.

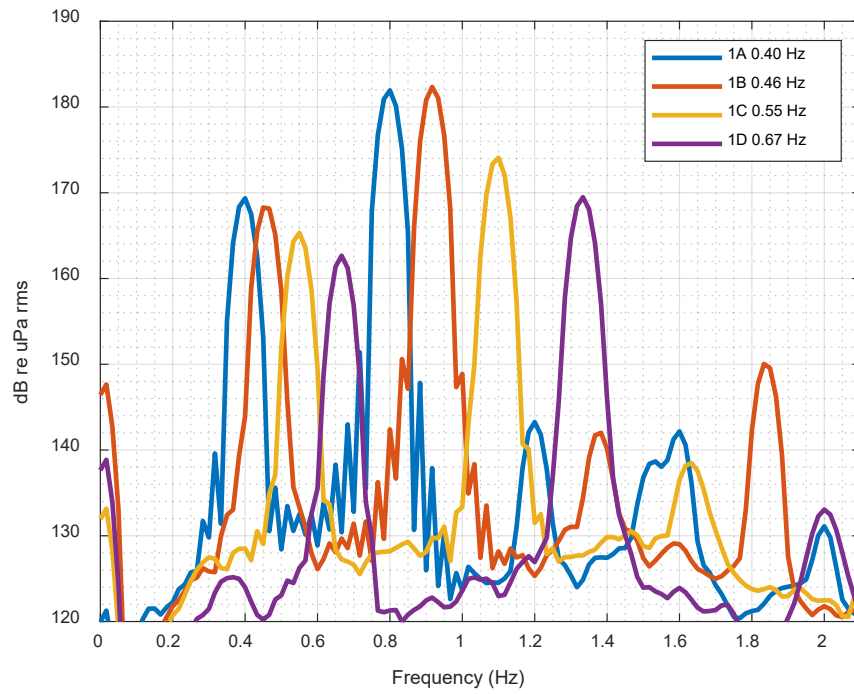


Figure 18. Comparison of bottom pressure spectra for regular (matched monochromatic) *LH* waves as a function of wave frequency.

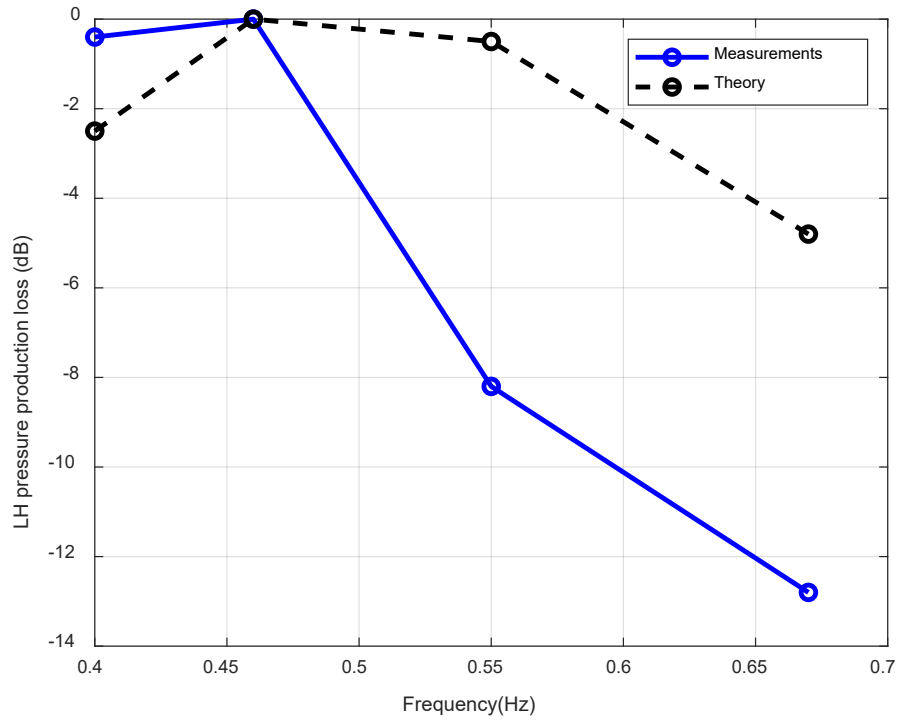


Figure 19. Comparison of bottom pressure spectral peaks for regular (matched monochromatic) *LH* waves as a function of wave frequency.

4.2.3 Irregular P - M waves as a function of frequency

Here we characterize the LH performance as a function of frequency, for matched irregular P - M waves. The waves are perfectly opposed and the P - M spectral peaks are selected to be at the same frequencies as used previously for regular waves. The cases were 5A, 5B, 5C, 5D, and 5E. The corresponding wave frequencies were 0.40, 0.46, 0.55, 0.67, and 0.46 Hz, and the wave heights were 10.0", 7.9", 5.6", 3.5", and 7.9", respectively. Case 5E differs from 5B only in that it uses the azimuthally spread P - M generation mode. The results for 0.40 Hz are the same as the irregular baseline case previously shown (Case 5A).

Figure 20 shows the bottom pressure power spectra, equalized to flatten the sensitivity across all frequencies. Rather than narrow LH peaks as seen with monochromatic regular waves, here we observe broadband energy corresponding to the LH interactions, and their peaks occur at slightly higher than the double frequencies of 0.80, 0.92, 1.10, and 1.34 Hz, respectively. The Airy wave pressures are also seen to be stronger than their corresponding LH pressures, although they will attenuate significantly in deeper waters. Both the Airy pressure and the LH pressure decrease with frequency in these cases. Pressure production is clearly better for lower frequencies. Part of this is explained by the reduction of wave height with frequency achievable in the MASK tank. Comparing the 0.46 Hz cases with and without azimuthal spreading, it is clear that the no-spreading case generates significantly more pressure than the spreading case. Due to the broadband nature of the spectra, it is difficult to identify and compare with peak values for the irregular P - M pressures. Therefore, we defer from presenting quantitative comparisons of pressure production losses, though the differences are apparent from the current figure.

