



UNIVERSITY OF PLYMOUTH

**AN EXPERIMENTAL STUDY ON WAVE POWER ABSORPTION FROM A
BREAKWATER INTEGRATED OSCILLATING WATER COLUMN**

by

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in partial fulfilment of the requirements for the degree of

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Abstract

As commonly acknowledged in contemporary times, the utilization of wave energy stands as a highly promising green energy concept. Within this domain, the Oscillating Water Column (OWC) Wave Energy Converter (WEC) emerges as a notable subset which is briefly introduced in this paper, regarding its historical evolution within both industry and academia. The main objective of this study is to enhance comprehension of the key parameters governing OWC devices, including hydrodynamic factors like wave amplitude, wave angle, water depth, and a geometric factor, namely orifice size. To achieve this, an experimental setup was created within the small basin at the COAST Laboratory of the University of Plymouth. The experimental conditions and test day observations are noted, and the findings are evaluated with the procession of the experimental data via MATLAB and Excel. Final product of the experimental tests, namely the Capture Width Ratios, allowed to make comparisons of different wave setups and provided an insight to find the most efficient wave energy harnessing scenarios of this OWC device.

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List of Symbols

A = Wave Amplitude (m)

A_c = Chamber surface area (m²)

B = Chamber width (m)

c = Wave celerity (m/s)

c_g = Group velocity (m/s)

d = Opening ratio (*dimensionless*)

ε_{owc} = Capture width ratio (*Dimensionless*)

f = Wave Frequency (Hz)

g = Gravitational acceleration (m/s²)

H_{inc} = Incident Wave height (m)

h = Water Depth (m)

h_s = Submergence Depth (cm)

k = Wave number (*Dimensionless*)

N = Wave Count (*Dimensionless*)

n = Free Surface Elevation (m)

P_{inc} = Incident Wave Power (W)

P_p = Average Pneumatic pressure per wave (W)

p = Instantaneous Pressure (Pa)

q = Instantaneous Airflow (m³/s)

R = Orifice dimension (size) (mm)

ρ_w = Water Density (kg/m³)

S = wave steepness (*dimensionless*)

t_e = Time window ending point (*s*)

t_s = Time window starting point (*s*)

T = Wave Period (*s*)

v = Instantaneous Velocity of water surface inside chamber (*m/s*)

x = opening height (*m*)

θ = Wave Angle (*degrees*)

λ = Wavelength (*m*)

Δt = Time step (*s*)

ω = Angular frequency (*rad/s*)

φ = Wave phase (*rad*)

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1 Introduction

Offshore renewable energy area is becoming extremely popular in recent decades across the globe since the traditional energy production methods are obsolete and environmentally costly and non-friendly. As the concept of WEC is widely acknowledged by many countries worldwide, research focused on estimating the wave energy potentials of many seas and oceans (Sağlam et al. 2010). Hence, a wave energy converter (WEC) device placement in coastal structures has been suggested as an idea to exploit green energy from waves. In industry and academia, there has been investigated several types of wave energy transformation methods with numerical analysis and experimental studies related to the WECs in general. In this study, oscillating water columns (OWC) will be used to demonstrate how viable can a breakwater integrated OWC system be under different wave circumstances. For that regard, an OWC with a cylindrical shape chambered device along a vertical breakwater, which was theoretically examined in Zheng et al. (2019) is used to evaluate hydrodynamic performances and pressure changes due to different physical parameters of OWC and the regular wave conditions.

1.1 Aims

In this experimental study, an OWC is installed into a vertical caisson breakwater. The free surface elevations inside the OWC Chamber and around the breakwater, and air pressure inside the OWC chamber is recorded, based on which the wave energy extraction efficiencies of the breakwater integrated OWC can be evaluated. The aim of this study is to perform physical tests, which will be conducted in the coastal basin at the COAST laboratory, to evaluate the hydrodynamic performance of a breakwater integrated OWC under different wave conditions and physical parameters of the OWC.

1.2 Objectives

By putting forth this study and performing the experimental tests in the COAST laboratory, the following objectives are aimed to be achieved.

- To obtain basic information about OWCs from the literature, making a historical summary, introducing OWC, collecting information regarding advantages, disadvantages, stating working principles and how OWCs transform energy from waves. Checking the existing literature in terms of numerical and physical modelling of an OWC.
- To identify the physical and technical characteristics of the OWC used in the experimental tests of this study, which is previously produced in the COAST laboratory, and to demonstrate its integration to a vertical caisson breakwater.
- To demonstrate parameters that could significantly affect the energy conversion efficiency of OWC under changing conditions and collect the necessary data, such as wave frequency, wave angle, submerged depth of OWC, and opening size of the top of OWC.
- To study the behaviour of breakwater integrated OWC under certain conditions, observe and compare the conversion ratios of the energy obtained from waves and determine the optimal experimental parameters in which the OWC converts most energy.

2 Literature Review

Extensive research is being conducted to comprehend the efficiencies, governing equations, and fundamental principles of Wave Energy Converters (WECs). Both academia and industry have made significant strides in developing numerous techniques for wave energy generation. Among these, Oscillating Water Columns (OWCs) are widely acknowledged as one of the most efficient WEC sub-divisions for harnessing wave energy in both academic and industrial settings. (Mustapa et al. 2017).

One of the oldest study regarding OWC devices has been conducted in the University of Bristol 45 years ago, a pioneering investigation into Oscillating Water Column (OWC) devices, led by Evans et al. (1978). Despite the modern OWC concept being recognized since the 1940s, it has occasionally been referred to by an alternate name, the Masuda Device (Falcão et al, 2016). This nomenclature is attributed to a former Japanese naval commander who initially conceptualized the notion of harnessing energy from oceanic waves to build self-powered wave buoys situated in expansive open waters. Subsequently, this innovative concept underwent extensive scholarly exploration and found practical realization through the development of scaled models within industrial and academic contexts. Consequently, in numerous research endeavours, scholars attempted to incorporate fundamental principles of Oscillating Water Columns (OWCs) into both 2D and 3D numerical simulations utilizing modified geometric configurations, and it has been conducted a multitude of physical experiments in laboratories worldwide.

In one of the initial studies in this field, Evans et al.(1978), tried to establish mathematical foundations on 2D and 3D models to calculate the power absorbed by

the device and the efficiency by comparing the incident wave power to the absorbed wave power, with the use of linear wave theory.

The study by Mustapa et al. (2017) not only provides a brief overview of all wave energy converter devices, but also demonstrates how WECs can be integrated into shoreline structures to take advantage of construction budgets. In their study, wide range of examples of breakwaters with the integration of several types of OWC devices are explained in detail. Furthermore, the study also gives valuable information of the OWC-WEC devices, regarding their physical shape, working principles and industry share and real-life applications.

As Heath et al. (2012) described in their paper, an OWC comprises two key elements: a chamber and a power take off (PTO) system. In general, the utilization of OWC technology involves the manipulation of the water level within this chamber, through the manipulation of wave frequencies. This process results in a fluctuation of the internal air pressure within the chamber. The dynamic alteration of pressure subsequently drives the rotation of a turbine, thus enabling the generation of power as seen in Figure 2-2. In addition, the study claims that the OWCs among all WEC devices, have a significant presence in both industry and academia, as represented in Figure 2-1 (Mustapa et al. 2017).

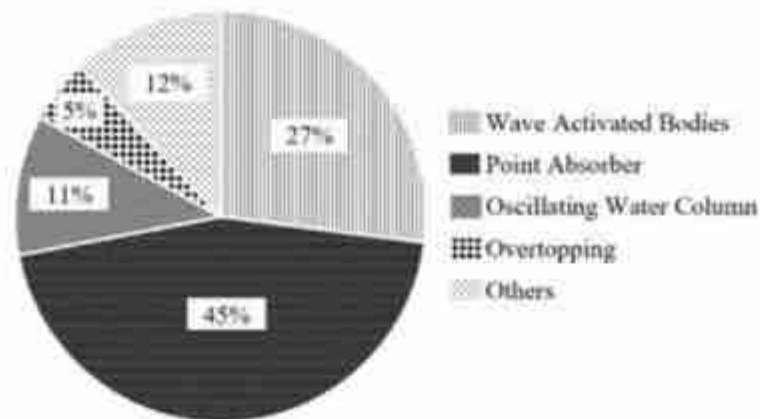


Figure 2-1. Distribution of Usage of Wave Energy Converter Devices (Mustapa et al. 2017)

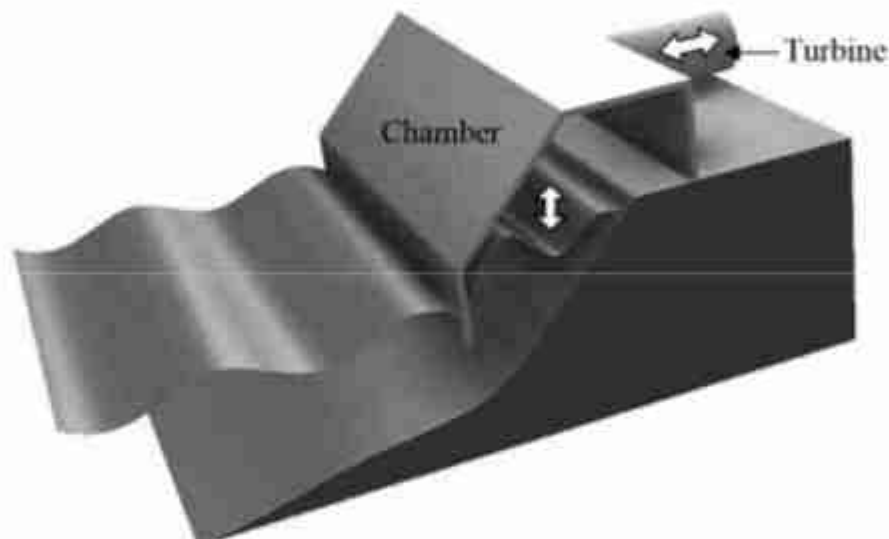


Figure 2-2: General view of an OWC system (Mustapa et al. 2017).

Zheng et al. (2019) presented a new theoretical design for an OWC device in their paper. Their design differed from previous research and included three-dimensional mathematical modelling. The goal of the study was to assess the hydrodynamic performance and power output of this new device, as depicted in Figure 2-3. After completing mathematical analyses, some findings were revealed about how OWC performance changes by using different dimensions of the device, such as the radius

of the OWC chamber, the thickness of the chamber wall, and the submergence of the chamber. Furthermore, comparisons were made between breakwater integrated OWCs and those that are isolated in offshore environments, both under the same wave conditions. The theoretical studies were based on linear approximation for small wave steepness without any consideration of the viscous effect. Therefore, their model may overestimate the performance of the device in terms of wave power absorption, and not be suitable for extreme wave conditions.

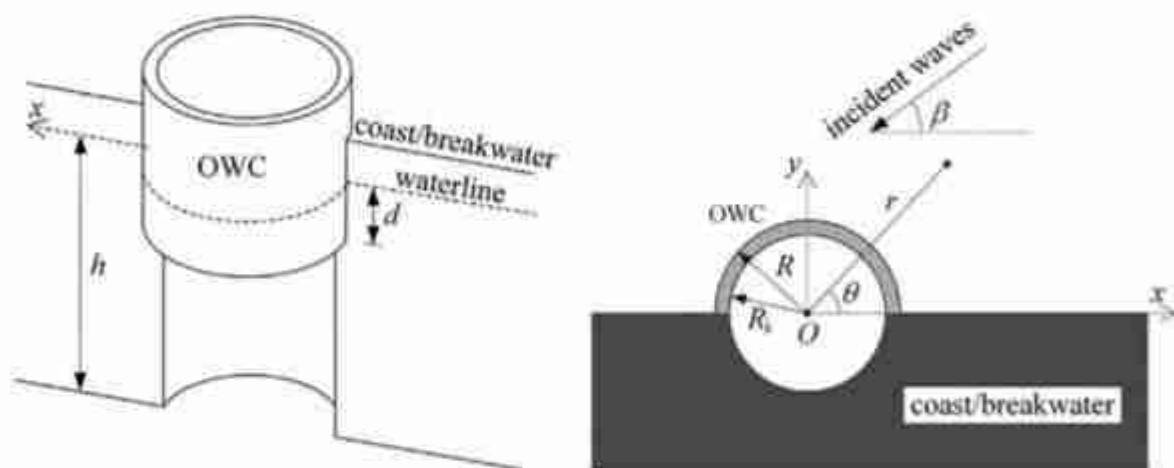


Figure 2-3: A cylindrical chambered device installed along a coast/breakwater
Zheng et al. (2019)

Mahnamfar et al.(2015), conducted an empirical investigation at Istanbul Technical University with the intention of examining the way parameters inherent to the Oscillating Water Column (OWC) system influence the amplitude of power absorption from wave interactions. Their primary aim was to identify an optimal parameter configuration that would facilitate the maximum energy extraction from a diverse range of twenty distinct wave arrangements that were subjected to experimentation. Within the study, two parameters tailored to the specific investigation were introduced and explored: the "opening height" denoted as (x), and the "opening ratio" represented as

(d). A pivotal objective of their research was to analyse the impact of the OWC's opening height, which consequently provided insights into the implications of another dimensionless parameter, the opening ratio. The research article vividly delineates the experimental setup and associated dimensions, as depicted in Figure 2-4. In a separate investigation conducted by Mahnamfar et al. (2019) at Shiraz University, they examined an OWC device within a coastal structure. They subjected this device to testing under sixty-four distinct wave scenarios and conducted numerical modelling. The aim was to gain insights into the impacts of the geometric characteristics of the OWC device and the effects of geometric specifications of the breakwater where the device was installed.

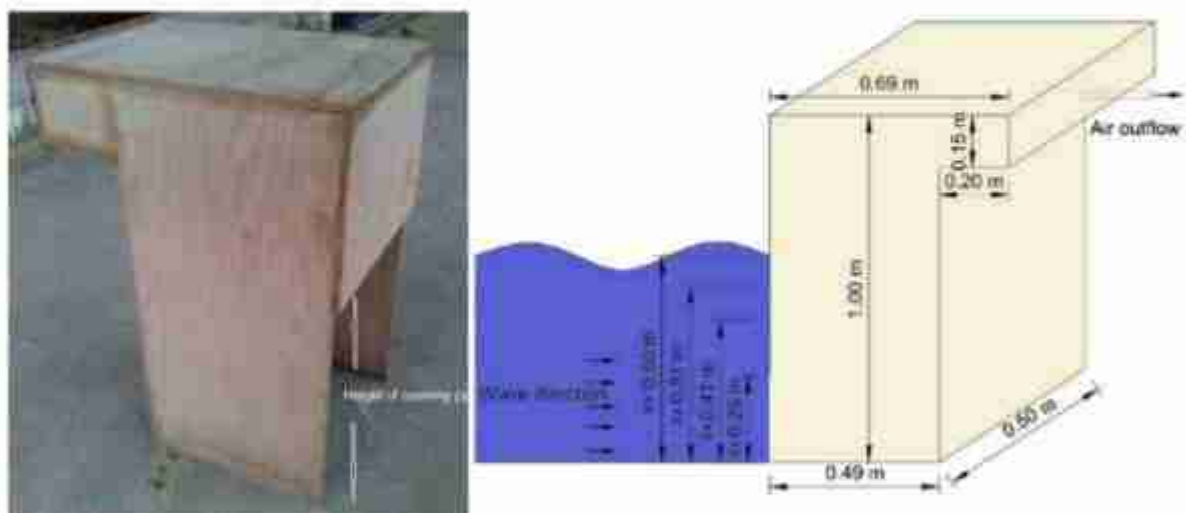


Figure 2-4: General View of the Experimental Setup of Mahnamfar et al.(2015)

In a study by Çelik et al. (2019), the need for more experimental research on OWC WECs was highlighted and a laboratory-based experimental study was suggested. Therefore, a 1:30 scale model of an OWC was created to conduct experiments in a flume tank that measures 22 m in length, 1 m in width, and 1 m in height (see Figure 2-5). The study mainly focused on the effects of the opening bottom

height of the OWC device under different wave steepness values. Henceforth, the results of the experimentation demonstrate that the dimensions of the orifice (R), opening height (x), and the wave steepness (S) notably influence the hydrodynamic functionality of the OWC. Beyond these factors, further deductions are also drawn, such as the substantial impact of water column surface motion within the chamber, particularly concerning the absorption of incoming wave energy, thus affecting the hydrodynamic performance of the OWC (Çelik et al. 2019).

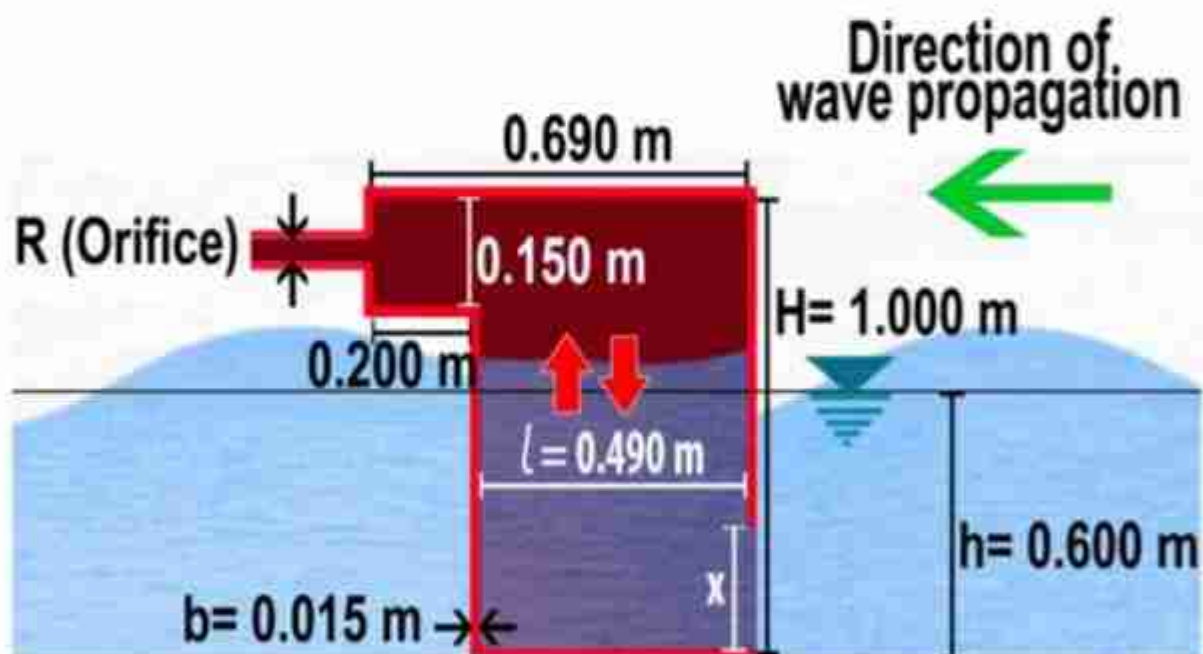


Figure 2-5: An OWC device designed by Celik et al.(2019)

The study of Perez-Collazo et al. (2019) tried to offer an alternative monopile system which operates as an OWC device. The experimental tests are conducted with regular and irregular waves with a 1:40 scaled model. The aim for the study was to establish fundamental steps on understanding the pros and cons of a potential hybrid monopile wind-wave system. As a result, they found that the most efficient orifice size

was %0.5. Likewise, another study by Perez-Collazo et al. (2018) was conducted to raise the comprehension of the hybrid systems by using a 1:50 scaled device under regular and irregular waves.