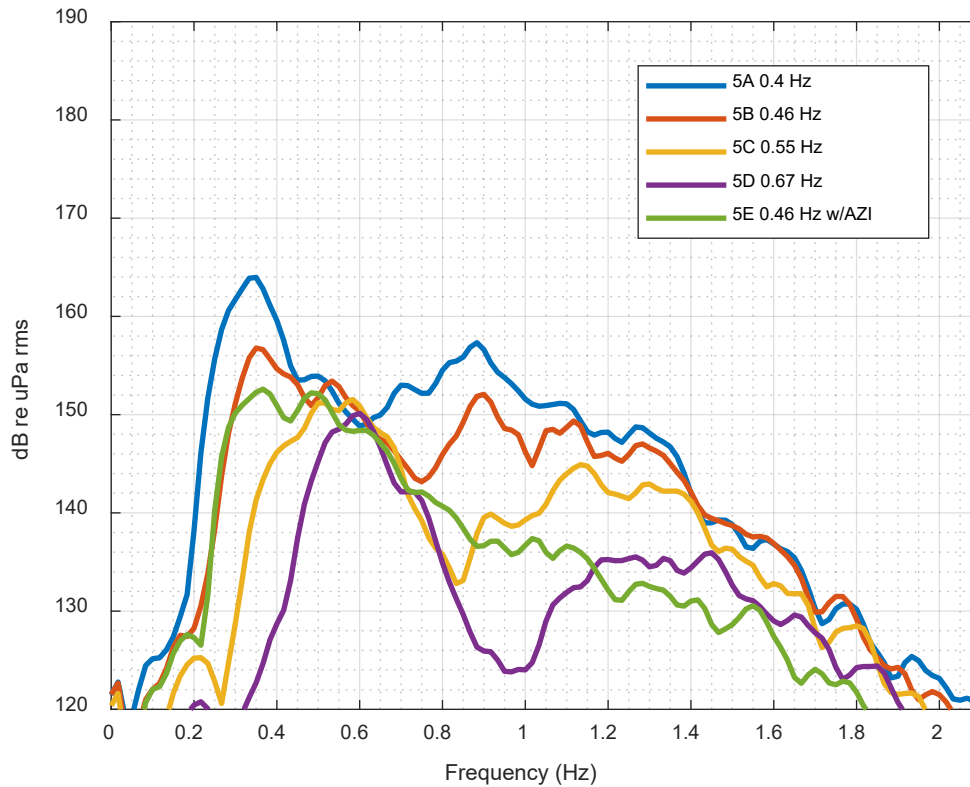


Figure 20. Comparison of bottom pressure spectra for irregular (P - M) LH waves as a function of wave frequency.

4.3 FREQUENCY-MISMATCHED CASES

4.3.1 Regular waves with frequency mismatch

Now we consider cases when the frequencies of the two regular opposed *LH* waves are not perfectly matched. From one side of the MASK tank, the baseline case (1A) waves were generated, with a wave frequency of 0.40 Hz. From the other side of the tank, opposing waves of frequencies 0.40, 0.46, 0.55, and 0.67 Hz were generated, with corresponding wave amplitudes of 13.4", 13.4", 10.9", and 7", respectively.

Figure 21 shows the sensitivity to frequency mismatch for these cases, with the baseline case (1A) being the reference. We see the *LH* effect is still produced for 0.46 and 0.55 Hz cases, but not for the 0.67 case. As expected, the pressure produced drops off with increased mismatch. We also observe that when we have frequency mismatch, the *LH* peak occurs at the sum of the two wave frequencies (in lieu of the double frequency). This is seen at 8.6 Hz (0.40+0.46) and 9.5 Hz (0.40+0.55). No *LH* peak is discernable for the mismatched case of 0.40 and 0.67 Hz. The Airy wave peaks are seen to broaden for 0.46 Hz, and then become separated double peaks for 0.55 and 0.67 Hz cases.

Figure 22 shows the *LH* pressure production loss for the theoretical prediction and the experimental measurements. The reference in this case is the baseline case (1A), and compared with the amount of frequency mismatch. In this case, the theoretical curve assumes no frequency mismatch losses and just captures the variations due to changing wave height frequency. We do not currently have a model for mismatch losses, but the data taken in the tank show the behavior of the losses. The *LH* pressure production losses for the measurements are also shown. The measurements show small drops in level for small frequency mismatch, but then drop very quickly with increasing frequency mismatch.

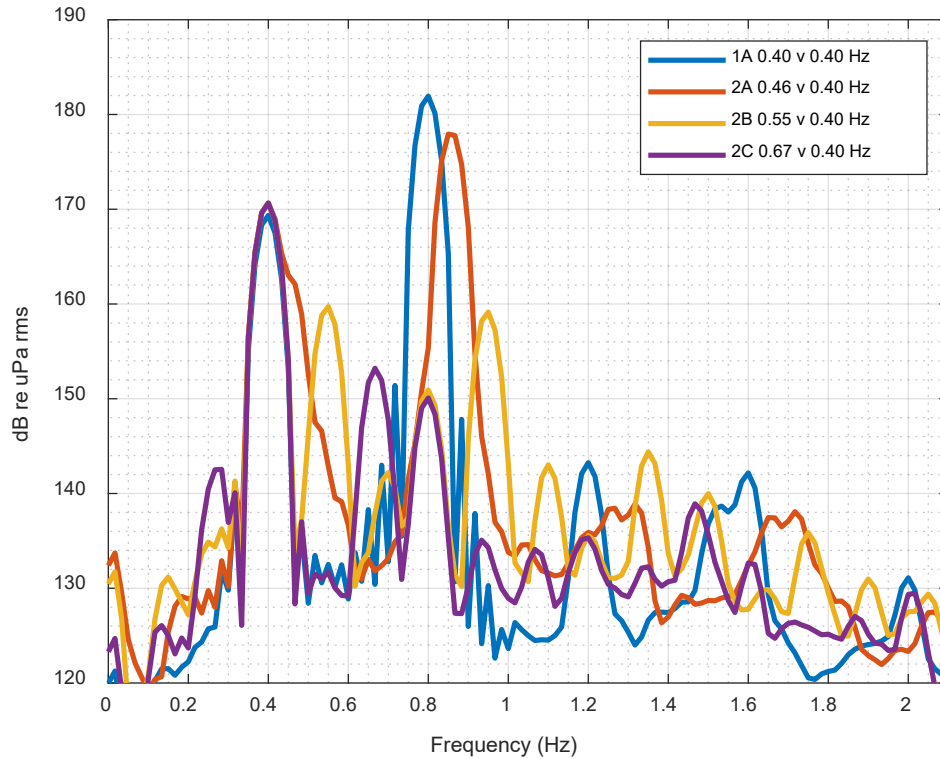
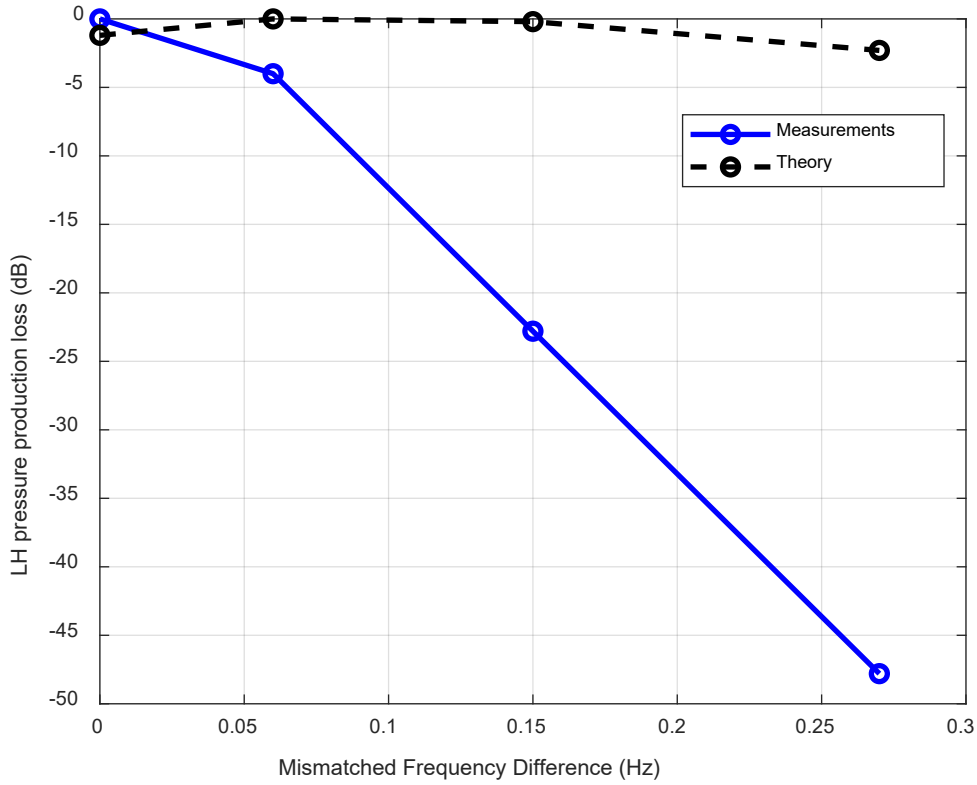


Figure 21. Comparison of bottom pressure spectra for regular (mismatched monochromatic) *LH* waves with various amount of frequency mismatch.



- The theoretical reference curve is expected loss due to wave height variations only, with perfect frequency matching.

Figure 22. Comparison of bottom pressure spectra for regular (mismatched monochromatic) *LH* waves with various amount of frequency mismatch.

4.3.2 Irregular *P-M* waves with frequency mismatch

Here we consider cases when the frequencies of the two irregular opposed *P-M* waves are not perfectly matched with the exact same sea surface spectrum. From one side of the MASK tank the baseline irregular *P-M* case (5A) was generated, with specified *P-M* peak at 0.40 Hz and wave height of 10". From the other side of the tank, opposing irregular waves with *P-M* spectrum peaks of 0.40, 0.46, 0.55, 0.67 and 0.46 Hz were generated, with wave amplitudes of 10.0", 7.9", 5.6", 3.5", and 7.9", respectively. These correspond to cases 5A, 6A, 6B, 6C, and 6D, respectively. The only difference between case 6A and 6D is that the latter includes azimuthal spreading.

Figure 23 shows the bottom pressure power spectra, equalized to flatten the sensitivity across all frequencies. As with the matched irregular *P-M* waves, we observe broadband energy corresponding to the *LH* interactions, and their peaks occur higher than the double frequencies of 0.80, 0.92, 1.10, and 1.34 Hz, respectively. Both the Airy pressure and the *LH* pressure decrease with frequency for these cases. Pressure production performance is significantly reduced with increased frequency mismatch. The performance is also incrementally worse than for the matched frequency cases (compare with Figure 21). Comparing the 0.46 Hz case with azimuthal spreading (green curve), it generates significantly less pressure than the azimuthal spreading case (yellow curve).