Orphin et al. (2022) undertook a distinctive investigation concerning the validation of experimental setups and the analysis of uncertainties. This particular methodology diverges from earlier research approaches and offers valuable insights into comprehending the precision and dependability of experimental assessments. The study encompassed the establishment of two distinct experimental configurations within the facilities of Queen's University Belfast (QUB) and Australian Maritime College (AMC), using the same WEC device. The rationale behind this dual experimentation was to meticulously observe and draw comparisons from the outcomes of WEC experiments conducted within nearly identical or akin laboratory conditions, thereby enabling a comprehensive exploration of uncertainty analysis. Beyond the assessment of uncertainties, the research extended to a comparative evaluation of the resultant parameters. This not only involved the inspection of uncertainties but also entailed an investigation into the interrelation among these outcome parameters. A visual representation of the laboratory conditions and a comprehensive overview of both experimental setups can be found in Figure 2-6 and Table 1.

Parameter	Queen's University Belfast Laboratory	Australian Maritime College Laboratory
Scale	1:30	1:30
Environment	Shallow Water Wave Basin	Shallow Water Wave Basin
Basin Specifications	35m x 12m x 1m, 16-element wavemaker	18m x 12m x 1m, 24-element wavemaker
Test Duration & Sampling Rate	200 Hz, 30 Seconds	120 Hz, 30 Seconds
Wave Conditions	$H_1=1.8$ m, $H_2=3$ m, $T = 7-15.6$ seconds	$H_1=1.8$ m, $H_2=3$ m, $T = 7-13.7$ seconds

Table 1: Experimental Setup Parameters and Laboratory Conditions, Orphin et al.(2022)



Figure 2-6: Experimental Setup for same WEC Device in AMC and QUB Laboratories, Orphin et al.(2022)

In another study, Ning D., et al. (2020) put a different experimental design with dual-chambered OWC device modelling (see Figure 2-7 and Figure 2-8). Their study examined the hydrodynamic performance of a dual-chambered OWC device under various conditions. Even though the dual chambered OWC devices demonstrates improved hydrodynamic performance in resonance frequencies when compared to single-chambered OWC devices in theory, there is a dearth of experimental research on the topic. Hence, the experimental investigation highlighted several noteworthy outcomes. This research conducted by Ning et al. claimed that the performance of

the dual-chamber OWC converter was better than the single-chamber version. Furthermore, a significant finding indicated that the optimal proportion of orifice size to chamber surface area lies within the range of 1.5% to 2% for the given experimental configuration. Additionally, the study observed a reduction in hydrodynamic efficiency with increasing wave steepness, and a corresponding increase in efficiency as the outer-chamber draft decreases.

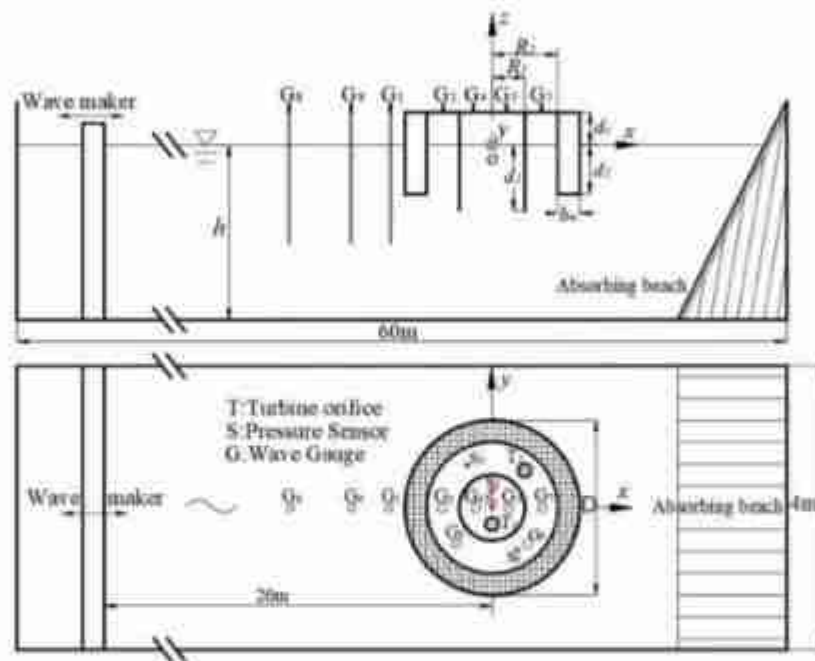


Figure 2-7: General view of a dual-chambered OWC WEC device, Ning et al. (2020)



Figure 2-8: Physical models of a dual chambered OWC WEC device in the Left and a single chambered OWC WEC device on the right, Ning et al. (2020)

Sheng et al.(2012) found that during the initial phases of Wave Energy Converter (WEC) development, physical testing was often conducted considering simplified dynamic effects in experiments, lacking a solid theoretical foundation. The validity of these physical models in representing real-world scenarios remained uncertain without reliable theory to support them. Consequently, they introduced a theoretical analysis to address the potential challenges related to physical modelling and scaling. This analysis provides valuable perspectives for enhancing the efficacy and assessment of small-scale model utilization and testing (Sheng et al. 2012).

The study of Sheng et al. (2014) was aimed to progress into the numerical description of the thermodynamics inside an OWC chamber, and offering a numerical method, by validating the findings with the experimental data.

An experimental study was conducted to define hydrodynamic characteristics of multi-chambered OWC device in the study of Kim, et al.(2023). The experimental

tests were run with regular waves within a flume tank, by using single-chamber, dual-chamber, triple-chamber setups with different wave conditions.

Carlo et al. (2023) focused on a U-OWC type of WEC in their study (see Figure 2-9). Their primary aim was to assess the hydrodynamic efficiency of this U-OWC device, and to observe the resonance generator parameter sets with different geometries. The experimental tests were conducted with 1:30 scale ratio in their laboratory, and to extend the collected data, the physical model was also generated in OpenFOAM software to conduct a numerical analysis. The collaborated experimental and numerical data was analysed to evaluate the hydrodynamic efficiency of the U-OWC, regarding the orifice size and the width of the U-OWC.

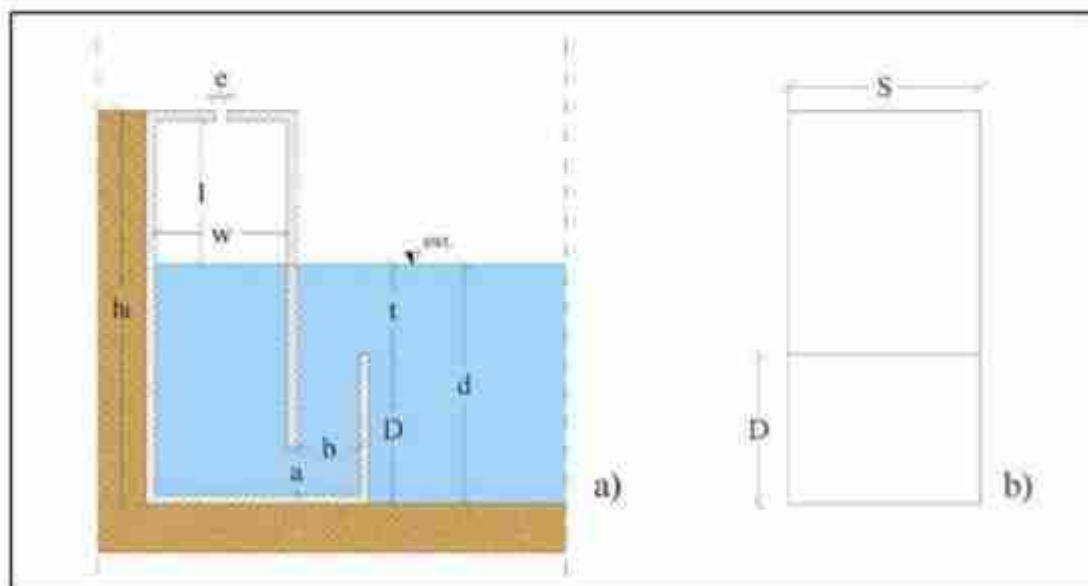


Figure 2-9: The U-OWC device used in the experimental study, Carlo et al. (2023).

Figure (a) represents the side view and Figure (b) is the front view. The geometric parameters are the governing variables in the study

Apart from the scholarly literature, the first successful industrial OWC WEC application took place in Islay, Scotland in 1988. The project is investigated with an

engineering aspect at Whittaker et al. (1997). An OWC, which has a capacity of 75 kW, is constructed within the scope of the project. The station is made up of three main components: a reinforced concrete wave capture chamber, a turbine generator unit on a portal frame, and a control room as seen in Figure 7. The wave capture chamber has a front wall that inclines at 30 degrees from the vertical, with the bottom edge sitting one meter below the low water level. It also features a vertical back wall, roof, and side walls that enhance the natural height of the gully. In the rear wall, there are two openings, one with an adjustable orifice plate and the other with turbine ducting, both openings are one meter in diameter. This study discusses many aspects of the OWC devices in industry, such as generated power outputs, dimensions, and the natural behaviour of an actual OWC structure in long term and provides beneficial ideas about how the efficiency of an OWC device be augmented by collecting the feedback from the device in place.

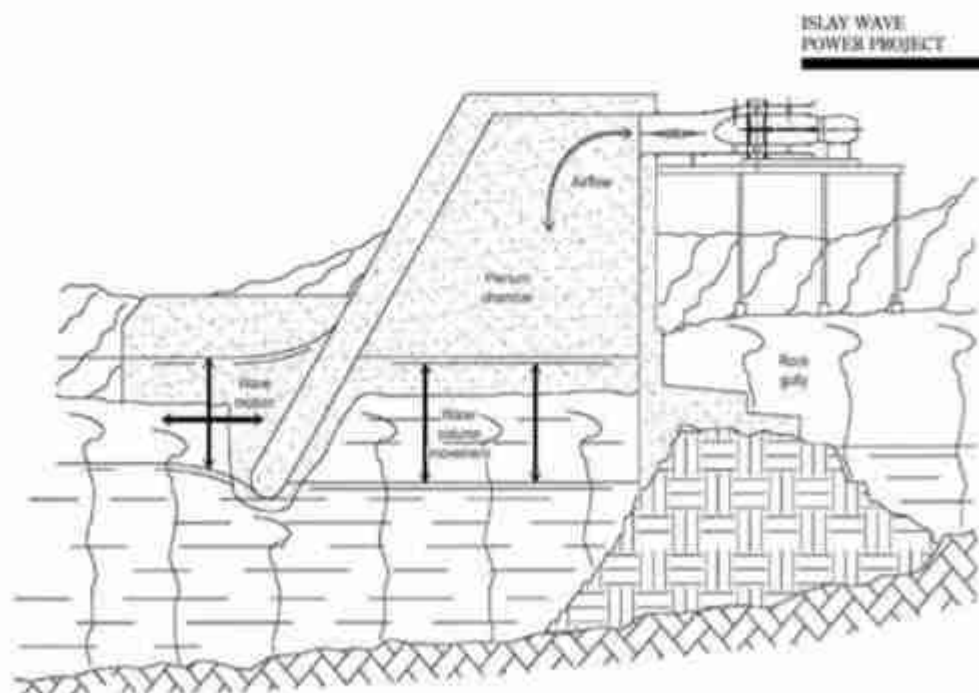


**Figure 2-10: As an industrial practice, the OWC WEC device in Islay, Scotland
Whittaker et al. (1997)**



Figure 2-11: The OWC WEC device structure in Islay Project, Whittaker et al. (1997)

The study of Boccotti P. (2007) focused on a comparison of an OWC and U-OWC devices installed on breakwaters in industry. The study considered light sea states and extreme weather conditions separately and the performances of two devices are compared to each other with that approach. As a result, findings showed that the U-OWC demonstrated a better performance in many aspects comparing to a conventional OWC device.

3 Methodology/Procedure

In this research, the primary aim is to assess the Oscillating Water Column (OWC) performance under various wave scenarios. To achieve this goal, an experimental setup was established at the COAST laboratory within the University of Plymouth. Following the execution of these experiments, the gathered empirical information was analysed using both Excel and MATLAB. This analysis involves computing the power generated by the OWC for each distinct wave configuration per single wave. Additionally, MATLAB is utilized to create visual representations of the results, enabling a comparative assessment of the OWC device's effectiveness across diverse conditions.

3.1 Experimental Setup

The experiments took place within a basin situated at the COAST lab in the University of Plymouth. All necessary safety protocols were met, including the completion of risk evaluations prior to commencing the experiments (refer to Appendix D). **Figure 3-1** provides an overview of the OWC apparatus incorporated into a vertical breakwater structure, accompanied by wave measurement instruments in its vicinity, all within the confines of the small basin designed for wave generation.



Figure 3-1: General View of Experimental Setup With Breakwater (A), and Empty Basin Test Setup (B)

The distance between the wave paddles and the vertical breakwater measured seven meters. An orifice plate was affixed to the OWC chamber, and an internal pressure sensor was employed within the chamber to monitor fluctuations in air pressure throughout various tests and wave configurations. Among the six wave gauges, one was positioned within the chamber to observe internal water movement, while the remaining five were situated outside the breakwater system (see Figure 3-2). The whole setup was connected to a computer equipped with the suitable software, enabling the generation of either regular or irregular waves based on user preferences.

Furthermore, both the pressure sensor data and wave motion could be simultaneously observed through distinct software interfaces. Within this experimental setup, a scale factor of 1:50 was adopted. The dimensions of the entire setup, the placements of the pressure sensor and wave gauges, as well as the distances between the wave gauges and the OWC, are all depicted in **Figure 3-2**. As seen in that illustration, 3 of 6 wave gauges are surrounding the OWC device, one wave gauge is placed on the incoming direction, one wave gauge is embodying to the vertical breakwater and the last remaining wave gauge is inside to measure the water fluctuations inside the chamber. The OWC device has 40 cm of diameter, and a 27 cm of bottom opening while the upper part of device is 24 cm of height, which makes in total, 51 cm of device height. The vertical breakwater is 61 cm in the setup.

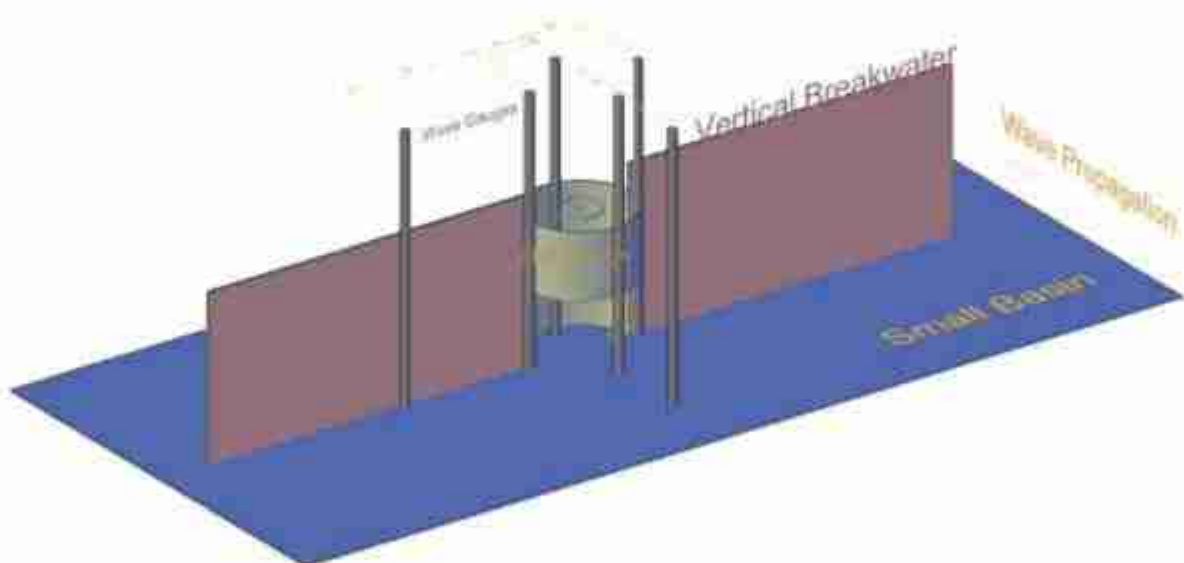


Figure 3-2: General Positions of the Experimental Setup Components

For the purposes of this study, regular waves were generated using wave paddles under designed conditions. A total of 143 different wave setups were run when the OWC device with a breakwater was present, and ninety-nine empty basin tests were conducted without the breakwater and OWC system. All tests were executed

through software for a duration of 60 seconds, with a sampling rate of 128 hertz. Additionally, an extra 30-second recording period was included to observe any further pressure fluctuations after each test. Table 2 provides a comprehensive list of the wave setups and their corresponding test numbers to enable easy tracking of wave setups and avoid confusion. For instance, the test number 053 represents the case of when the wavemaker generated waves with 1.76 Hz, with 0.025 m wave amplitude, with default orifice size 20 mm, default water depth 40 cm, and default wave angle 0 degrees. On the other hand, the empty basin test numbers are not listed in this table to avoid confusion. They were specifically conducted to replicate wave conditions in the absence of a breakwater, enabling the calculation of Incident Wave Power.

	Tests varied in Wave Amplitude (in mm): Orifice size is 20 mm, Wave angle is 0, and water depth is 40 cm					Tests varied in Wave Angle (in degrees): Wave Amplitude is 0.01m, Orifice is 20 mm, and Water Depth 40 cm			Tests varied in Orifice Size (in mm): Wave amplitude is 0.01 m, Wave angle is 0, and Water Depth is 40 cm				Tests varied in Water Depth (in cm): Wave Amplitude is 0.01 m, Wave Angle is 0, Orifice size is 20 mm
Freq	5	10	15	20	25	5	10	15	10	14	26	30	30
0.63 Hz	001	012	023	034	045	056	067	078	089	100	111	122	133
0.87 Hz	002	013	024	035	046	057	068	079	090	101	112	123	134
1.06 Hz	003	014	025	036	047	058	069	080	091	102	113	124	135
1.22 Hz	004	015	026	037	048	059	070	081	092	103	114	125	136
1.36 Hz	005	016	027	038	049	060	071	082	093	104	115	126	137
1.47 Hz	006	017	028	039	050	061	072	083	094	105	116	127	138
1.57 Hz	007	018	029	040	051	062	073	084	095	106	117	128	139
1.67 Hz	008	019	030	041	052	063	074	085	096	107	118	129	140
1.76 Hz	009	020	031	042	053	064	075	086	097	108	119	130	141
1.85 Hz	010	021	032	043	054	065	076	087	098	109	120	131	142
1.93 Hz	011	022	033	044	055	066	077	088	099	110	121	132	143

Table 2: Test naming Matrix with four groups of parameters and the frequencies.

3.2 Definition of Scenarios

The definition of Scenarios is thought to help provide a better understanding regarding the results under similar conditions, as it is crucial to appreciate the consequences of

the varied conditions precisely in this experiment. There are four different groupings that make up the scenarios. The following default criteria were initially chosen before tests :

- Wave Amplitude : 0,01 m
- Wave Angle : 0 degrees (perpendicular to the breakwater)
- Orifice Size : 20 mm
- Water Depth : 40 cm

In addition to these numbers, 143 other scenarios are generated using the following scenario groups and thirteen different wave settings, each of them has eleven frequencies. (see Table 2 for test number list with frequencies).

3.2.1 Wave Amplitude Scenarios

Within this specific set of experiments, the primary focus is the exploration of how variations in wave amplitude impact the functioning of the Oscillating Water Column (OWC) device. There exists a working hypothesis asserting that alterations in wave amplitude exert an influence on the operational efficiency of the OWC system (Li et al. 2023). For this experimental study, a standardized amplitude of 0.01 meters, as introduced into the wavemaker software, has been designated as the default. In conjunction with this standard amplitude, various alternative wave amplitudes, referred to as target amplitudes, have been introduced into the investigation. These include amplitudes of 0.005 meters, 0.015 meters, 0.02 meters, and 0.025 meters, respectively.