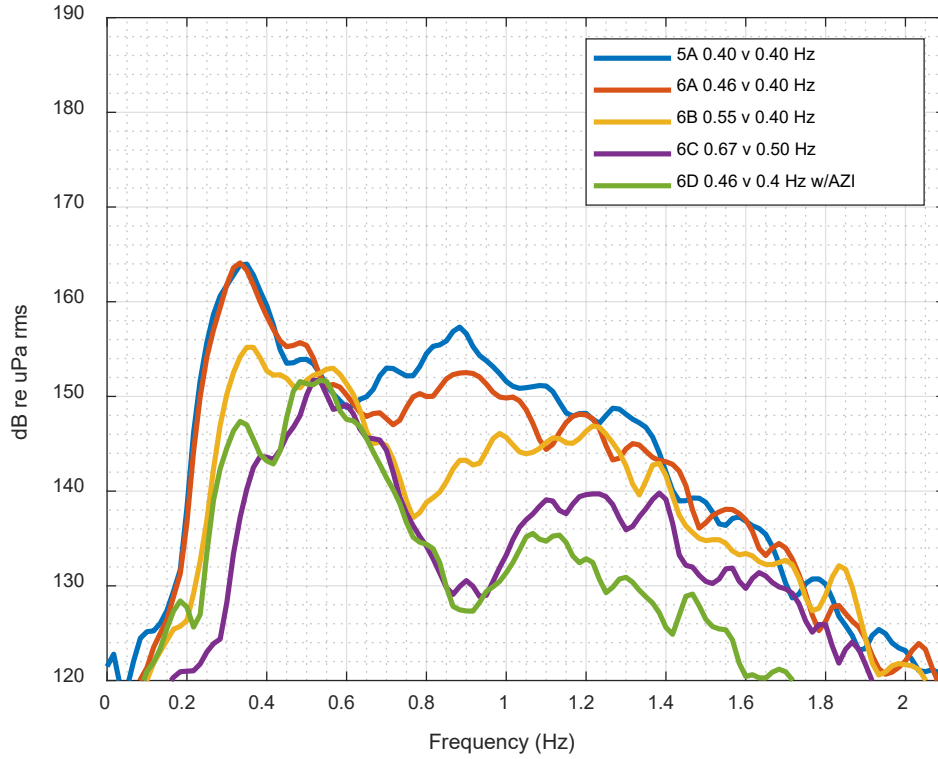


Figure 23. Comparison of bottom pressure spectra for irregular *P-M LH* waves with various amount of frequency mismatch.

4.4 OBLIQUE ANGLE CASES

4.4.1 Regular waves with oblique encounter angles

The *LH* theory assumes the encountering waves are traveling directly opposed to each other. A series of experimental runs was conducted to better understand the degradation of *LH* pressure production with increasingly oblique encounter angles. The oblique angle is defined here as the angle away from the directly opposed wave's condition, i.e., oblique angle of zero is for directly opposed wavefronts, and oblique angle of 90° is for orthogonal waves.

Figure 24 shows the results of several runs in the MASK tank with regular (monochromatic) waves of fixed frequency 0.46 Hz. The wave heights for all waves were fixed at 13.4", and the oblique angle was varied over values of 0, 13, 26, 36, 46, 53, 60 and 90°. The figure shows the *LH* pressure power spectrum occurring at the double frequency of 0.92 Hz for all cases. As the oblique angle is varied from 0° to 90°, the *LH* the amplitude is reduced mostly monotonically.

The blue curve of Figure 25 shows the comparison of *LH* spectral pressure peak level with a regular baseline case (which is perfectly opposing, with an oblique angle of zero) level. The losses in *LH* pressure production are apparent as the wave encountering angle becomes larger, i.e., increasingly oblique. We are currently evaluating a theoretical model for pressure decreases due to obliqueness [13] against these measurements, but the data collected in the tank show -20 to -25 dB of loss at oblique angle of 45°, and provide an indication of the sensitivity to obliqueness.

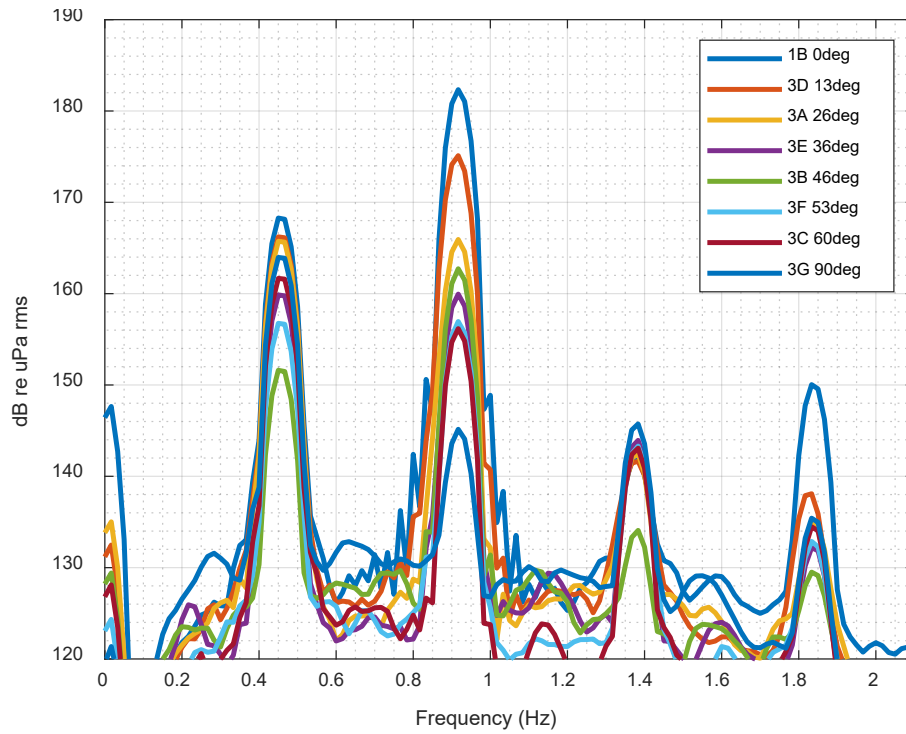


Figure 24. Comparison of bottom pressure spectra for regular (matched monochromatic) *LH* waves as a function of oblique encounter angle.