Consequently, these experiments encompass the generation of 55 distinct wave scenarios. Each of these scenarios is characterized by a unique combination of the

five wave amplitude values mentioned above, and these wave scenarios are analysed across a total of eleven different frequencies. The aim is to comprehensively assess and understand the intricate interplay between wave amplitude variations and the performance of the OWC device, providing valuable insights into its operational efficiency under various conditions, regarding wave amplitude.

3.2.2 Wave Angle Scenarios

This experimental setup also explores the impact of wave angles by introducing varying wave angle configurations. In most of the experiments, the tests take place within a flume tank due to its feasibility, where it is not possible to adequately capture the influence of wave angles on OWC devices. Therefore, the presence of a spacious 3D environment in this test allows for the generation of waves at specific angles to investigate wave angle impacts.

As a result, the default angle of 0 degrees is selected, indicating that the generated waves approach the breakwater in a perpendicular direction. Meanwhile, other angle scenarios are examined, encompassing wave angles of 5 degrees, 10 degrees, and 15 degrees. In total, thirty-three tests are conducted to systematically assess the effects of wave angles on the efficiency of the OWC system.

3.2.3 Orifice Size Scenarios

Within an Oscillating Water Column (OWC) device, the orifice, also referred to as the orifice plate during experimental phases, emerges as a component of paramount importance, necessitating meticulous selection. Due to its significant impact on the overall efficiency of the OWC system, the dimensions of the orifice size have become a prominent subject of discussion concerning OWC Wave Energy Converter (WEC)

devices (Ning et al. 2016). Additionally, it is noteworthy that previous research, exemplified by the work of Sheng et al. (2012), has revealed the absence of a linear correlation between the size of the orifice and both the exemption of airflow and OWC efficiency.

In the current experimental configuration, a specific orifice size measuring 20 mm in diameter has been deliberately chosen, a dimension that equates to 1% of the total surface area encompassed by the cylindrical chamber. Concurrently, alternative orifice sizes of 10 mm, 14 mm, 26 mm, and 30 mm have been established. These respective dimensions correspond to fractional percentages of the total surface area of the cylindrical chamber, specifically 0.25%, 0.50%, 1.7%, and 2.25%.

The findings explained in the studies conducted by Sheng et al. (2012) and Ning et al. (2020) collectively advocate for the notion that the optimal areal ratio, which signifies the relationship between the orifice area and the chamber surface area, typically falls within the range of 0.5% to 2% and 1.5% to 2%, respectively. Importantly, it is observed that these criteria are generally adhered to in the context of the experiments of this study. Consequently, this investigation encompasses the comprehensive evaluation of forty-four distinct wave tests, primarily aimed at discerning the implications stemming from variations in orifice size, while keeping all other conditions unaltered at their default settings of the orifice size with other default conditions.

3.2.4 Water Depth Scenario

The depth of water within the basin represents another critical parameter, impacting both the wave characteristics generated by the software and the submergence depth of the OWC device. Consequently, it is clear that water depth plays a significant role

in the efficiency of the OWC device in these experiments. To address this, a default water depth of 40 cm was chosen, resulting in a submergence depth of 13 cm. Additionally, a secondary condition with a water depth of 30 cm was defined, leading to a submergence depth of 3 cm.

3.3 Processing the Data and Calculation Methods

A total of 242 experiments were conducted in the basin, resulting in the generation of 143 Free Surface Elevation files and 143 Pressure files in *.txt and *.lvm formats, respectively, and 99 Empty Basin Free Surface Elevation files, in *.txt format. These files were synchronized with the same time array. A systematic labelling approach was applied to ensure clarity and prevent confusions for future ease of use. MATLAB was utilized for data processing, calculation, and visualization. For a comprehensive understanding of the procedures, refer to the detailed MATLAB script provided in Appendix A, which includes explanatory notes.

The determination of pneumatic power (P_p) harnessed from the OWC chamber can be computed through various approaches employing surface elevation and pressure data. The subsequent equation (1) is employed to evaluate the power output produced by the OWC device, and a comprehensive explanation is provided in the work of Mahnamfar, et al. (2015).

$$P_p = \frac{1}{N.T} \int_{t_2}^{t_2} p q \, dT \quad (1)$$

In this context, (p) denotes the instantaneous pressure, and (q) represents the airflow passing through the orifice. Both parameters can be estimated using the dataset gathered from 143 experimental cases, each corresponding to specific frequencies.

The integration boundaries are defined by the selected time window during the testing phase for computation.

This study assumes that the fluid (air) within the OWC chamber is incompressible. Therefore, any compressed air generated by wave oscillations within the chamber exits without any loss of volume. Additionally, it is accepted that the velocity of the water column inside the chamber is equal to the velocity of the airflow passing through the orifice. Following this straightforward approach, the airflow quantity is determined by multiplying the velocity of the water surface (v) by the surface area of the chamber (A_c). Consequently, the following equation is applied to calculate the instantaneous airflow (q) based on the provided free surface elevation data.

$$v = \frac{\eta_{i+1} - \eta_i}{\Delta t} \quad (2)$$

$$q = vA_c \quad (3)$$

In these equations, η_i indicates the free surface elevation in the $(i)th$ time step. Once the free surface elevation velocity inside the chamber is found, the airflow can be derived since the chamber surface area (A_c) is known and fixed.

Subsequently, the instant power ($P_i = pq$) is obtained by multiplying the instantaneous airflow (q) and pressure (p) values, as indicated in equation 1. The cumulative total power is then determined by integrating this instantaneous power sum.

Following this, the total power is divided by the corresponding period and wave count (N) within the specified time window. This calculation yields the average power output per individual wave and named as pneumatic power (P_p). In this investigation, a wave count of ten ($N = 10$) was chosen for this purpose.

To assess the capture width ratio (ε_{owc}) under specific parameter settings, it is essential to compare the pneumatic power (P_p) generated by the device to the incident power (P_{inc}) delivered by the same wave conditions. This incident power is determined using the method outlined in (Çelik et al. 2019).

$$\varepsilon_{owc} = \frac{P_p}{P_{inc}B} \quad (4)$$

$$P_{inc} = \frac{1}{8} \rho_w g H_{inc}^2 C_g \quad (5)$$

In this equation, density of water (ρ_w), and gravitational acceleration (g), are fixed and known, group velocity (C_g) can be derived for each test by using the following formulas:

$$C_g = \frac{c}{2} \left(1 + \frac{2kh}{\sin(2kh)} \right) \quad (6)$$

$$c = \frac{\lambda}{T}, \quad \lambda = \frac{2\pi}{k}, \quad \omega = \frac{2\pi}{T} \quad (7)$$

$\omega^2 = gk \tanh(kh)$ by solving the dispersion relation equation iteratively, all required parameters are found to solve (5), except (H_{inc}) which is referred as incident wave height. In this regard, the empty basin tests were conducted in the basin, to generate the incident waves without the OWC system to be able to see how much power a

single wave can produce theoretically, and how amount of this power can be exerted by the OWC device when it exists. Thus, the incident wave height (H_{inc}) is the last parameter to complete the equation (5), which was calculated for each test from the free surface elevation data on MATLAB (see Appendix B).

Initially, it is imperative to assess the data quality and eliminate any extraneous noise within the dataset. Consequently, the application of a fitting curve that accurately models the actual free surface elevations over a specified time window is justified. Employing fitting curve techniques in MATLAB, the curve is designed to conform to a sinusoidal function, as elucidated in the comprehensive MATLAB script presented in Appendix B.

$$Func = A \cos(\omega t + \varphi) \quad (8)$$

In theory, the free surface elevation is ideally represented by the function (8), where (A) signifies the wave amplitude, (ω) denotes the angular frequency, and (φ) indicates the wave phase. These parameters vary concurrently over the same time array, forming a sinusoidal function. For the purposes of this study, this applies within the defined time window (commencing at the 20th second) for each test.

The primary objective is to derive the most accurate wave amplitude and wave phase values from this function that best match the measured free surface elevation curve. This alignment is sought for the specified time window and known angular frequency. Consequently, the amplitude determined by the script will equate to half of the incident wave height (H_{inc}), which is subsequently utilized in equation (5) to calculate the incident wave power in Excel (see Figure Appendix 1: The Wave Parameters and Calculation of Incident Wave Power).

Once the (P_p) and (P_{inc}) found from above, the capture width ratio (ε_{owc}) can be estimated for each test via following,

$$\varepsilon_{owc} = \frac{P_p}{P_{inc}B} \quad (4)$$

Here, Chamber Width (B) is the parameter to complete the equation (4). Since the incident wave power (P_{inc}) means the power generated by an individual wave per one meter, this value needs to be multiplied with the chamber width. Capture width ratios (ε_{owc}) are the final product of this experimental study, which shows the most and least efficient configurations to harness the wave power, regarding frequencies, wave angles, orifice sizes, and water depths, introduced as scenarios in chapter 3.1.

4 Results and Discussions

In this chapter, the experimental findings undergo evaluation, accompanied by a discussion of these results. To improve the comprehension of the results analysis, they are segmented into four sections, permitting a more comprehensive examination of the impact of each parameter set.

4.1 Free Surface Elevations

As outlined in Chapter 3, Free Surface Elevation (FSE) data constitutes one of the two pivotal parameter sets for evaluating the Capture width ratios (ϵ_{owc}) in this study. FSE values for the same wave conditions were measured twice for the sake of comparison. Initially, FSE data was collected to compute the airflow (q) in the presence of the OWC device. Subsequently, in the second phase, both the OWC device and the breakwater were removed, and empty basin tests were conducted. Consequently, the results from the FSE data are categorized into two distinct sections and analysed separately.

However, it is noteworthy that the wave amplitudes propagated in both cases (with OWC and without OWC) consistently fall below the target amplitudes specified by the wave generator software. In all scenarios, the actual wave amplitudes are notably smaller than the theoretical expectations. Nevertheless, this discrepancy does not impact the calculation process since the measured wave amplitudes are exclusively utilized to compute pneumatic power (P_p) and incident wave power (P_{inc}) for all scenarios, thereby determining the Capture width ratios (ϵ_{owc}).

4.1.1 Free Surface Elevations with Breakwater Integrated OWC

The initial set of 143 experiments yielded both Free Surface Elevation (FSE) and Pressure data files, and subsequent visualizations were generated through MATLAB

processing (refer to Appendix A). A noteworthy observation from these visualizations is the presence of regular patterns in FSE fluctuations within the chamber under specific frequencies.

These visualizations comprise a total of eleven subplots, each depicting the alteration in surface elevation for a particular frequency range, spanning from 0.63 Hz to 1.93 Hz. The initial five figures highlight FSE variations within the chamber when the sole changing parameter was the wave amplitude (A). Subsequently, the following three figures represent the cases where the wave angle (θ) was the variable factor. The subsequent four figures illustrate changes under varying orifice sizes (R), while the last figure demonstrates the alteration in FSE when the water depth (h) deviated from the default 40 cm in the basin to 30 cm (see test naming matrix, Table 2).

The red framed window is representing the specified time window, from which the average power calculation derived for correspondent parameter set.

- **Wave Amplitude Impact and Discussions (Figure 4-1 to Figure 4-5)**

In these specific scenarios, it became evident that wave climates with higher frequencies, particularly those exceeding 1.35 Hz, did not generate regular patterns of Free Surface Elevation (FSE) fluctuations. Furthermore, at a frequency of 1.57 Hz, an unexpected phenomenon or a resonance occurred: in all wave amplitude (A) conditions, FSE consistently demonstrated linear increases and decreases during the wave propagation from the paddles. This behaviour deviates from the patterns observed in other frequency conditions and needs to be addressed by further investigations.

For wave climates characterized by frequencies higher than 1.57 Hz, irregular FSE fluctuations are predominantly generated within the chamber. Additionally, the amplitude of piston motion was notably smaller compared to scenarios with lower-frequency waves. To illustrate, in a case with a frequency of 0.87 Hz and a target amplitude of 0.005 m, the maximum FSE amplitude within the chamber reached 0.002 m. In contrast, in a scenario with a frequency of 1.85 Hz and the same target amplitude, the corresponding FSE amplitude was approximately 0.0006 m (refer to Figure 4-1).

In summary, it was anticipated that the OWC device produced significantly lower airflow (q) through the orifice at higher frequencies. Additionally, the increase of wave amplitude resulted in the increase of the velocity of the water inside the chamber, which means the increase of airflow.

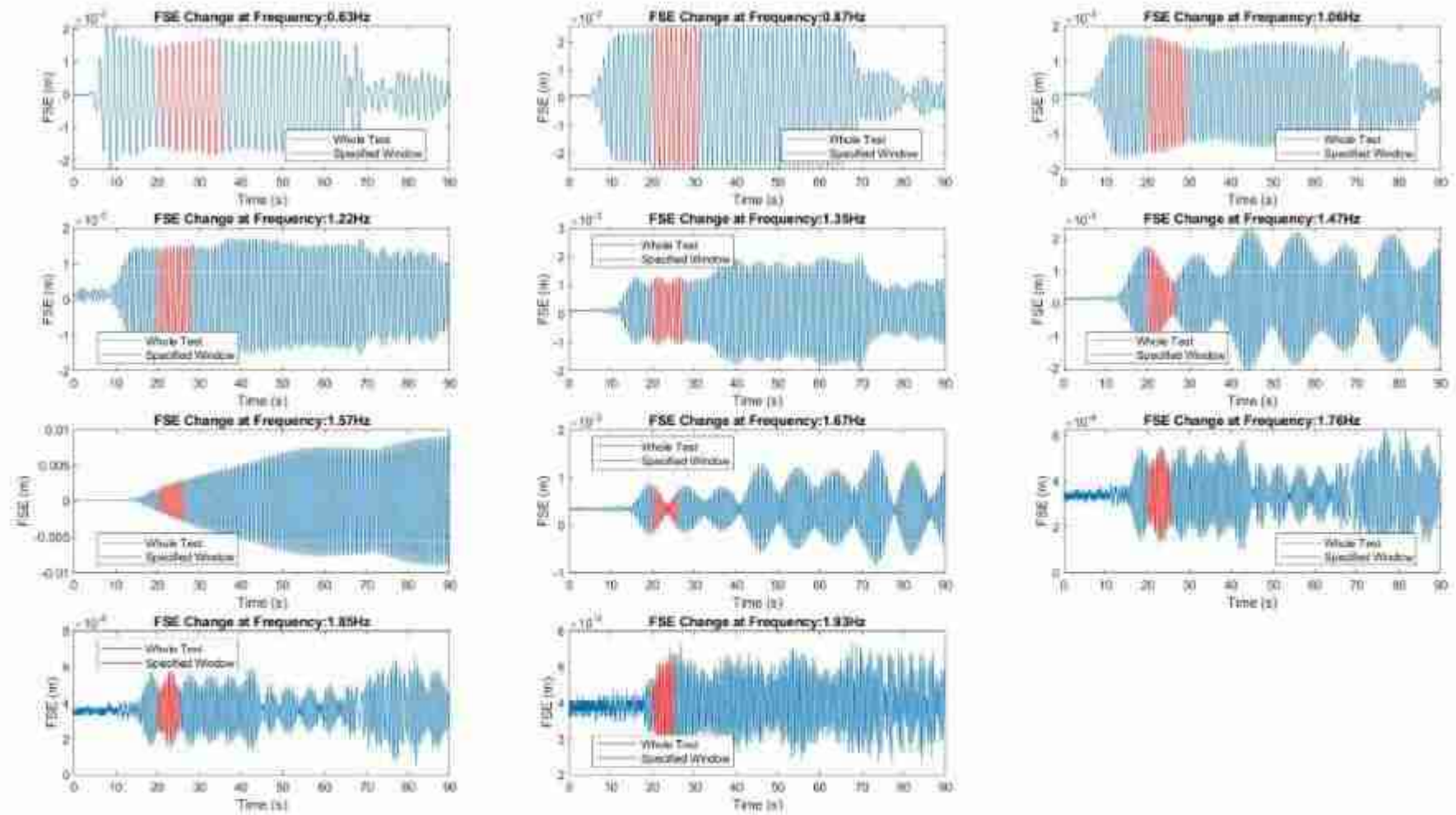


Figure 4-1: FSE change: wave amplitude=0.005 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