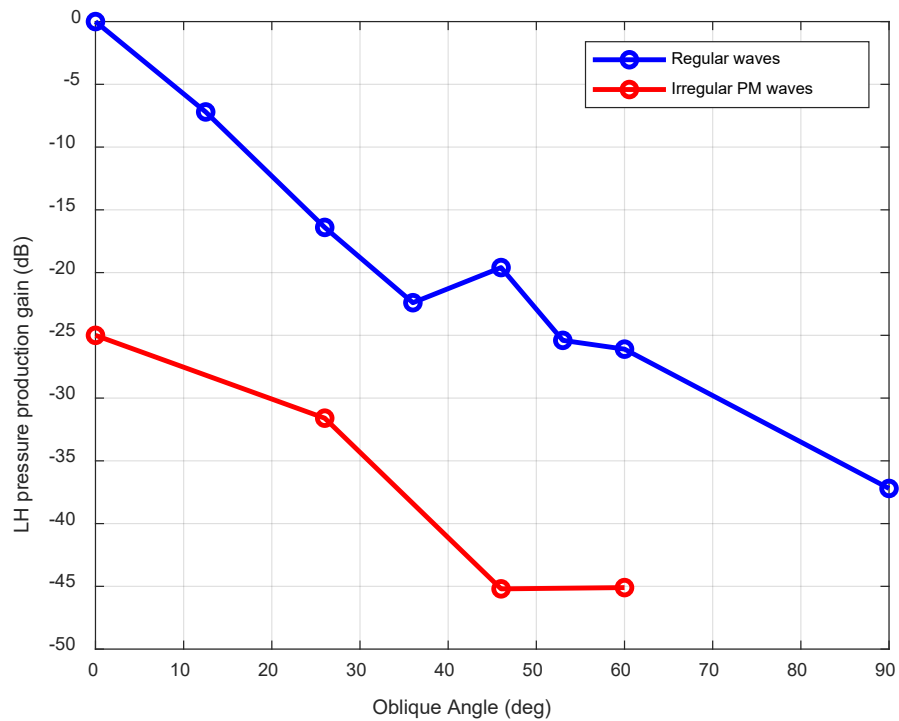


Figure 25. *LH* pressure losses as a function of the oblique angle, for matching wave frequencies.

4.4.2 Irregular *P-M* waves with oblique encounter angle

Now we consider irregular *P-M* waves with obliqueness. A set of experimental runs were made with the irregular baseline case of 5A, with a fixed *P-M* peak frequency of 0.40 Hz, and cases 7A, 7B, 7C, and 7D, with oblique angles of 0, 26, 46, 60, and 46°, respectively. The only difference between case 7B and 7D is that the latter includes azimuthal spreading. Figure 26 shows the results.

Overall, the pressure production for all of the oblique cases is significantly poorer than that of the perfectly opposed case. The 26° case does show a small peak at ~0.7 Hz. Interestingly, here the azimuthally spread case (Case 7D, 46°) shows slightly better performance than its unspread counterpart (Case 7B), presumably because with a spread energy sector, there is likely a stronger component in the opposing direction than other would produce.

The red curve of Figure 25 shows the comparison of irregular *LH* spectral pressure peak levels with its baseline (which is perfectly opposing, with an oblique angle of zero) level, as well as with the pressure production losses of the regular waves (blue curve). Like the losses for regular waves, the irregular waves' pressure production drops as the encountering angle becomes larger, with a similar slope. The irregular waves also produce less pressure than the regular waves, due to their reduced wave heights and the frequency spreading of their energy. This comparison shows about 20 dB lower levels for irregular pressure production.

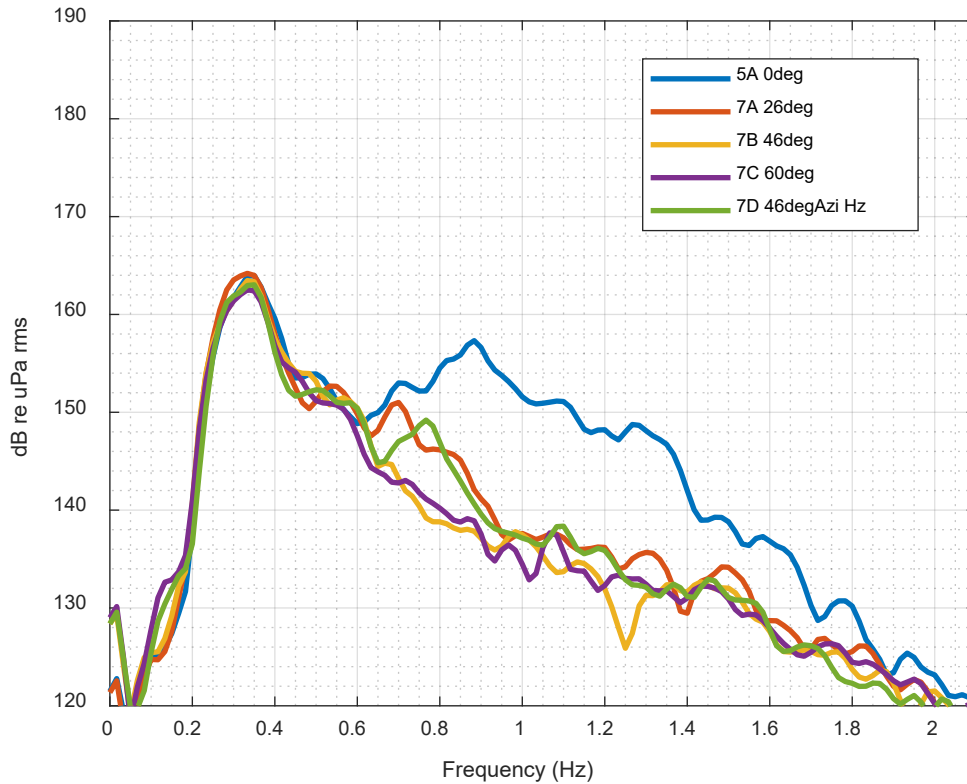


Figure 26. Comparison of bottom pressure spectra for irregular (matched *P-M*) *LH* waves as a function of oblique encounter angle.

4.5 CASES WITH BOTH FREQUENCY-MISMATCH AND OBLIQUENESS

4.5.1 Regular waves with frequency-mismatch and oblique angles

Previous results have shown the degradation in *LH* pressure production when two encountering wavefronts are mismatched in wave frequency or when they approach each other at oblique angles. Now we consider the case when both of these conditions may be present, and we treat first the case of regular monochromatic *LH* waves. We compare baseline case 2A, which has mismatched frequencies of 0.40 and 0.46 Hz, and oblique angle of 0° . This is the slightest mismatched case that we have considered in our experimentation. This baseline is compared with cases 4A–4G, which maintain the same frequency mismatch (0.40 and 0.46 Hz), but vary the oblique angle over 0 – 90° .

Figure 27 shows the resulting *LH* pressure spectra. The peaks of the *LH* pressure spectra are seen between 0.80 and 0.90 Hz. Similar to what was observed with the frequency-matched case, the peaks decrease with an increasing oblique angle. We observe that the shape of the peaks become less symmetric and that they begin to split into double peaks, as the oblique angle gets very large. On the whole, the results are quite similar, compared to Figure 24.

The green curve of Figure 28 shows the *LH* pressure production loss as a function of oblique angle for the regular wave mismatched-frequency case. This can be compared with the previous results for frequency-matched regular waves (blue curve). There is reasonable consistency between these cases, showing the same slope in loss. The levels obtained for the mismatch cases are several dB lower than those obtained for the matched cases.