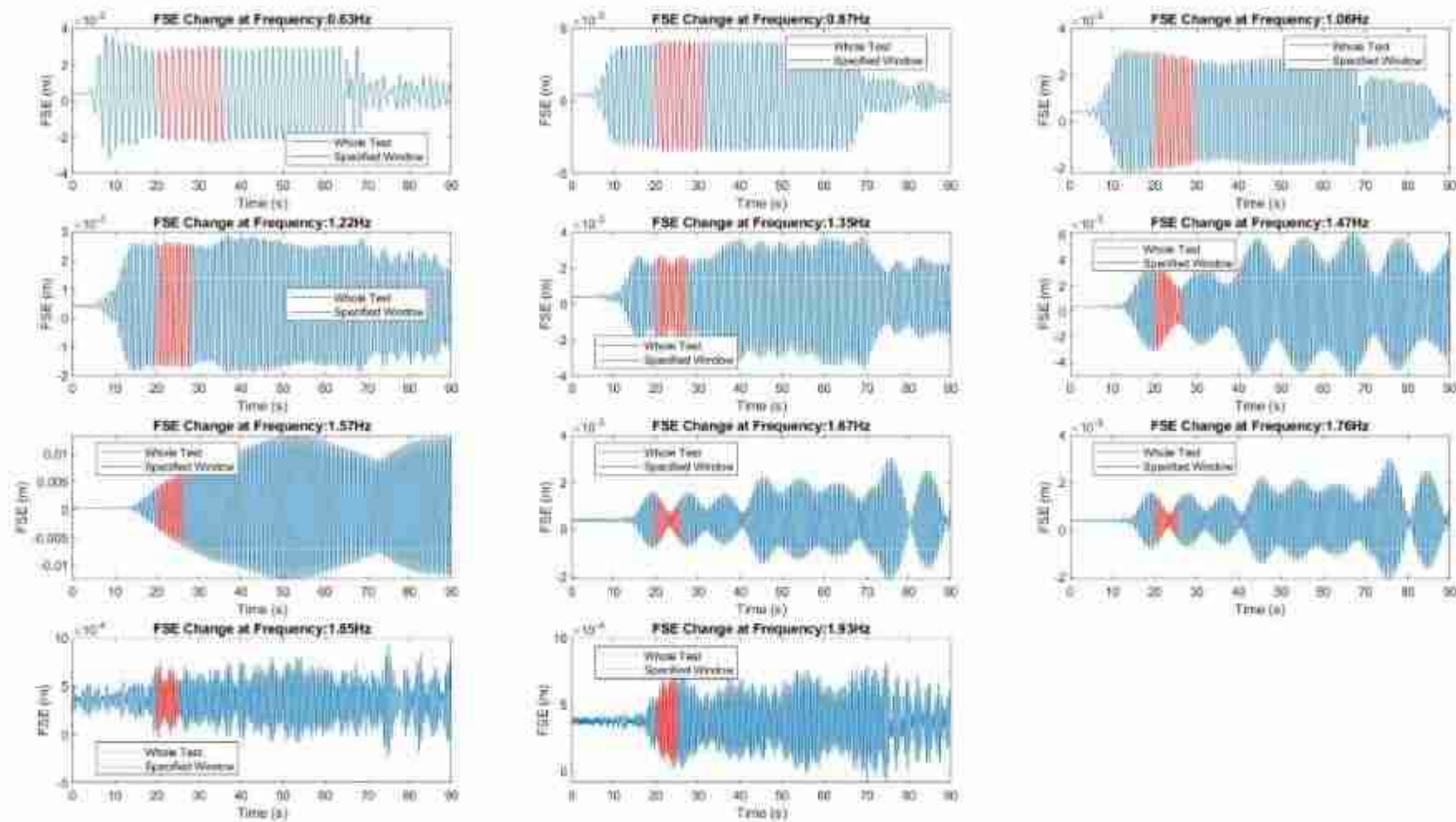


Figure 4-2: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

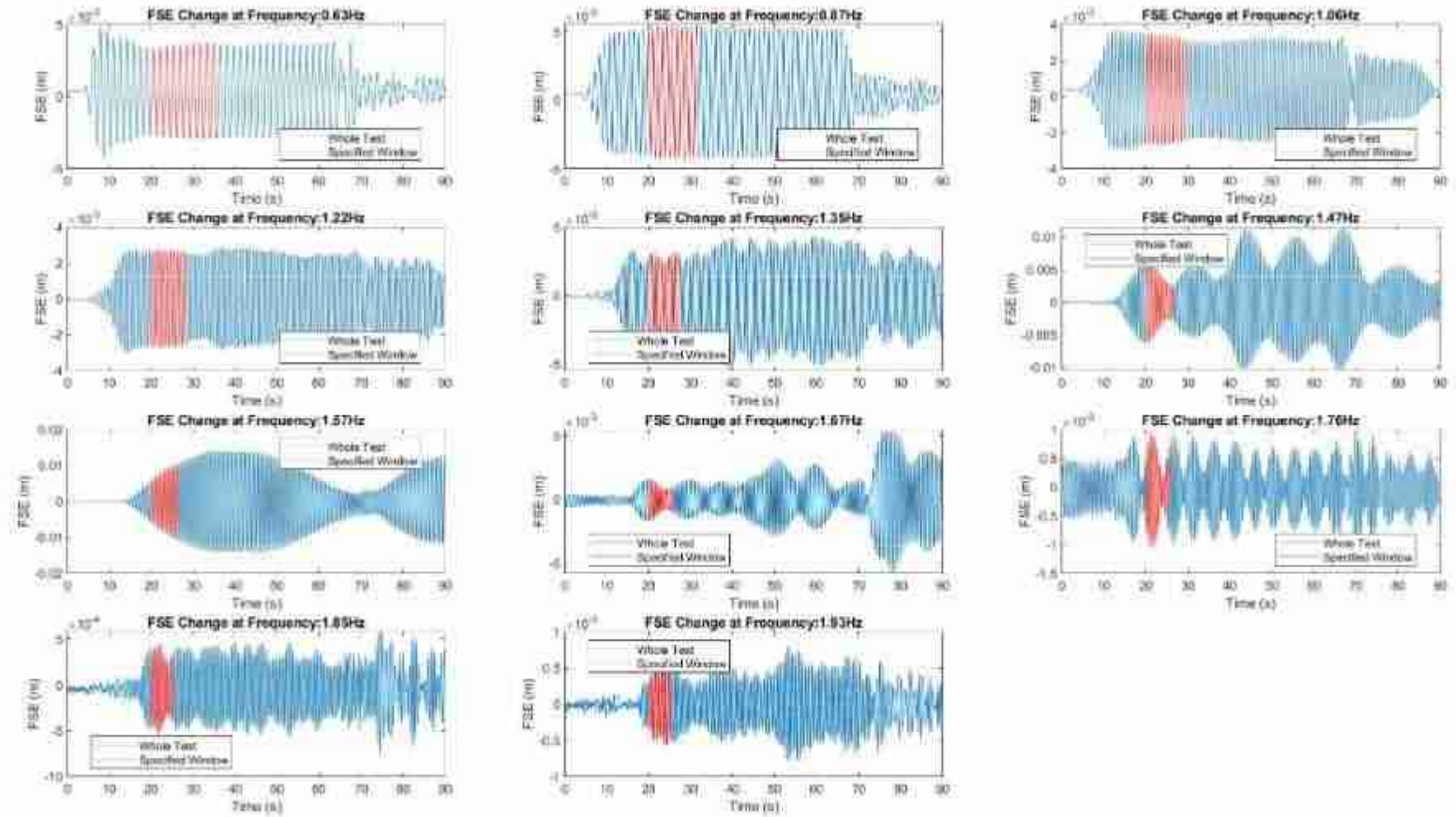


Figure 4-3: FSE change: wave amplitude=0.015 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

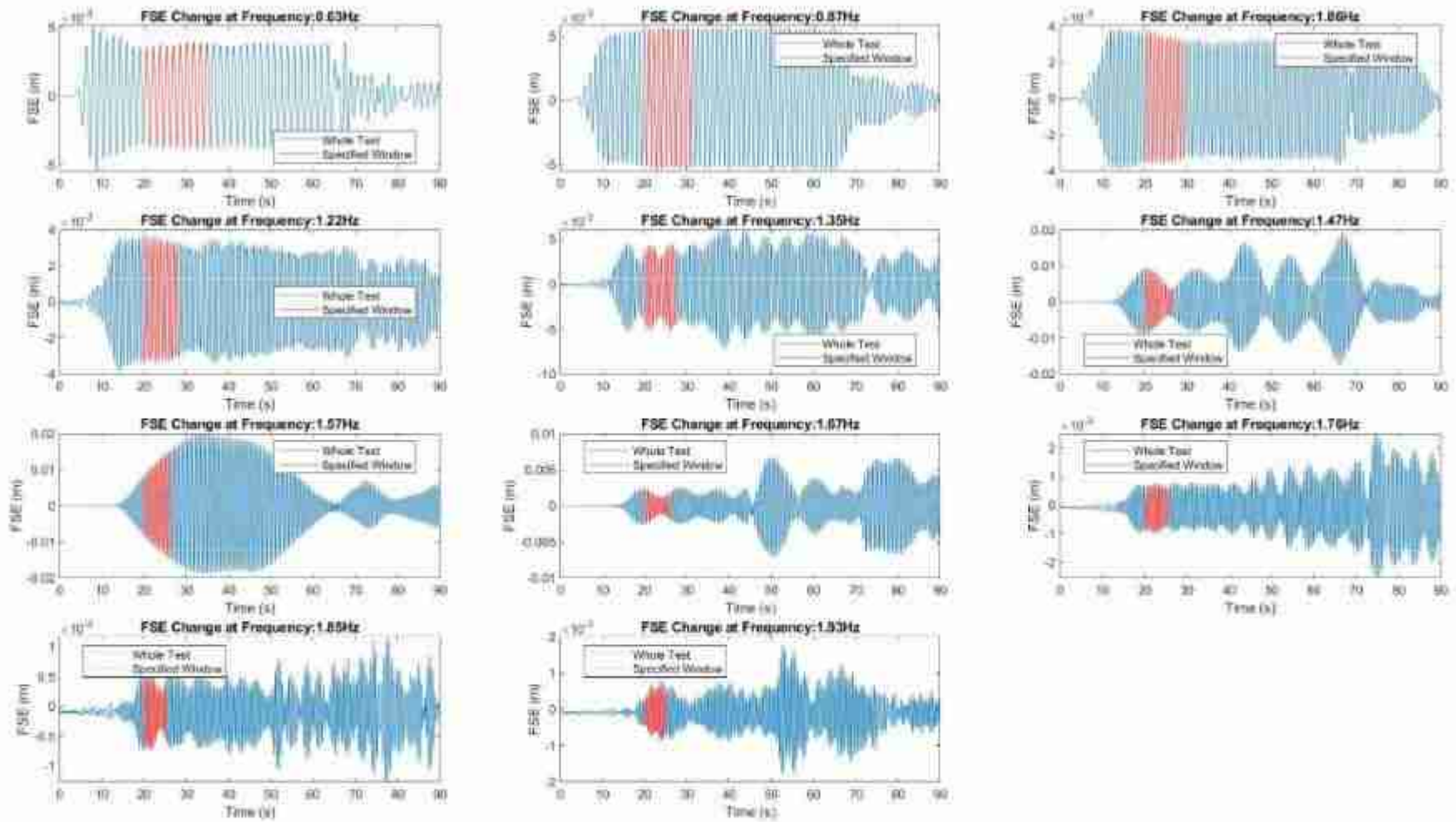


Figure 4-4: FSE change: wave amplitude=0.02 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

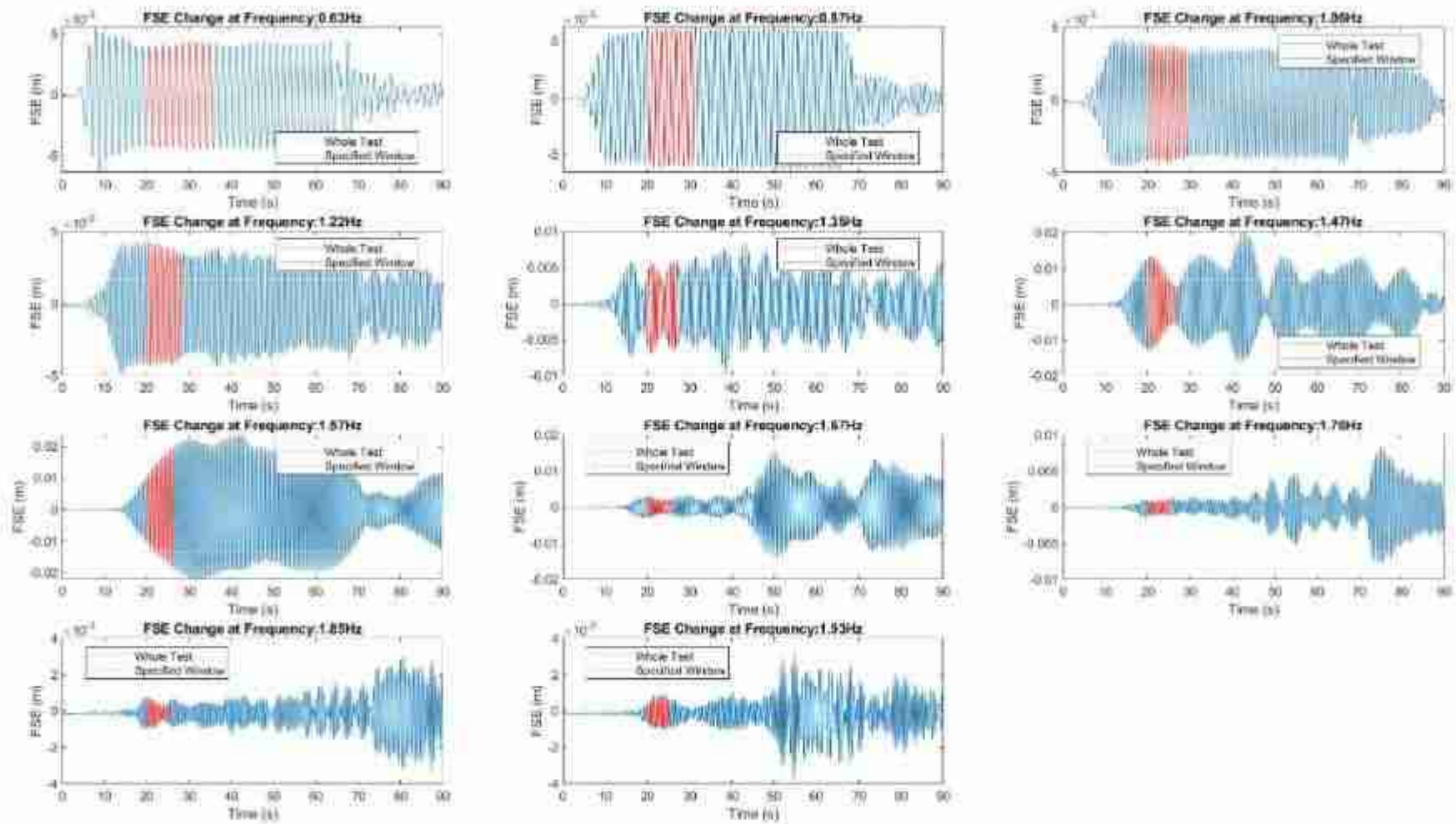


Figure 4-5: FSE change: wave amplitude=0.025 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

- **Wave Angle Impact and Discussions (Figure 4-6 to Figure 4-8)**

Investigating the wave angle (θ) effect on OWC device efficiency is a crucial phenomenon as the experimental tests with OWC devices are generally conducted without breakwater integration or in a flume, which was mentioned in previous section. Therefore, the results of wave angle setups were carefully observed throughout the experimental tests. In FSE terms, the wave angles in general did not make a significant difference when it was compared to the default perpendicular wave propagation, as expected. For instance, in the case of 1.22 Hz wave frequency, the perpendicular waves generated 0.002-0.0025 m of FSE amplitude inside chamber (see Figure 4-2), whereas the same frequency waves were generated 0.002 m of FSE amplitude for 5, 10, 15 degrees of wave angle setups. Moreover, it is worth noting that in certain test cases, the Free Surface Elevation (FSE) values turned out to be negative due to calibration issues within the test environment. These discrepancies should ideally be identified and rectified through various data quality checks before the data is processed in MATLAB. Nonetheless, in the context of this study, individual negative FSE values did not have influence in estimations. The consecutive changes in FSE amplitude over each time step, which represented the instantaneous velocity (v) of the water column within the chamber was used and exhibit positive amplitudes along with the pressure amplitudes (p). This calculation of instant power, as outlined in the MATLAB script provided in Appendix A, did not require the use of individual FSE values.

Consequently, it became evident that an increase in the wave angle did not lead to a substantial increase or decrease in the airflow discharged through the orifice by the OWC device.

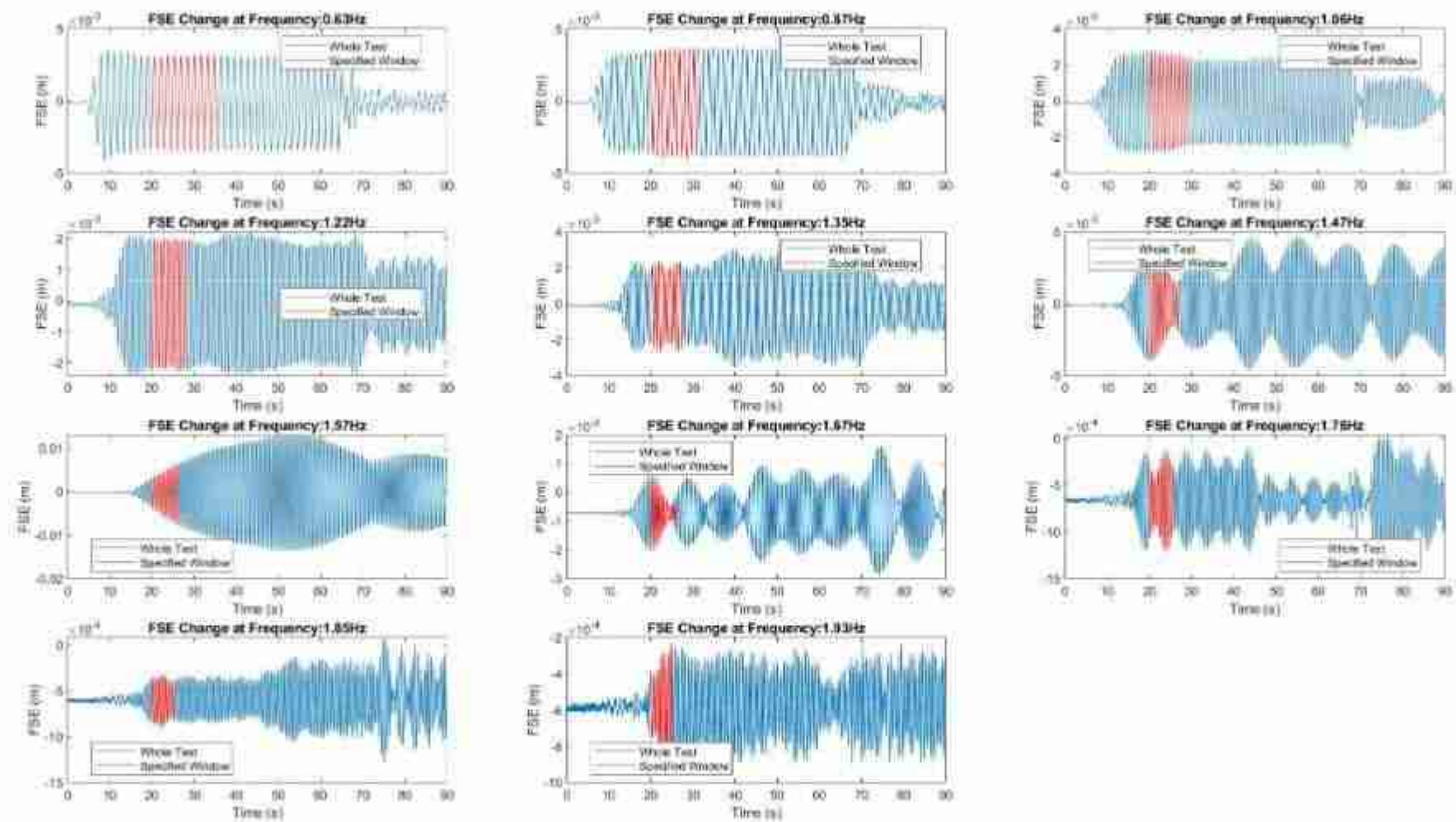


Figure 4-6: FSE change: wave amplitude=0.01 m, wave angle=5 degree, orifice=20 mm, water depth=40 cm

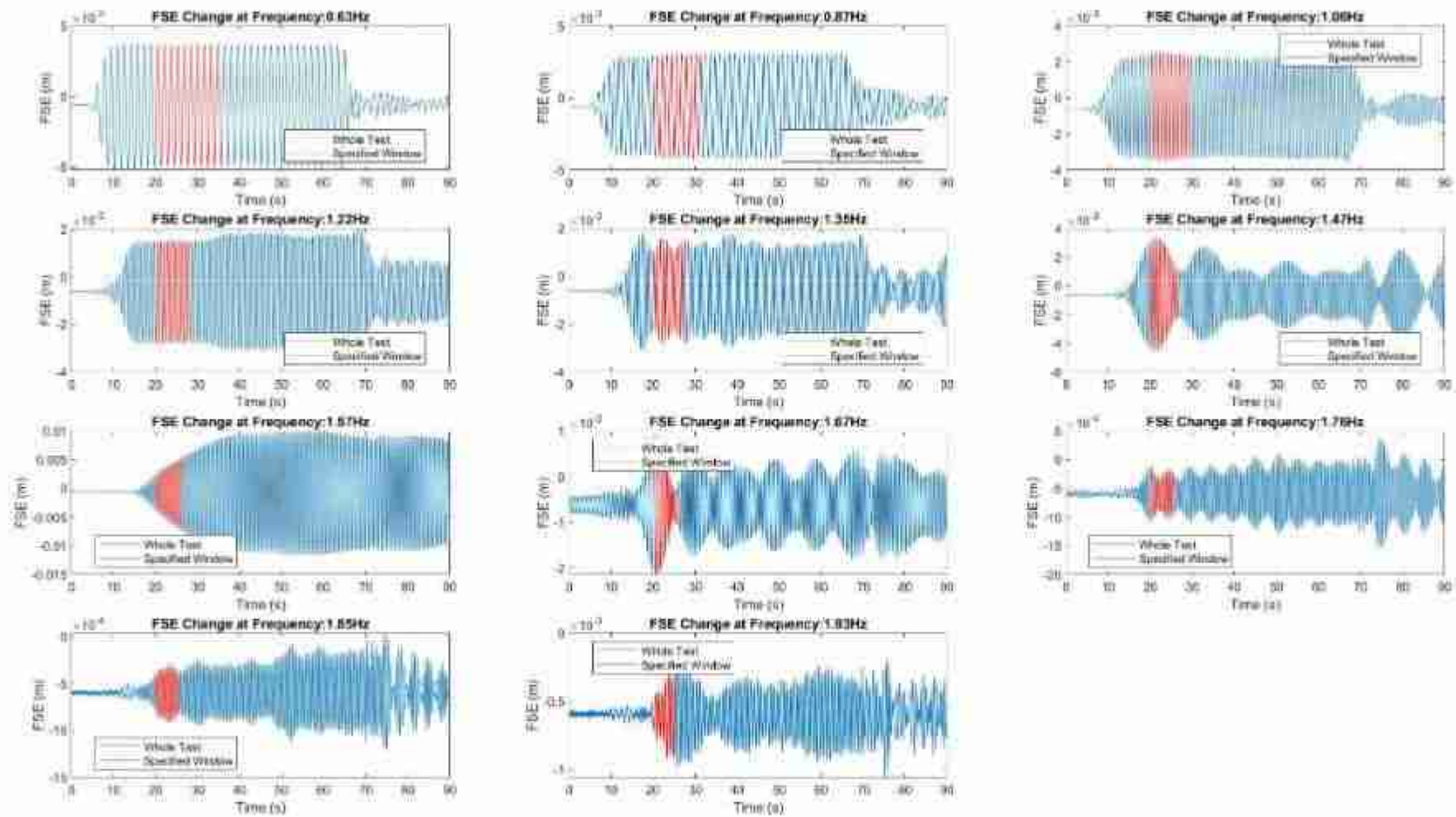


Figure 4-7: FSE change: wave amplitude=0.01 m, wave angle=10 degree, orifice=20 mm, water depth=40 cm

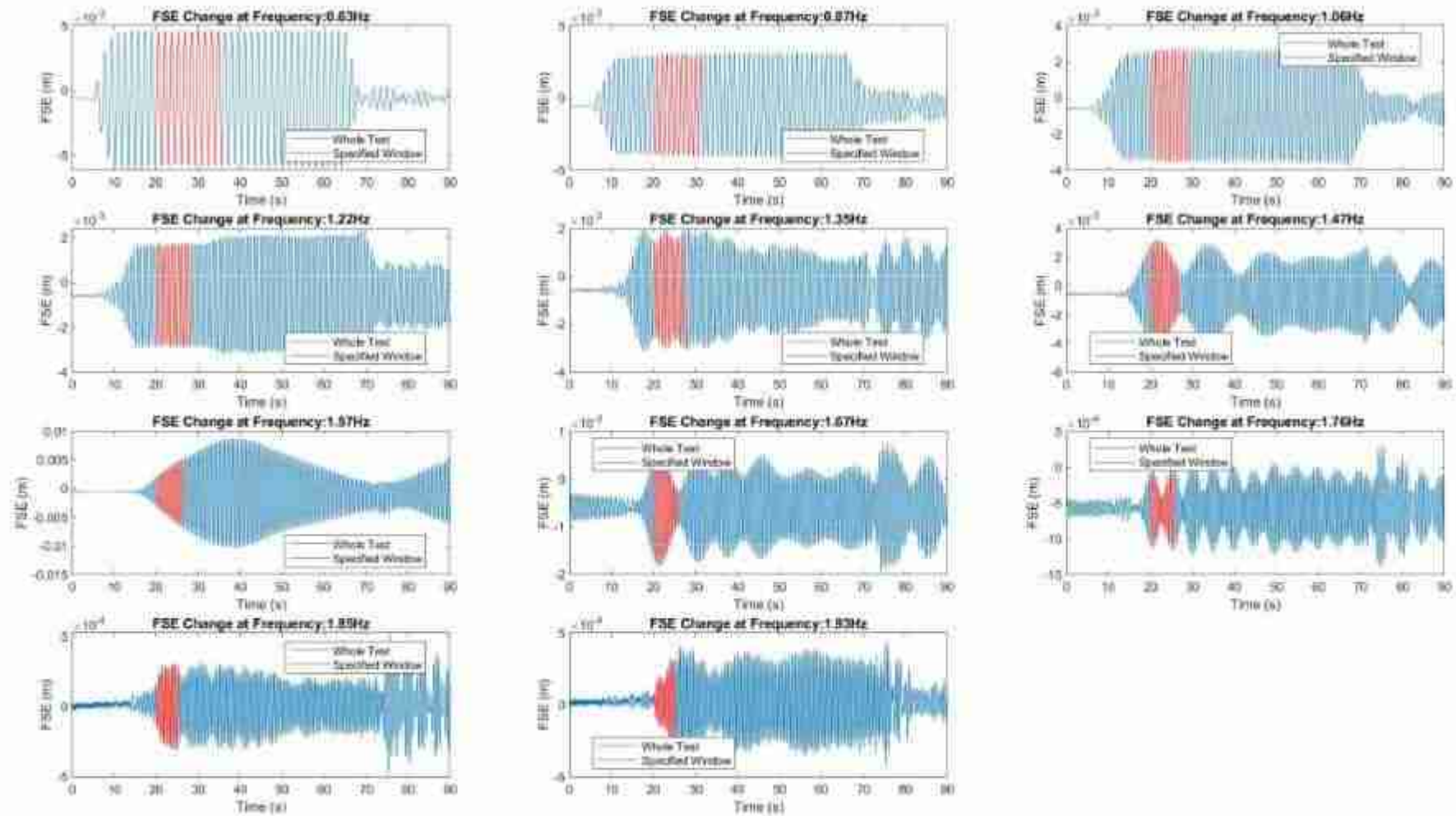


Figure 4-8: FSE change: wave amplitude=0.01 m, wave angle=15 degree, orifice=20 mm, water depth=40 cm

- **Orifice Size Impact and Discussions (Figure 4-9 to Figure 4-12)**

The experimental results involving variations in orifice size (R) were also examined. In theory, altering the orifice size should not significantly impact the Free Surface Elevation (FSE) amplitudes within the chamber, as the orifice plate is not considered a part of the wave climate. This theoretical assumption held true for high-frequency wave climates. However, notable differences in FSE amplitudes were observed in lower-frequency wave climates.

For instance, in the case of 0.87 Hz frequency wave climates, FSE amplitudes ranged from 0.8-1 mm, 1.8-2 mm, 5-6 mm, and 6-7 mm for orifice sizes of 10 mm, 14 mm, 26 mm, and 30 mm, respectively. In contrast, for 1.85 Hz frequency wave climates, the FSE amplitudes remained consistently around 0.4 mm across all orifice sizes. Moreover, the FSE amplitudes for 0.87 Hz and 1.85 Hz wave conditions for the default orifice size (20 mm) was 3.5-4 mm and 0.4 mm, respectively. Consequently, it was evident that the increase of the orifice size resulted in the increase of the FSE amplitudes in lower frequency (less than 1.35 Hz) conditions. On the contrary, the FSE amplitudes remained at same level for all orifice sizes with the cases which has a frequency larger than 1.35 Hz.

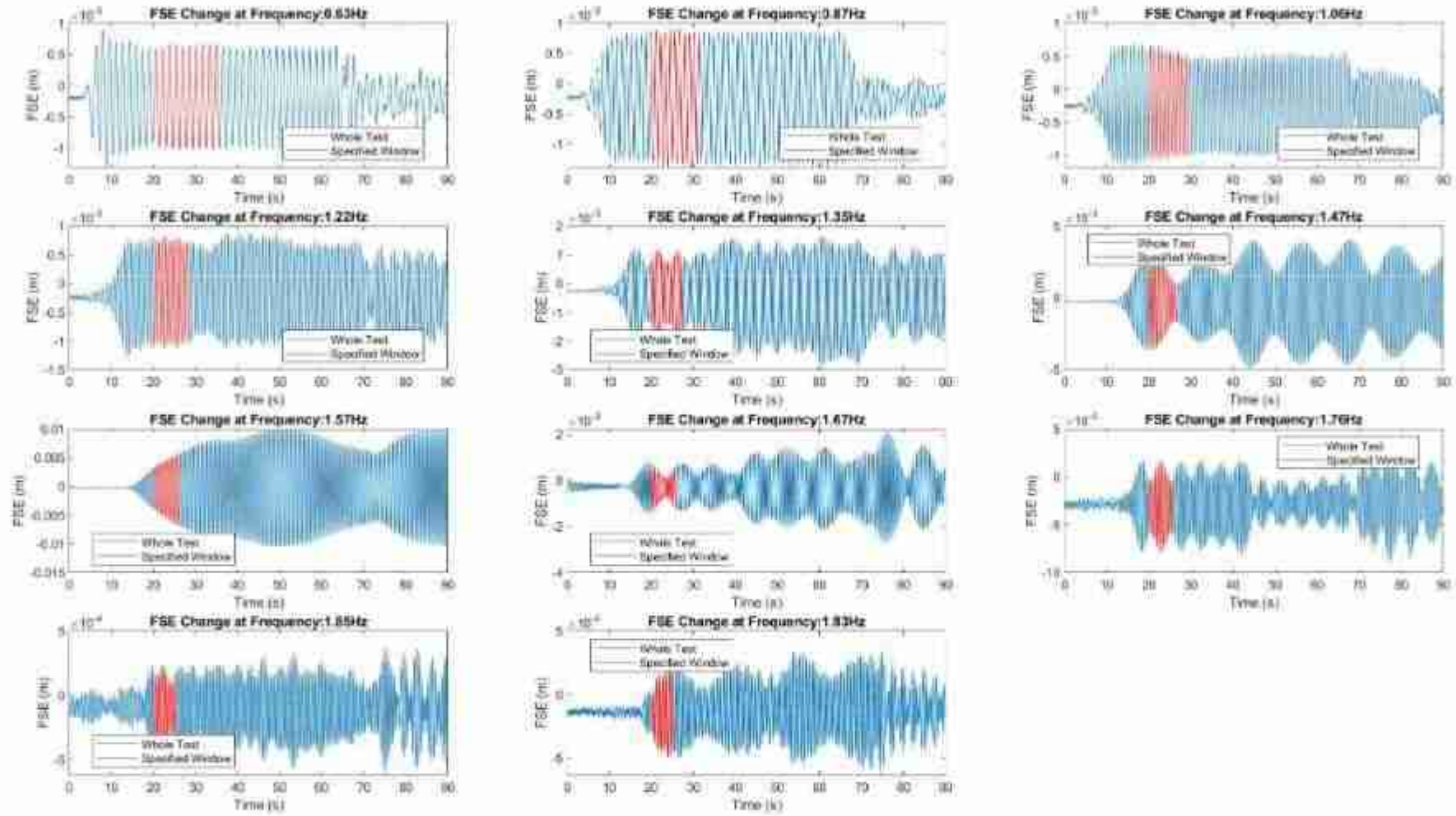


Figure 4-9: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=10 mm, water depth=40 cm

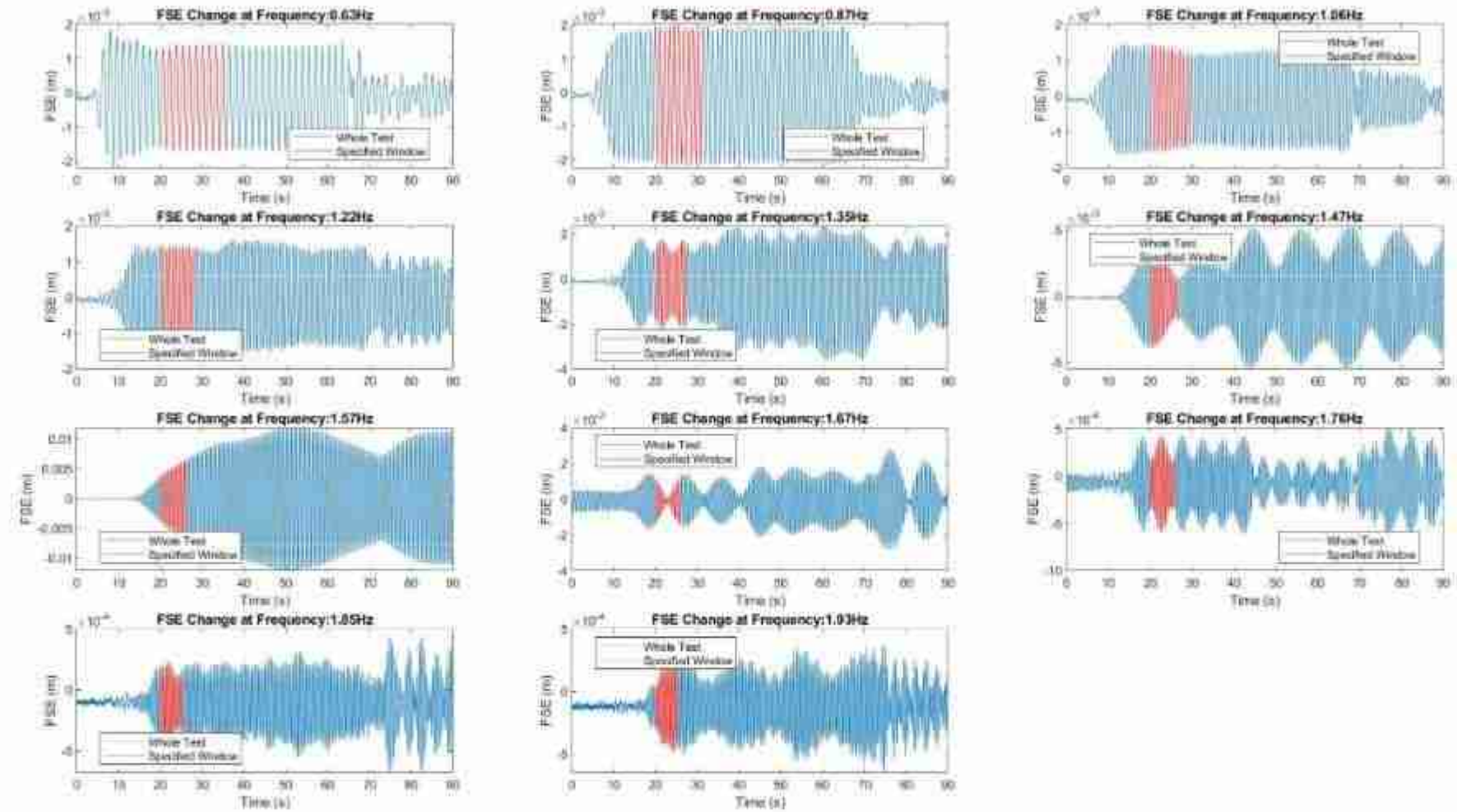


Figure 4-10: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=14 mm, water depth=40 cm

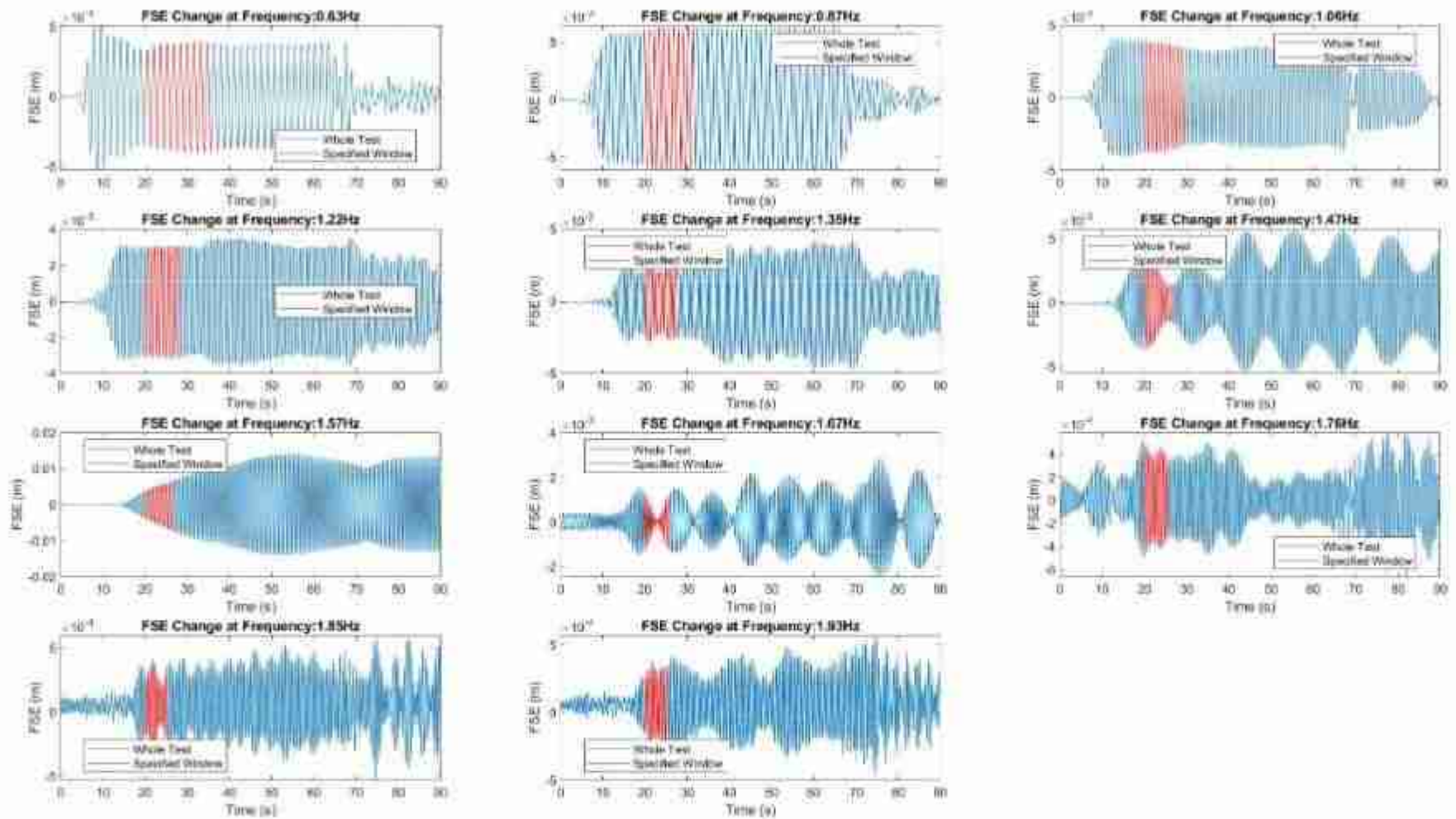


Figure 4-11: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=26 mm, water depth=40 cm