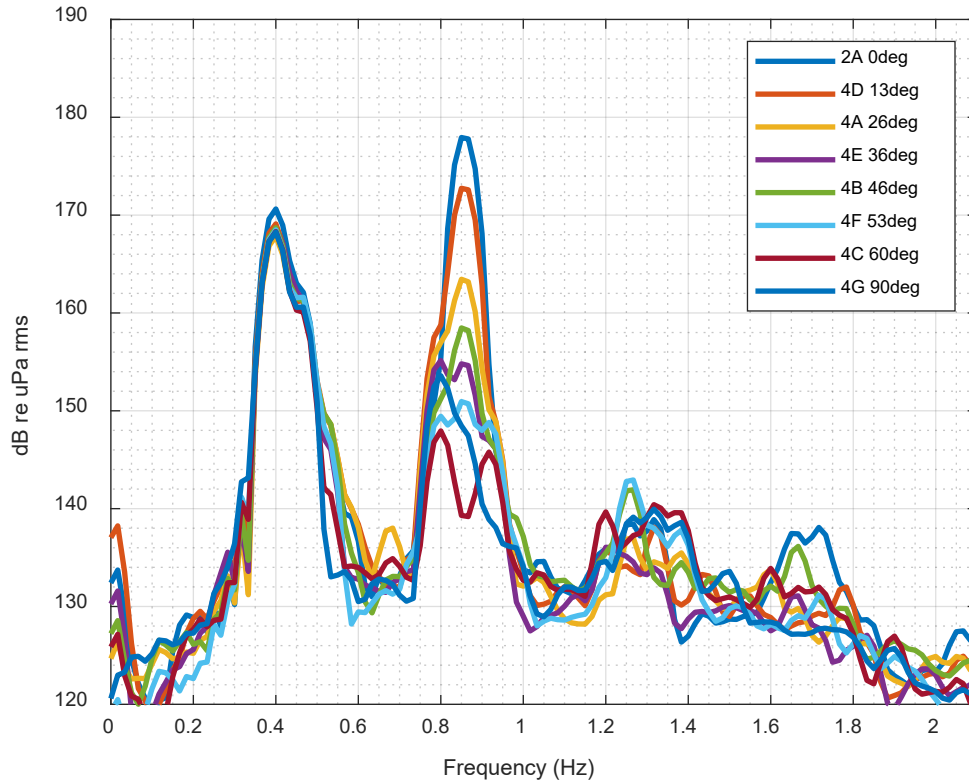


Figure 27. Comparison of bottom pressure spectra for regular (mismatched monochromatic) *LH* waves as a function of oblique encounter angle.

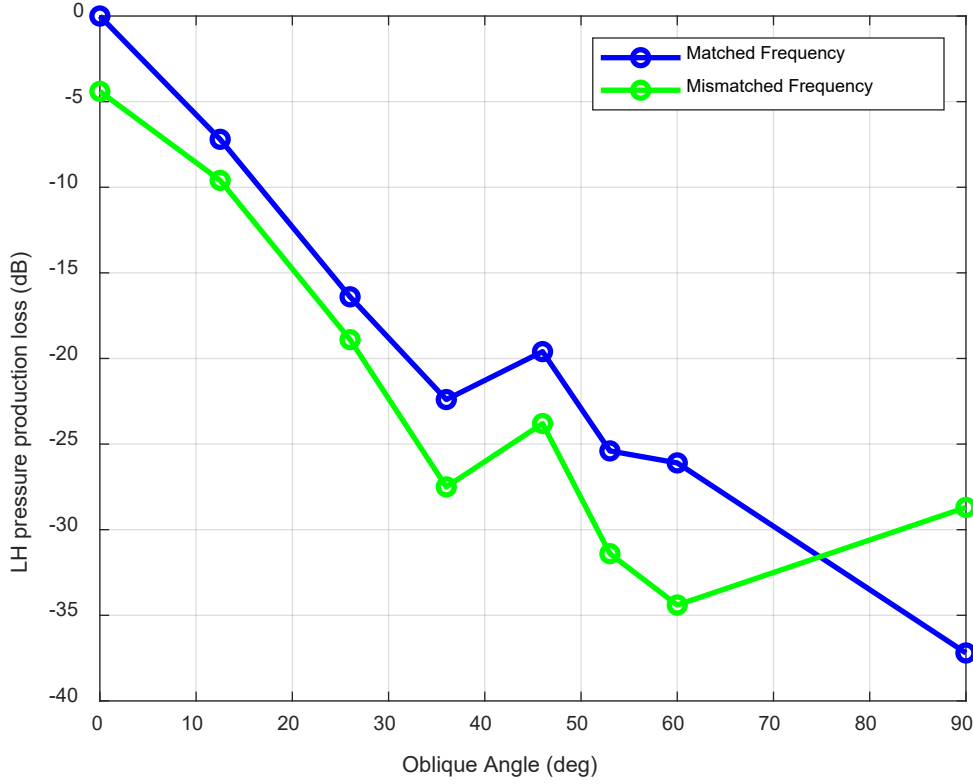


Figure 28. Comparison of bottom pressure spectra for regular (mismatched monochromatic) LH waves as a function of oblique encounter angle.

4.5.2 Irregular P - M waves with frequency-mismatch and oblique angles

Finally, we consider the case of irregular P - M waves for mismatched frequencies and oblique angles. The baseline for this is case 6A, which has waves in one direction with P - M spectrum peak at 0.40 Hz and the other wave in the opposite direction (oblique angle of 0°) with P - M spectrum peak at 0.46 Hz. This is the same mismatch applied to the regular waves (in the previous section).

Figure 29 shows the results of the LH pressure spectra for these cases. The results are seen to be very similar to those obtained for frequency-matched obliques case previously (compare with figure 26).

For both regular monochromatic and irregular P - M wave with obliqueness, it is expected that with increased frequency-mismatch (larger than the 0.06 Hz difference we have attempted here) would further degrade the pressure production performance.

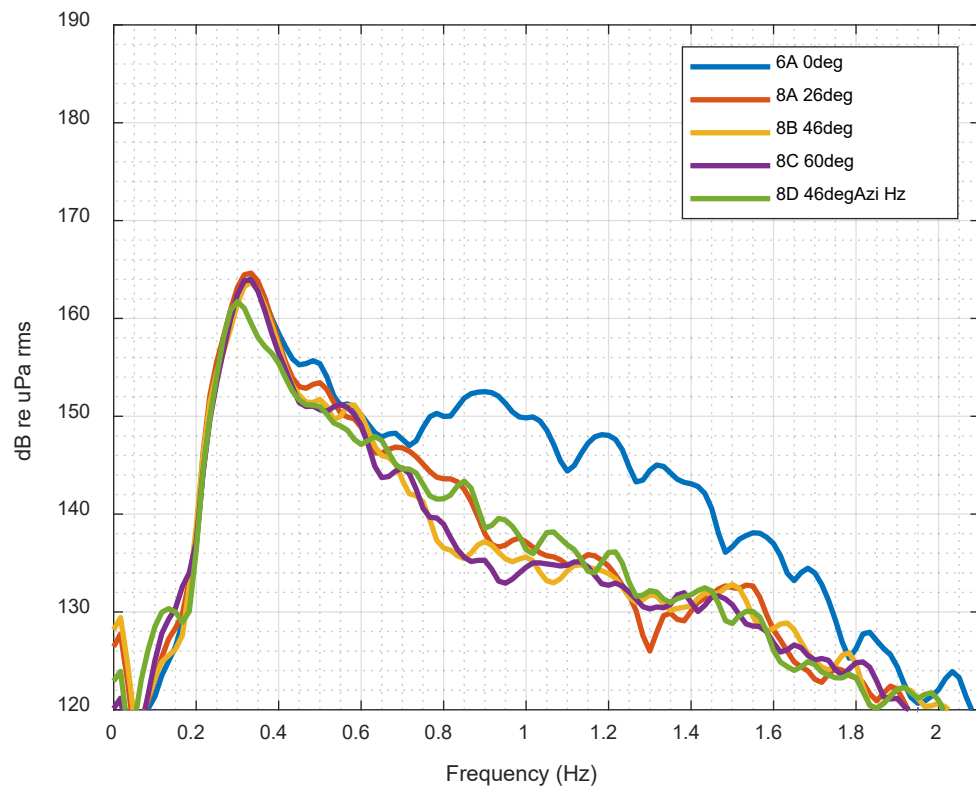


Figure 29. Comparison of bottom pressure spectra for irregular (mismatched Pierson-Moskowitz) *LH* waves as a function of oblique encounter angle.

5. CONCLUSIONS AND RECOMMENDATIONS

In 1950, Longuet-Higgins (*LH*) developed a theory describing the non-linear interaction of opposing ocean surface gravity waves that produces a second-order pressure field that extends throughout the water column to the seafloor. This second-order pressure field occurs at double (or sum of) the frequency of the two linear waves intersecting each other head-on at 180° . Unlike Airy waves, opposing waves of the same wave frequency appears as a “standing wave” and the resulting underwater pressure is unattenuated to any depth. Most existing wave energy harvesting approaches focus on energy produced by waves at the water surface. This wave tank experiment was part of a larger investigation to evaluate the potential for *LH* wave fields to produce pressure fields at the seafloor that could be utilized for energy harvesting. If harvestable, this energy source could provide electrical power to underwater sensors, communications nodes and undersea vehicles, etc.

The wave tank experiment was successfully executed, with 68 individual test cases conducted. The *LH* theory for the seafloor pressure production phenomenon was successfully demonstrated in the tank experiments by observation of the surface wave field and the underwater acoustic measurements. While absolute pressure levels were not obtained during experimentations, their relative levels were sufficient to characterize the *LH* performance. Through analysis of the experimental results, the sensitivity of Longuet-Higgins pressure production criteria was determined.

As expected, as encountering waves become increasingly mismatched in wave frequency and/or when they collide with increasingly oblique angles, the resulting bottom pressure decreases.

Based on our analysis, we make the following conclusions:

- When observing the wave surface, the baseline cases showing the characteristics of the Airy and *LH* waves are distinguishable. The Airy waves show clear unidirectional propagation, whereas the *LH* waves appear as standing waves.
- The Airy wave underwater pressure for unidirectional waves does not show the appreciable differences seen when running *LH* waves. The Airy waves are present in both cases and their spectral peaks are at the proper wave frequency and of the same amplitude.
- The *LH* pressure waves are stronger than the Airy waves, and they occur (as predicted by *LH* theory) at double the wave frequency for matched-frequency waves, or as the wave sum-frequency of mismatched-frequency waves.
- The peak *LH* pressure waves for regular waves are stronger than the peak pressure obtained using irregular *P-M* waves. However, the irregular *LH* waves show higher pressure in some regions away from the double frequency, due to the broadband nature of the *P-M* wave energy.
- The measured *LH* pressure production loss as a function of wave height is consistent with theoretical predictions.
- Measured *LH* pressure as a function of frequency shows partial consistency with theoretical predictions, while considering wave height differences. The reasons for one observed discrepancy are still being investigated.
- Analysis shows that frequency-mismatch in interacting waves causes significant drops in pressure production, for both regular monochromatic and irregular *P-M* waves.
- Analysis shows that oblique angles between the encountering waves' directions cause decreases in pressure production, both for regular monochromatic and irregular *P-M* waves. When frequency mismatch is introduced, similar degradation with obliqueness occurs, and with slightly lower loss due to the mismatch. The *P-M* cases show 20 dB lower pressure production level than regular waves near the double frequency.

More analysis of this experimental data set is justified, to focus on obtaining absolute calibrated pressure levels with the sensors we have employed. Also, additional analysis on the alternate CR1 hydrophone would provide some consistency checks on our results. This may also provide insight into the spatial (horizontal and vertical separation) dependencies of the *LH* pressure field during this experimentation.

Longer term recommendations are to continue studies of energy availability (locations, required oceanographic conditions, and pressure field strength). In addition, in the future, we recommend attempting in-ocean acoustic measurements to assess actual in-situ pressure levels that may be harvestable by undersea technology yet to be developed.