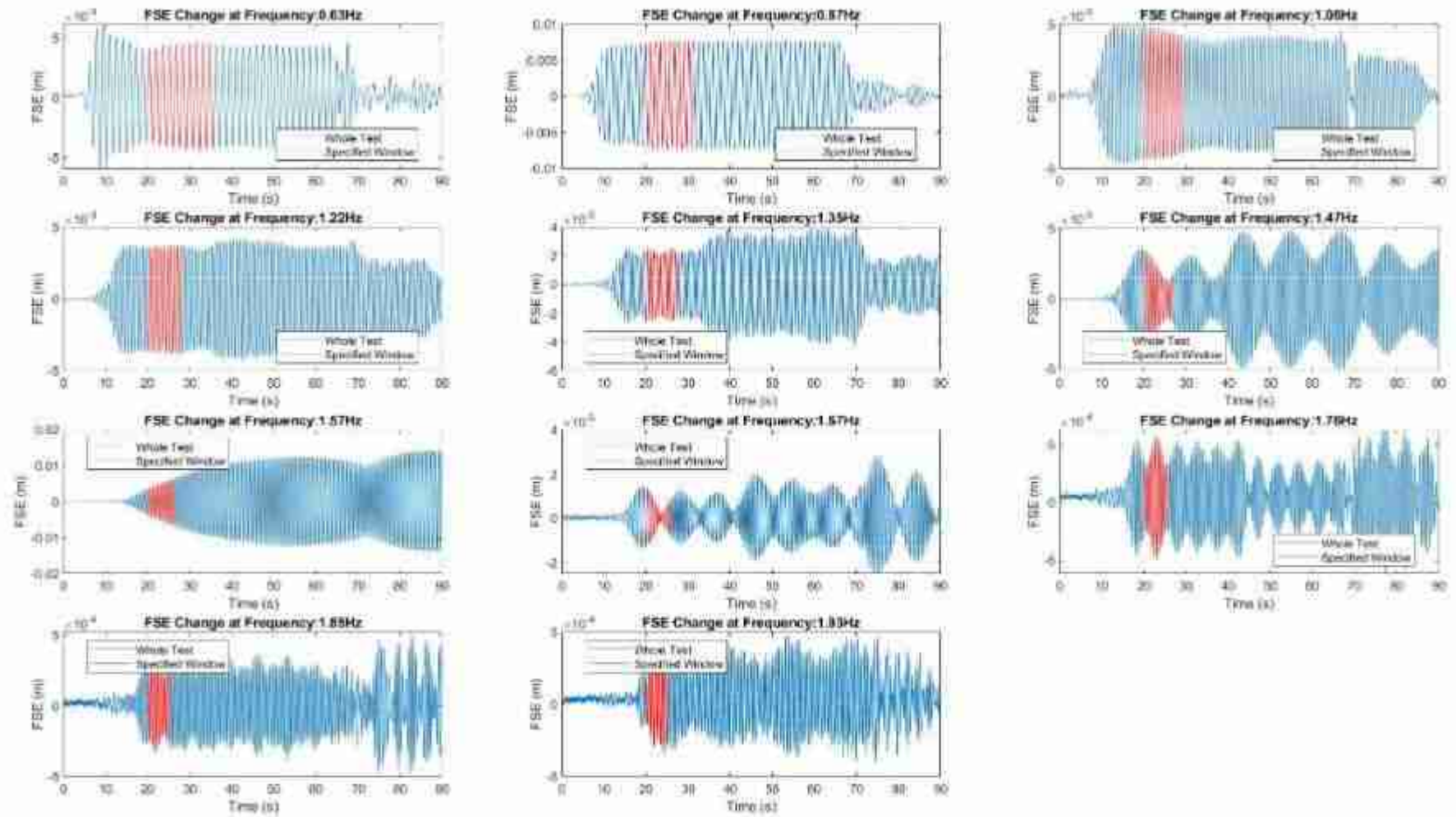


Figure 4-12: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=30 mm, water depth=40 cm

- **Water Depth Impact and Discussions (Figure 4-13)**

Alterations in water depth (h) were anticipated to significantly impact the efficiency of the OWC device (ε_{OWC}). Experiments showed that in many frequency ranges, a resonance phenomenon occurred, resulting in extremely large Free Surface Elevation (FSE) amplitudes within the chamber.

Among the eleven frequencies under investigation, even though the wave propagation from the paddles was limited to just 0.01 m for this particular wave climate, it is noteworthy that the wave conditions at frequencies of 1.47 Hz, 1.57 Hz, and 1.67 Hz resulted in extremely large Free Surface Elevation (FSE) amplitudes within the chamber, reaching heights of up to 0.04 m, 0.025 m, and 0.03 m, respectively. On the contrary, when considering low-frequency wave conditions (below 1.35 Hz) with this specific water depth (30 cm), the FSE amplitudes within the OWC were notably lower compared to the higher-frequency scenarios.

Overall, across all frequency wave climates, the FSE amplitudes observed with a water depth of 30 cm were substantially larger than those recorded in the default water depth of 40 cm conditions. In conclusion, the experiments highlighted that the water motion within the chamber was significantly more regular and larger in these scenarios compared to the default water depth (40 cm) wave conditions.

It is noteworthy that the generation of FSE amplitude in lower-frequency conditions (below 1.35 Hz) with two different water depths did not exhibit a dramatic difference. However, in the case of high-frequency wave climates (above 1.35 Hz), FSE amplitudes were notably reduced for the 40 cm water depth, while they substantially increased within the chamber under the 30 cm water depth conditions.

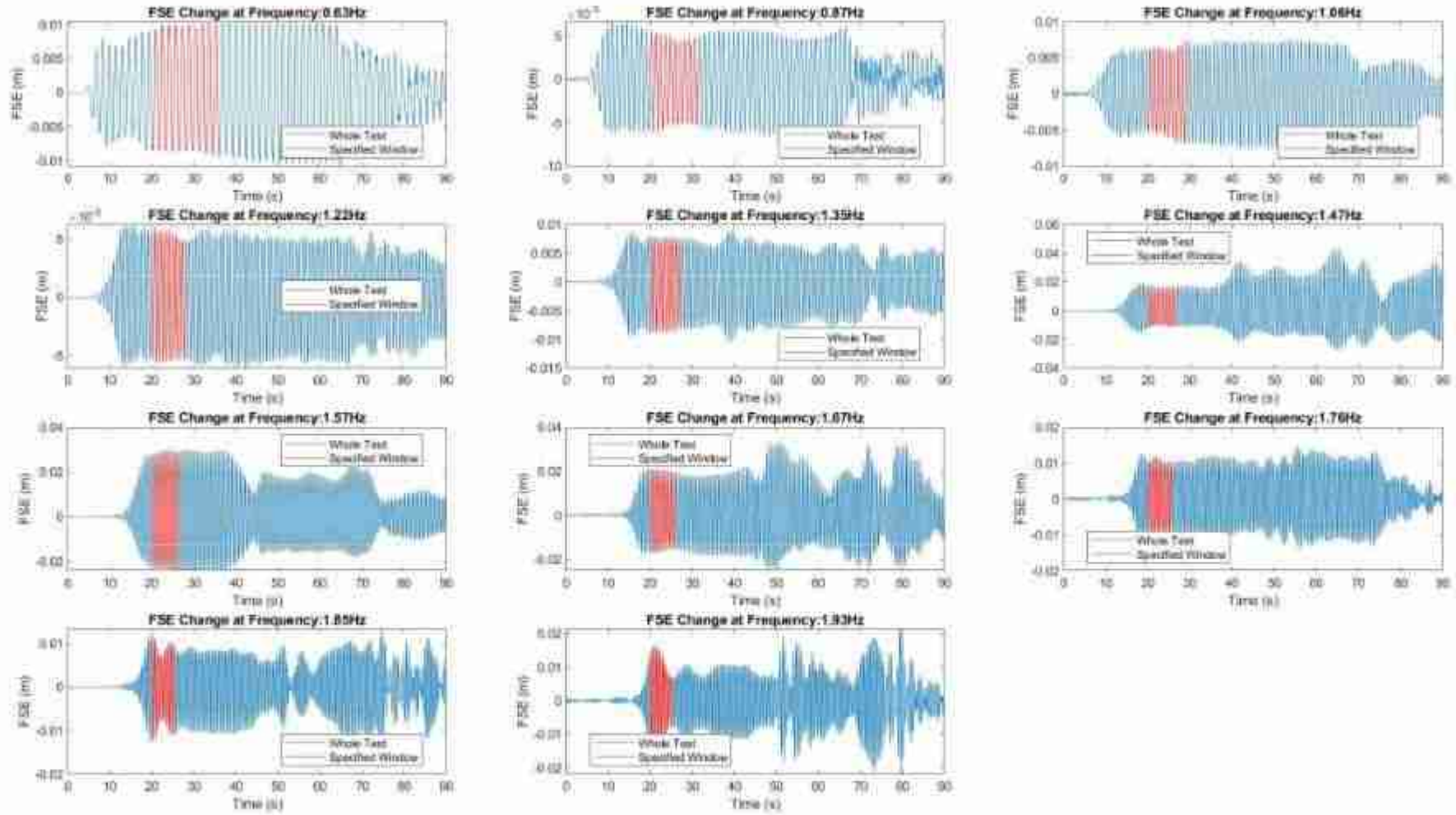


Figure 4-13: FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=20 mm, water depth=30 cm

4.1.2 Free Surface Elevations in Empty Basin

Empty basin tests are conducted to estimate the incident wave power (P_{inc}), without the OWC device and the breakwater system. It is expected to have more regular wave motion in this situation since nothing can generate reflections and standing waves around the wave measurers. The following figures are generated in MATLAB by using the fitting curve techniques to simulate the real experimental data, which is explained in chapter 3 in detail. The red curve represents the fitted curve, while the blue line is illustrating the real FSE data. The time array is on the x-axis, starting from the 20th second and ends in the moment where that certain frequency wave condition generates the amount of wave of wave count ($N = 10$), whereas the FSE amplitude is on the y-axis for both curves. In each figure, there are eleven subplots showing the FSE motion under different frequencies. The top and the bottom points of the curve give the wave amplitudes for that certain test set.

- **Wave Amplitude EB Tests and Discussions (Figure 4-14 to Figure 4-19)**

The target wave amplitudes were processed via the wavemaker software after removing the breakwater and OWC system. As mentioned, the aim to conduct the empty basin tests were only to measure the FSE amplitudes to derive the incident wave power (P_{inc}). The results of empty basin tests did not only allow users to estimate the required values, but also gave an insight about the performance and accuracy of the wavemaker system in varied conditions. As seen from the **Figure 4-15** to **Figure 4-19**, the measured FSE amplitudes were not close to the target wave amplitudes in terms of FSE. Additionally, it is evident that the low-mid frequency wave climates generated FSE amplitudes which were closer to the target wave amplitudes than the higher and lower frequency wave climates (see **Figure 4-14**). As an example,

across all fifty-five tests conducted, the waves with a frequency of 1.93 Hz consistently fail to attain even half of the specified target amplitudes. Conversely, waves with a frequency of 1.22 Hz consistently achieve nearly the designated target wave amplitudes. In summary, the empty basin tests indicated that an augmentation in wave amplitude (A) led to a corresponding rise in Free Surface Elevation (FSE) amplitude, consequently resulting in an increase in Incident Wave Power (P_{inc}) across all frequency wave conditions.

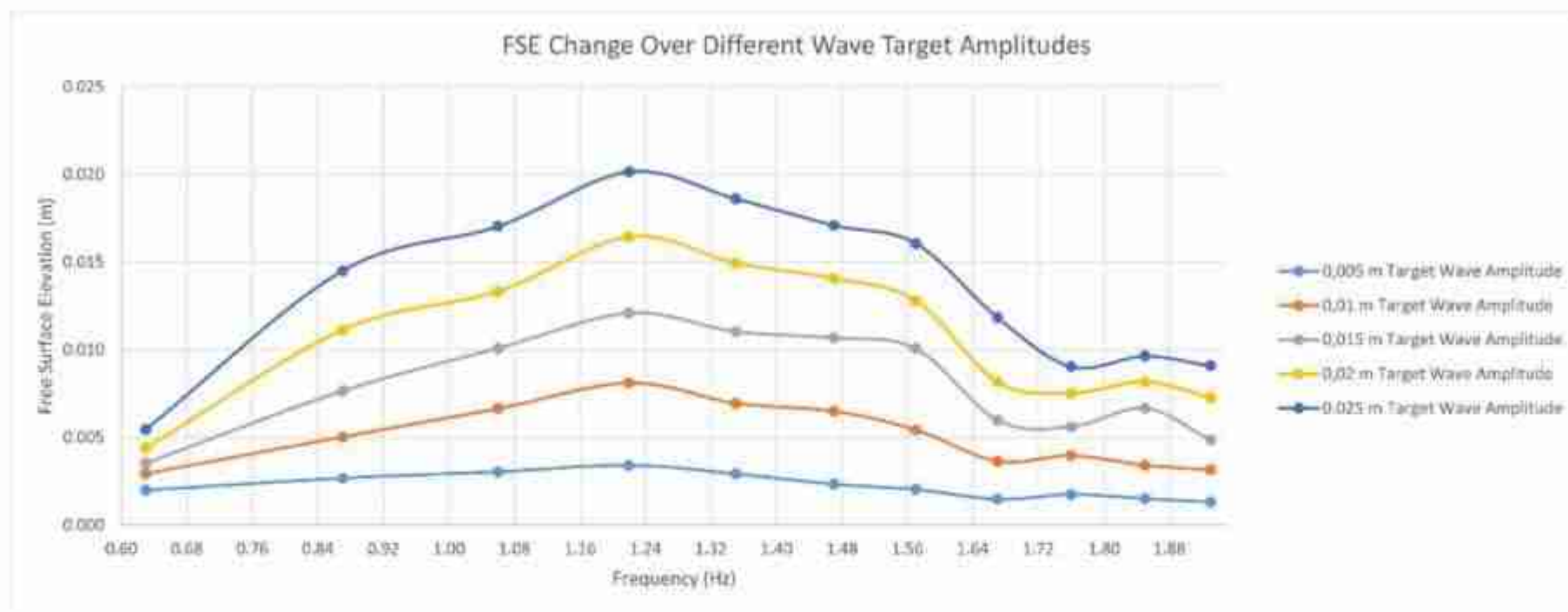


Figure 4-14: Empty Basin Wave Amplitude Tests Results

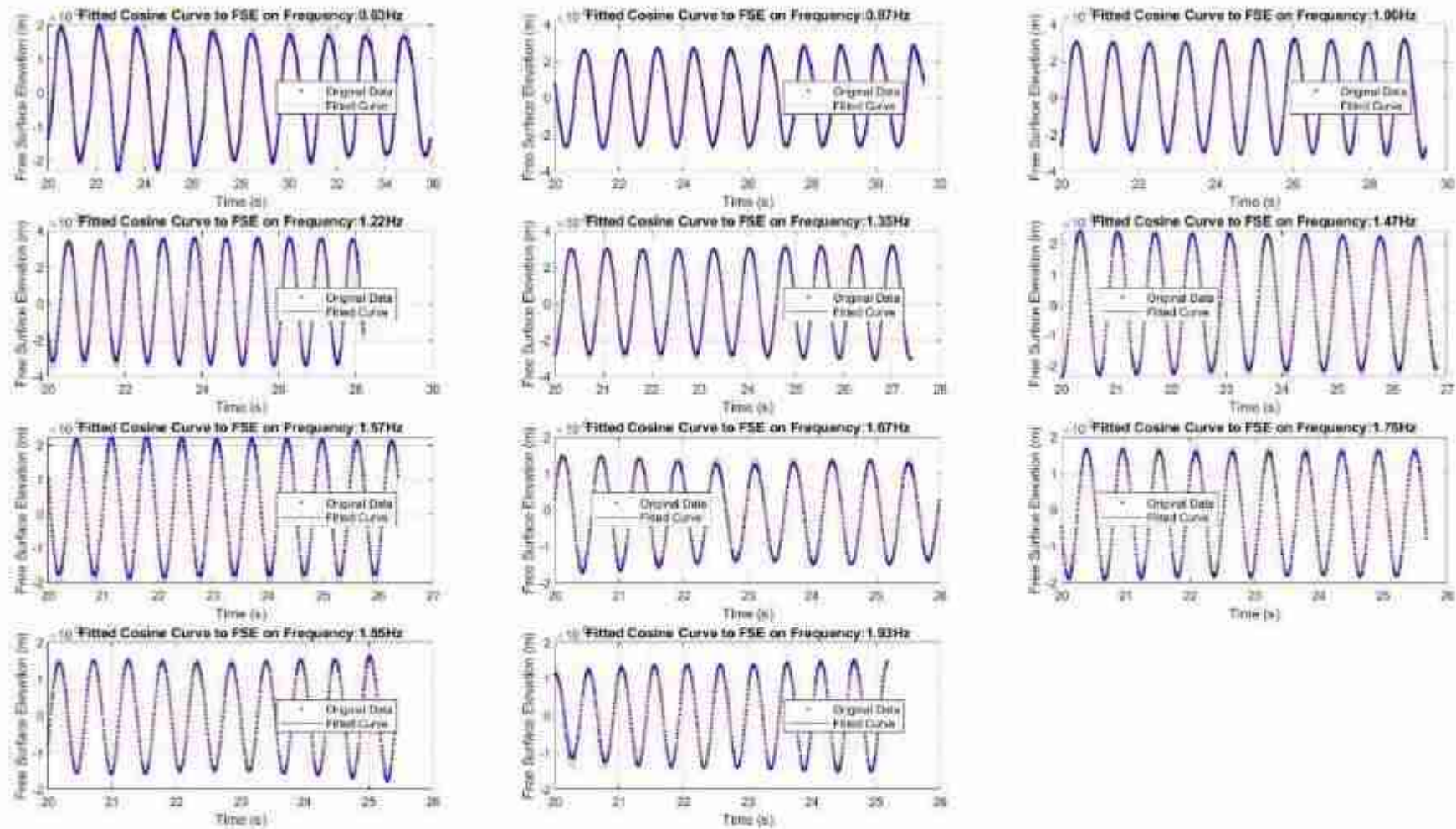


Figure 4-15: Empty Basin FSE change: wave amplitude=0.005 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