REFERENCES

1. Longuet-Higgins M.S. [1950] “A theory of the origin of microseisms,” *Philosophical Transactions of the Royal Society of London, Series A*, 243(857):1–35.
2. Cooper, R.I.B and Longuet-Higgins, M.S. [1951] “An experimental study of the pressure variations in standing water waves,” *Proceedings of the Royal Society*, Vol 206, Issue 1086.
3. Webb, S.C. and Cox, C.S. [1986] “Observations and modeling of seafloor microseisms”, *Journal of Geophysical Research: Solid Earth*, Vol. 91, Issue B7.
4. Bromirski, Peter .D., Stephen, Ralph A. [2013] “Are deep-ocean-generated surface-wave microseisms observed on land?”, *Journal of Geophysical Research: Solid Earth*, Vol. 118, Issue 7.
5. Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Preparatory Commission [2022] "Overview of the Verification Regime," accessed at <https://www.ctbto.org/verification-regime/background/overview-of-the-verification-regime/>.
6. Waxler, R. and Gilbert, K. E. [2006] “The radiation of atmospheric microbaroms by ocean waves”, *Journal of the Acoustical Society of America*, 119, 2651.
7. Duennebie, Fred K. et. al [2012] “Wind, waves, and acoustic background levels at Station ALOHA”, *Journal of Geophysical Research*, Vol 117, C03017.
8. Ying, Yingzi, Bean, Christopher J., Bromirski, Peter D. [2014] Propagation of microseism from deep ocean to land, *Geophysical Research Letters*, Vol. 41, Issue 18.
9. Korde, Umesh A., McBeth, Michael S [2019] “An Order of Magnitude Estimate for Sea-Floor Microseism Energy Available for Conversion,” unpublished white paper.
10. Richter, K.E.; Ayers, J.M. [2018] An Approach to Predicting Sediment Microbial Fuel Cell Performance in Shallow and Deep Water. *Appl. Sci.* 2018, 8, 2628, accessed at <https://doi.org/10.3390/app8122628>.
11. Lamb, H. 1932 *Hydrodynamics*, 6th ed. Cambridge University Press.
12. Richter, K., Wang, P.F. Ayers, J. [2020] “Assessing Longuet-Higgins double frequency on the shallow seabed”, NIWC Pacific Technical Report.
13. Korde U.A. and McBeth, M.S. [2022] “On using nonlinear wave interactions in multi-directional seas for energy conversion on the ocean floor”, *Applied Ocean Research*, v. 124, 2022, 103193.
14. D. Grimmer, P.F. Wang, H.C. Chen [2021] Modeling of Longuet-Higgins Pressure Waves at the Seafloor for Energy Harvesting, *Proceedings of the MTS/IEEE Oceans '21 Conference*, San Diego, California
15. Pierson and L. Moskowitz [1964] A proposed spectral form for fully developed wind seas based on the similarity theory of A. A. Kitaigorodskii. *J. Geophys. Res.*, 69, 5181–5190.
16. NSWC Carderock [2013] MANEUVERING AND SEAKEEPING BASIN (1961/2013) - Fact Sheet. West Bethesda, MD. NSWC Carderock Division, Code 852.
17. Ocean Sonics [2022] icListen SA35L hydrophone model description, accessed at <https://oceansonics.com/products/iclisten-sa35l/>.

This page is intentionally blank.

INITIAL DISTRIBUTION

84310	Technical Library/Archives	(1)
56406	D. Grimmett	(1)
72110	D. Rees	(1)

Defense Technical Information Center		
Fort Belvoir, VA 22060–6218		(1)

This page is intentionally blank.

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-01-0188		
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden to Department of Defense, Washington Headquarters Services Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From - To)		
October 2022		Final				
4. TITLE AND SUBTITLE				5a. CONTRACT NUMBER		
Wave Tank Experimentation of Seafloor Pressure Waves Induced by Ocean Surface Wave Interactions				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
				5d. PROJECT NUMBER		
6. AUTHORS				5e. TASK NUMBER		
Doug J. Grimmerett Dr. P.F Wang NIWC Pacific				5f. WORK UNIT NUMBER		
Dr. Umesh Korde Johns Hopkins University Michael McBeth NIWC Atlantic						
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER		
NIWC Pacific 53560 Hull Street San Diego, CA 92152-5001				TR 3307		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
Dave Rees, NIWC Pacific, NISE Program Director 53560 Hull Street San Diego, CA 92152-5001				NIWC Pacific NISE Program		
12. DISTRIBUTION/AVAILABILITY STATEMENT				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.						
13. SUPPLEMENTARY NOTES						
This is a work of the United States Government and therefore is not copyrighted. This work may be copied and disseminated without restriction.						
14. ABSTRACT						
In 1950, Longuet-Higgins developed a theory describing the non-linear interaction of opposing ocean surface gravity waves that produces a 2 nd -order pressure field that extends throughout the water column to the seafloor. This 2 nd -order pressure field occurs at double the frequency of the two linear waves intersecting each other head-on at 180°. Unlike Airy waves, opposing waves of the same wave frequency appears as a "standing wave" and the resulting underwater pressure is unattenuated to any depth. Most existing wave energy harvesting approaches focus on energy produced by waves at the water surface. This study is part of an investigation to evaluate the potential for Longuet-Higgins wave interactions to produce pressure fields at the seafloor that could be utilized for energy harvesting. If harvestable, this energy source could provide electrical power to underwater sensors, communications nodes and undersea vehicles, etc. This reported describes and details the results an experiment conducted in a wave tank to generate these conditions and measure the resulting underwater acoustic signals. The sensitivity to their generation conditions is evaulated and summarized, and recommendations are provided.						
15. SUBJECT TERMS						
Longuet-Higgins, microseism, microbarom, energy harvesting, standing waves, sea surface spectrum						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Doug J. Grimmerett	
U	U	U	SAR	54	19b. TELEPHONE NUMBER (Include area code)	
(619) 553-2842						

This page is intentionally blank.

This page is intentionally blank.

DISTRIBUTION STATEMENT A: Approved for public release. Distribution is unlimited.



Naval Information Warfare Center (NIWC) Pacific
San Diego, CA 92152-5001