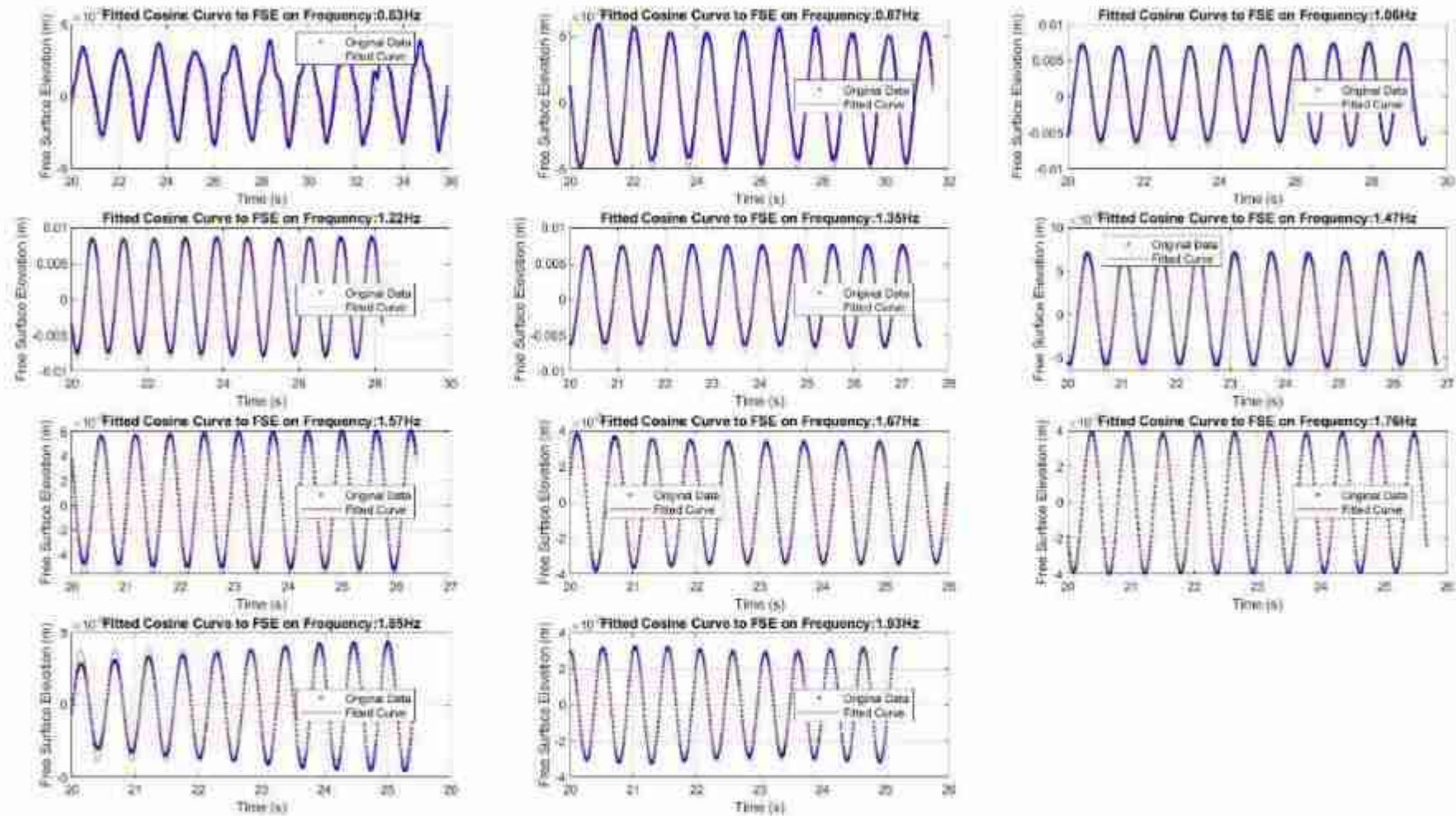


Figure 4-16: Empty Basin FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

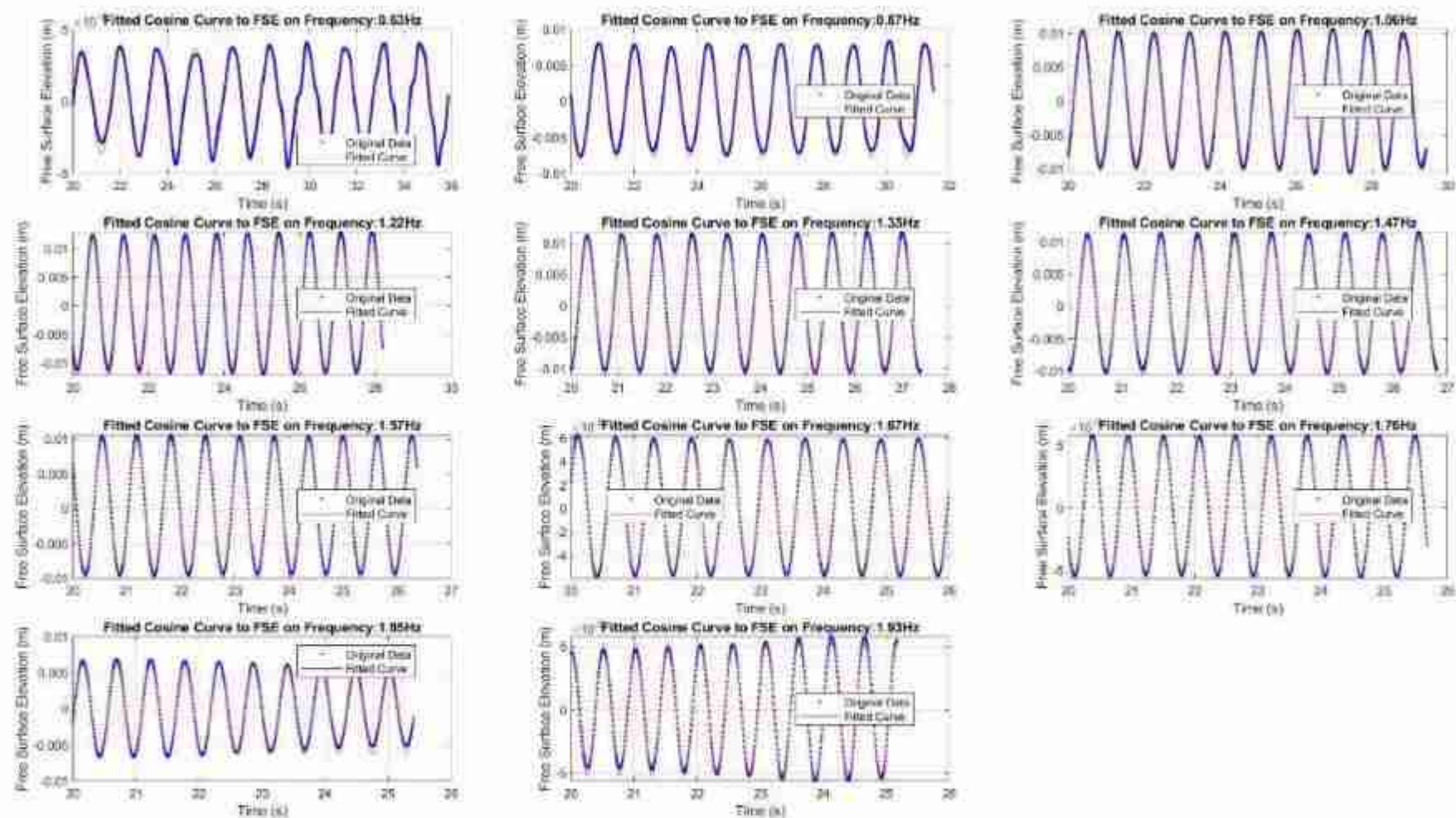


Figure 4-17: Empty Basin FSE change: wave amplitude=0.015 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

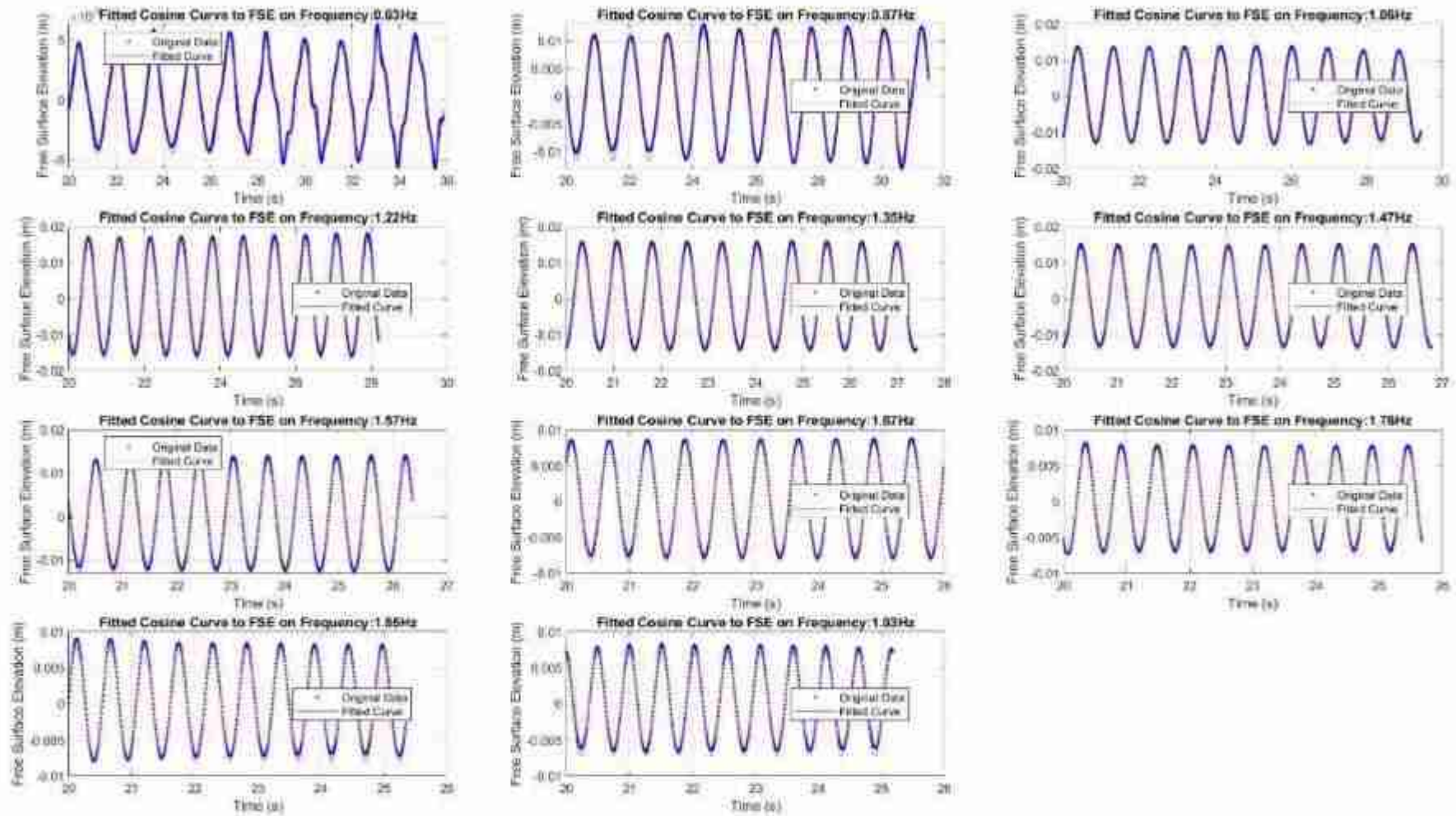


Figure 4-18: Empty Basin FSE change: wave amplitude=0.02 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

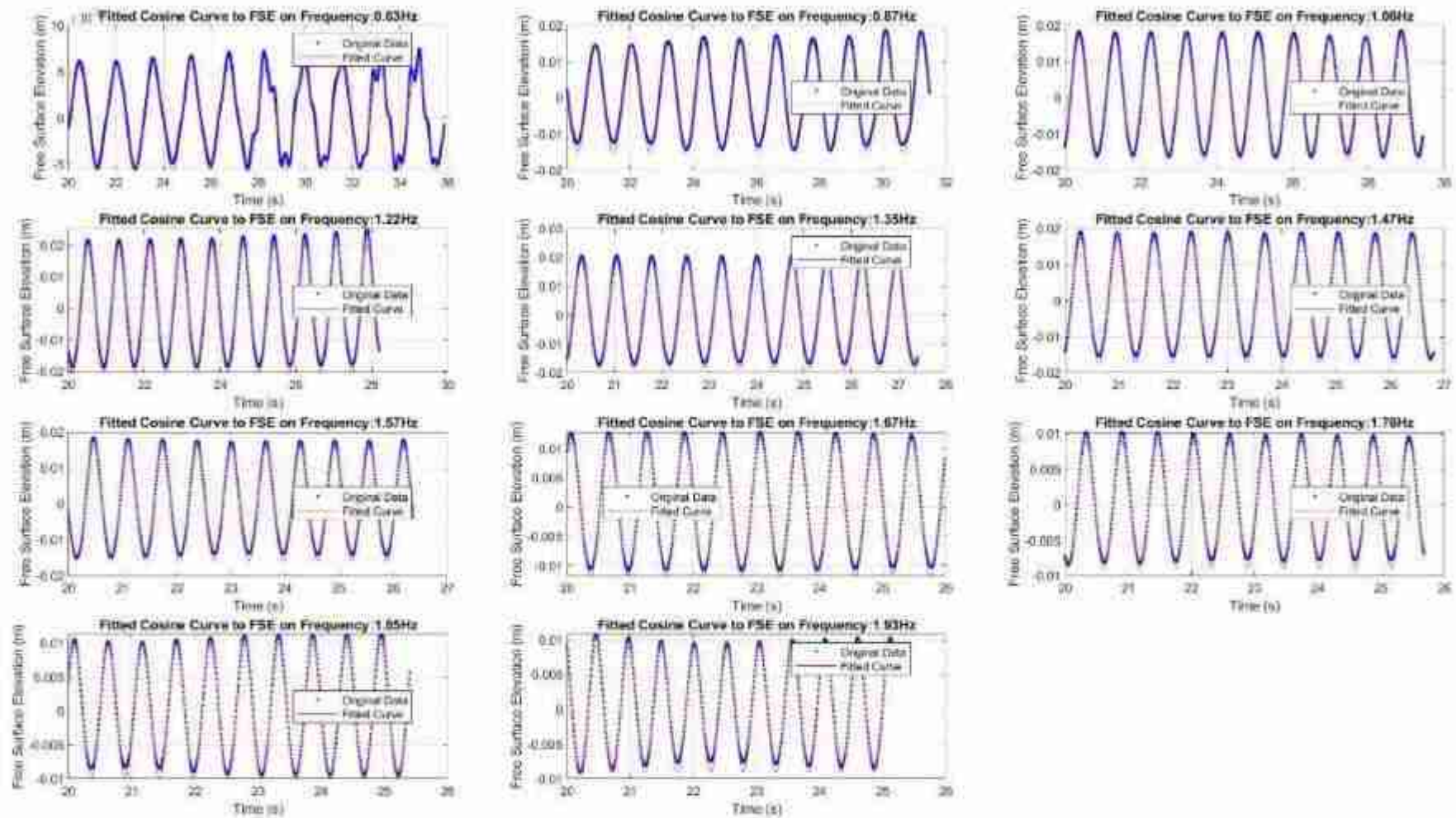


Figure 4-19: Empty Basin FSE change: wave amplitude=0.025 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

- **Wave Angle Varied EB Tests and Discussion (Figure 4-20 to Figure 4-23)**

In fact, the wave angle change should not make a significant difference in generating target amplitudes since the breakwater system is removed. The basin is large enough to lighten the effects of the reflections and standing waves in horizontal direction. Thus, the results of FSE amplitudes for the wave angle varied wave climates were following a remarkably close pattern as with the wave amplitude varied tests (see **Figure 4-20**). However, the wave angle varied empty basin test results were important for the primary target of the study, which is to simulate the conditions of the wave climate when a breakwater integrated OWC device installed. It might be appropriate to claim that the impact of the wave angle was extremely limited for the frequencies larger than 1.06 Hz, when it comes to generate FSE amplitude (A) and incident wave power (P_{inc}).

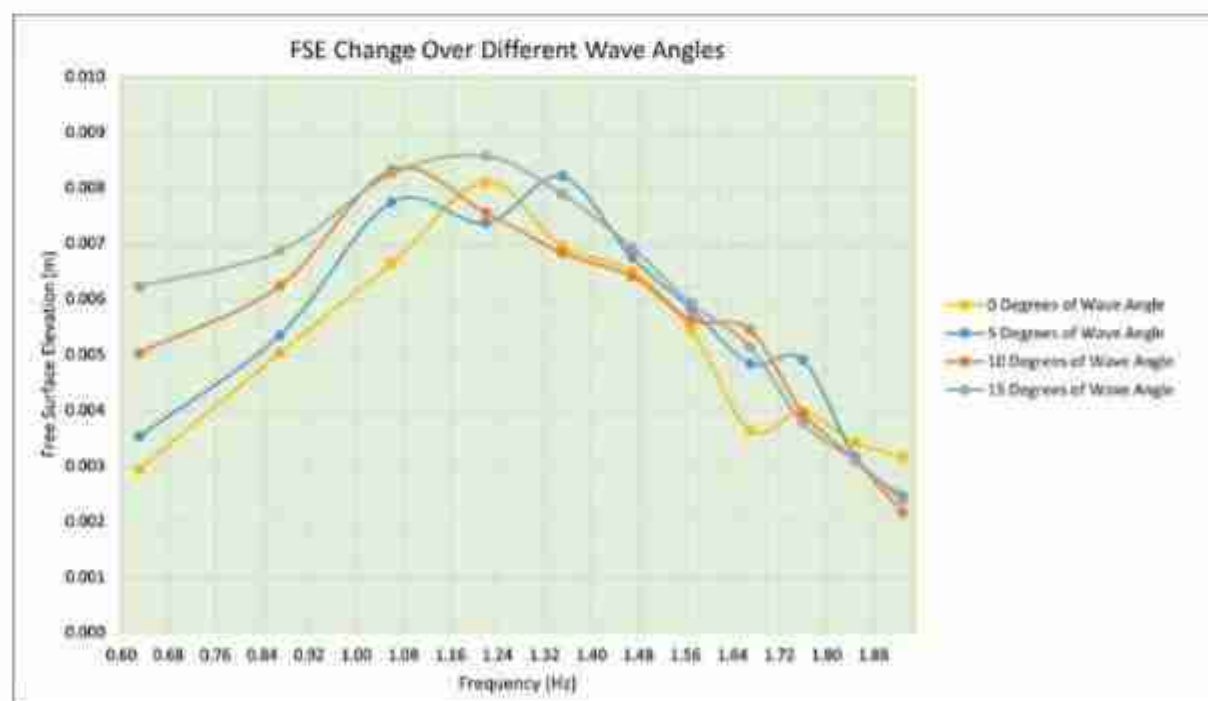


Figure 4-20: Empty basin wave angle varied test results

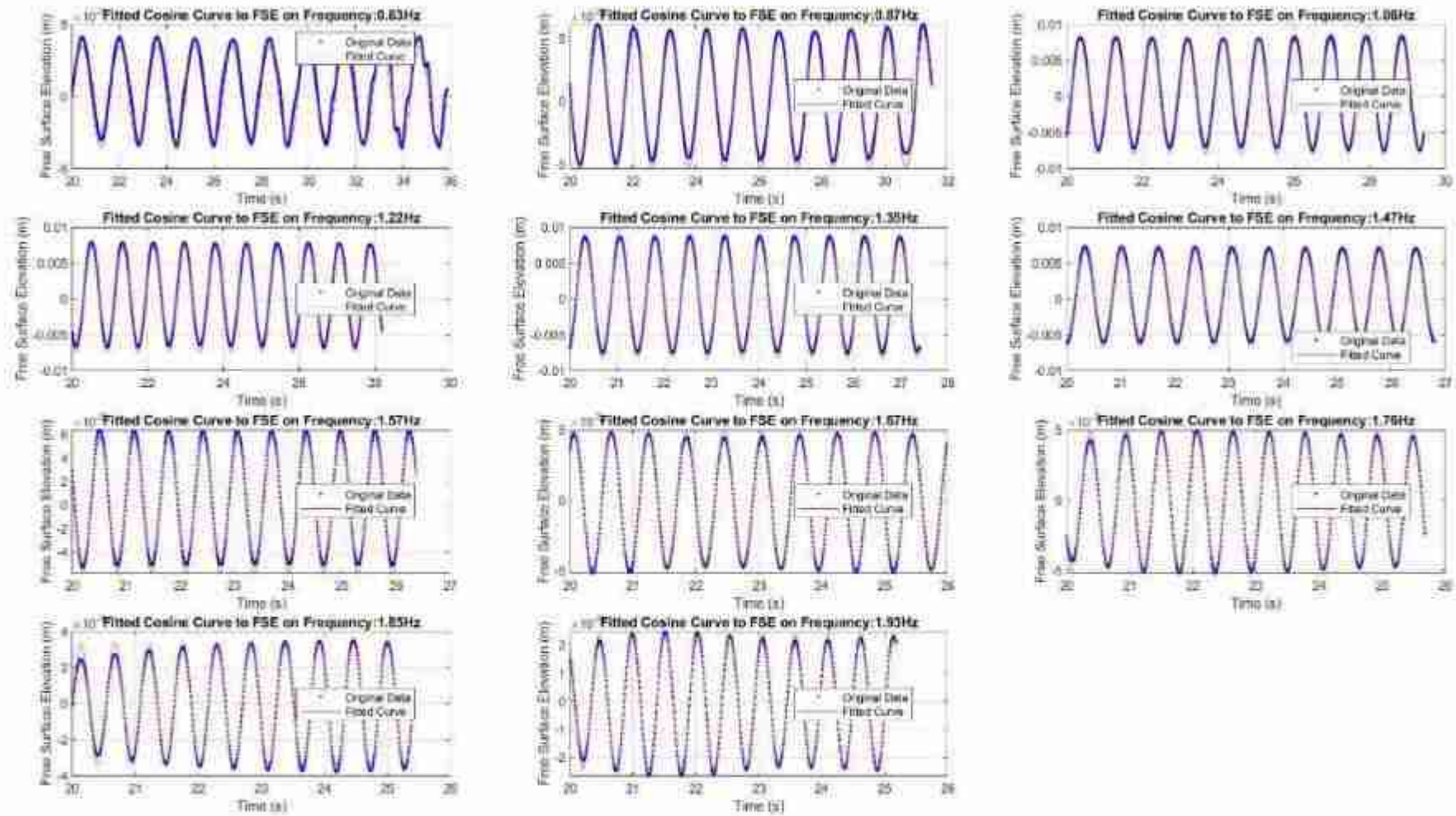


Figure 4-21: Empty Basin FSE change: wave amplitude=0.01 m, wave angle=5 degree, orifice=20 mm, water depth=40 cm

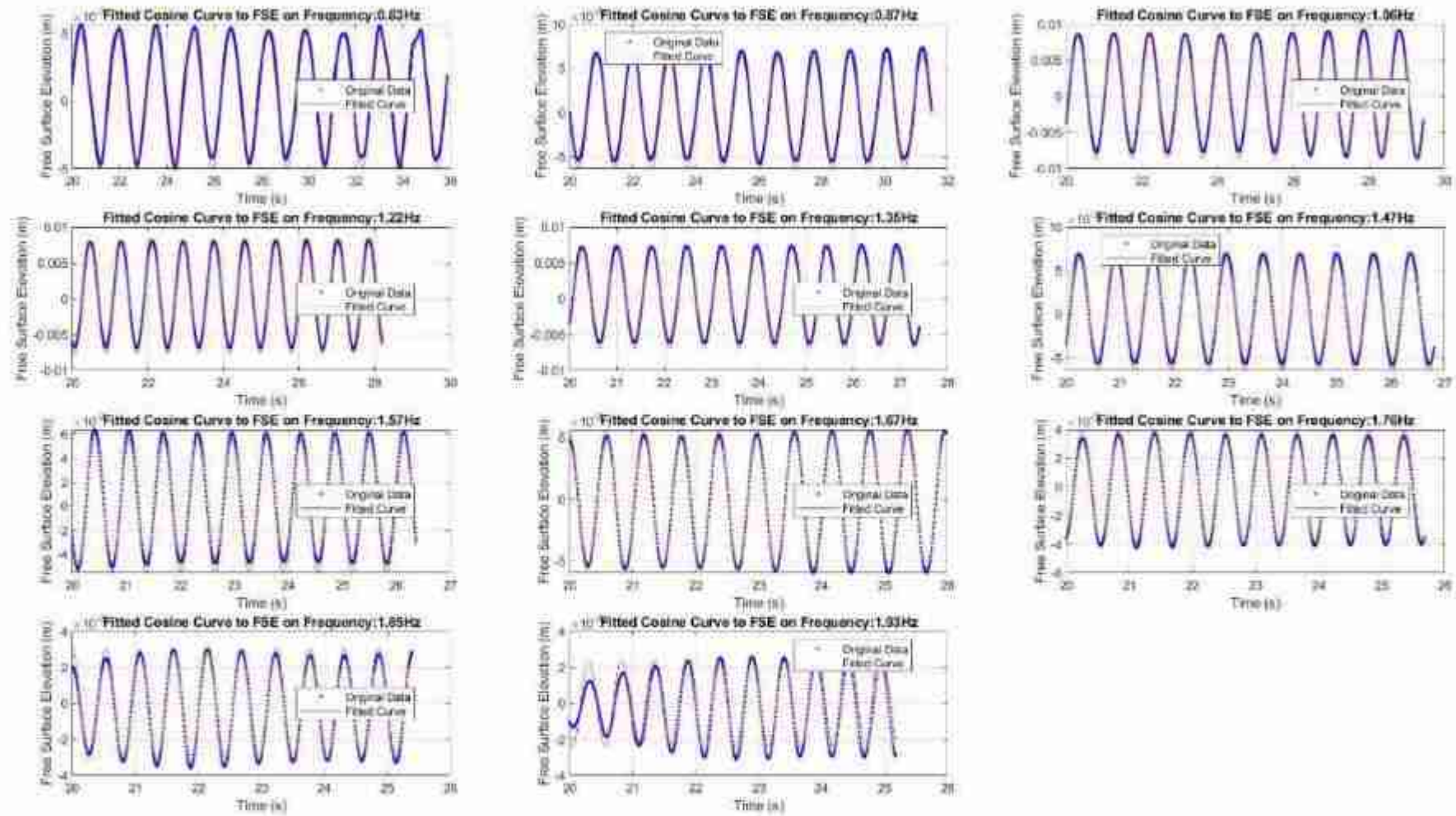


Figure 4-22: Empty Basin FSE change: wave amplitude=0.01 m, wave angle=10 degree, orifice=20 mm, water depth=40 cm

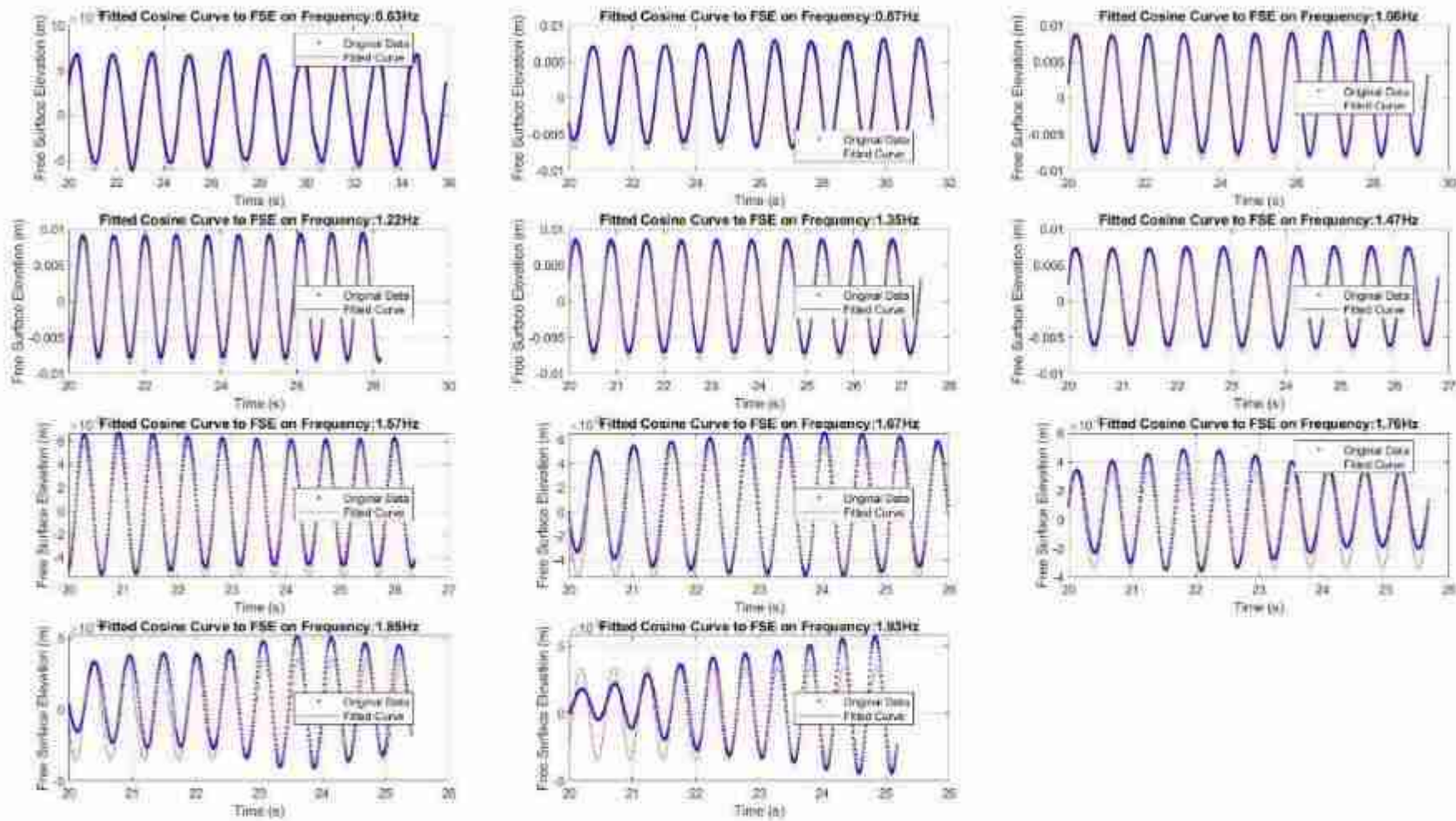


Figure 4-23: Empty Basin FSE change: wave amplitude=0.01 m, wave angle=15 degree, orifice=20 mm, water depth=40 cm

- **Water Depth Varied Empty Basin Tests and Discussions (Figure 4-25)**

As the OWC device is not present during the empty basin tests, the only remaining subset of results within the empty basin tests pertains to variations in water depth (h). To investigate this, a scenario was created where a 30 cm water depth was implemented in the basin, mimicking the setup with the breakwater system. Subsequently, eleven tests were conducted to assess the outcomes of these empty basin tests.

The results of the tests with varying water depths of 30 cm demonstrated a significantly higher level of success in achieving the target wave amplitude 0.01 m. Notably, the default target wave amplitude of 0.01 m was effectively generated by the wave paddles under the condition of a 30 cm water depth. On the contrary, wave paddles were not successful in generating the target wave amplitude 0.01 m in 40 cm water depth conditions (see Figure 4-24).

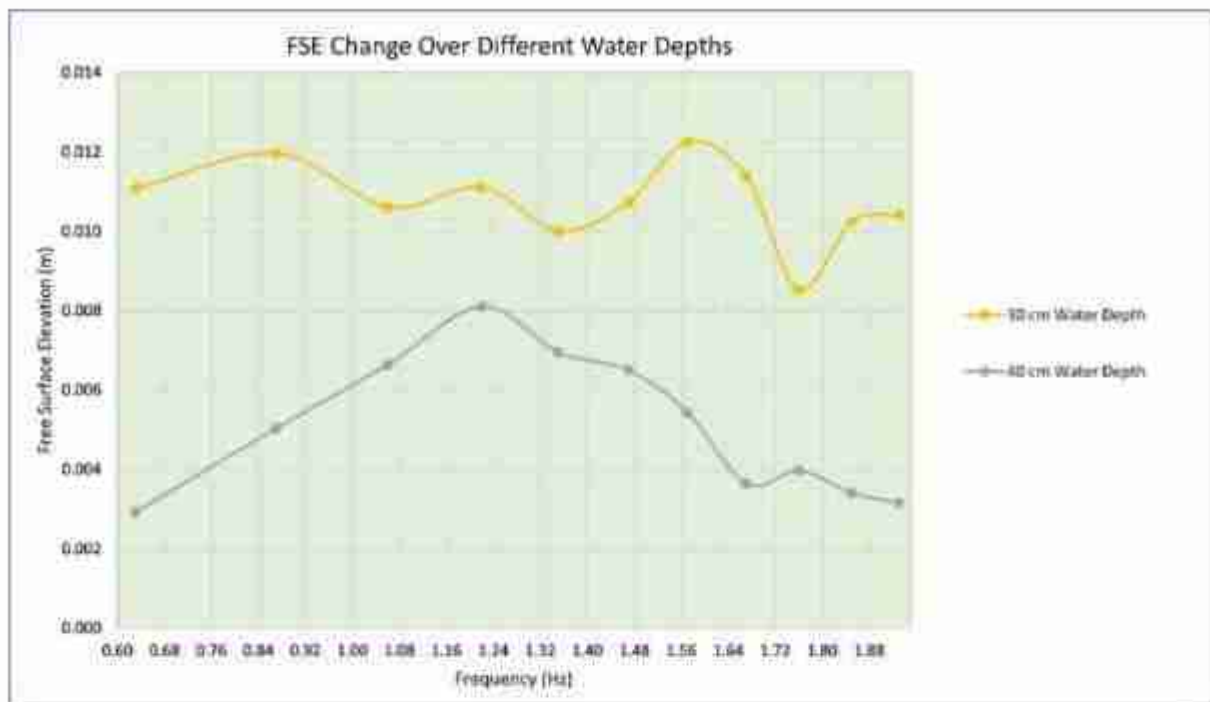


Figure 4-24: Empty basin water depth varied test results

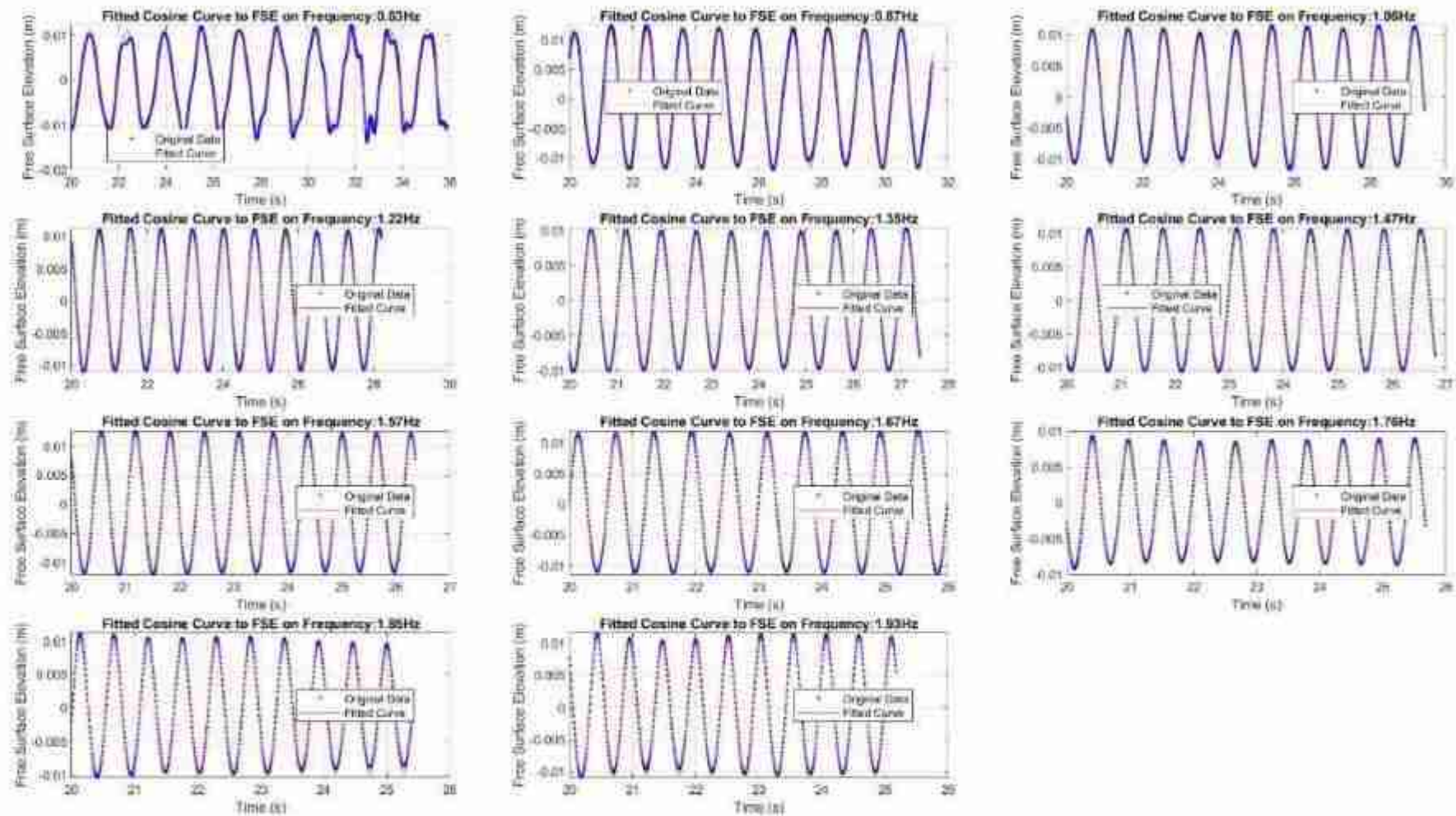


Figure 4-25: Empty Basin FSE change: wave amplitude=0.01 m, wave angle=0 degree, orifice=20 mm, water depth=30 cm

4.2 Results of Pressure Fluctuations and Discussions

The other data component obtained from the experiments is the pressure files. During a test, when a wave interacts with the OWC device, this interaction results in a water motion inside the chamber. By employing an air pressure sensor inside the OWC, the instantaneous pressure (p) alterations can be monitored via the software. Finally, the recorded air pressure data is saved to a *.lvm file for each test setup. In the figures below, the air pressure changes can be seen in the specified time window, with the same wave count ($N = 10$) akin to Free Surface Elevation results. The most prominent outcome of the Pressure changes is that the high frequency wave climates are not giving a regular alteration in all scenarios, except the 30 cm water depth wave climates. The high frequency wave climates (over 1.47 Hz) only generated exceedingly small amplitudes of pressure change, which did not make a significant contribution to the pneumatic power (P_p) per single wave. On the contrary, the lower frequency wave climates (less than 1.35 Hz) resulted with regular pressure changes in most parts of the test durations, which allows to derive pneumatic power via the method explained in chapter 3.

Wave Amp. Impact on Pressure and Discussions (Figure -26 to Figure 4-30)

Upon closer examination of the instantaneous pressure (p) data derived from the wave amplitude varied test results, it becomes apparent that the background or idle air pressure inside the chamber was significantly higher when compared to the measured instantaneous pressures. To illustrate, in the case of the 0.005 m wave amplitude condition, the idle pressure can be approximated within the range of 3-4 Pa (refer to the subplots for 1.57 Hz, 1.76 Hz, and 1.85 Hz frequencies in **Figure -26**).

This level of idle air pressure is referred to as 'noise in data' during the data quality check phase. Consequently, the air pressure fluctuations inside the chamber induced by changes in wave amplitude were nearly negligible, especially for high-frequency scenarios (above 1.47 Hz). This observation implies that the propagated waves did not generate sufficient pneumatic power (P_p) that could be harnessed by the OWC device. Consequently, this leads to exceptionally low capture width ratios (ϵ_{OWC}). The largest amount of pressure fluctuation detected between successive waves under the 0.005 m condition was observed at a frequency of 0.87 Hz, ranging from 35 to 40 Pa.

The increase of wave amplitude generated larger pressure fluctuations inside the OWC chamber. However, the idle pressure was still significant for high frequency wave climates even for the case of 0.025 m wave amplitude, which was the highest amplitude assessed in experiments. The maximum pressure fluctuations between the consecutive waves for all wave amplitude varied tests always recorded for the frequency of 0.87 Hz in each set. In terms of numbers, 55-65 Pa range for 0.01 m amplitude, 85-95 Pa range for 0.015 m, 120-130 Pa range for 0.02 m, and 150-160 Pa range for 0.025 m are recorded via the air pressure sensor with 0.87 Hz frequency wave climates. The other frequency wave climates exerted much lesser pressure amplitudes comparing to the case of 0.87 Hz in all scenarios.

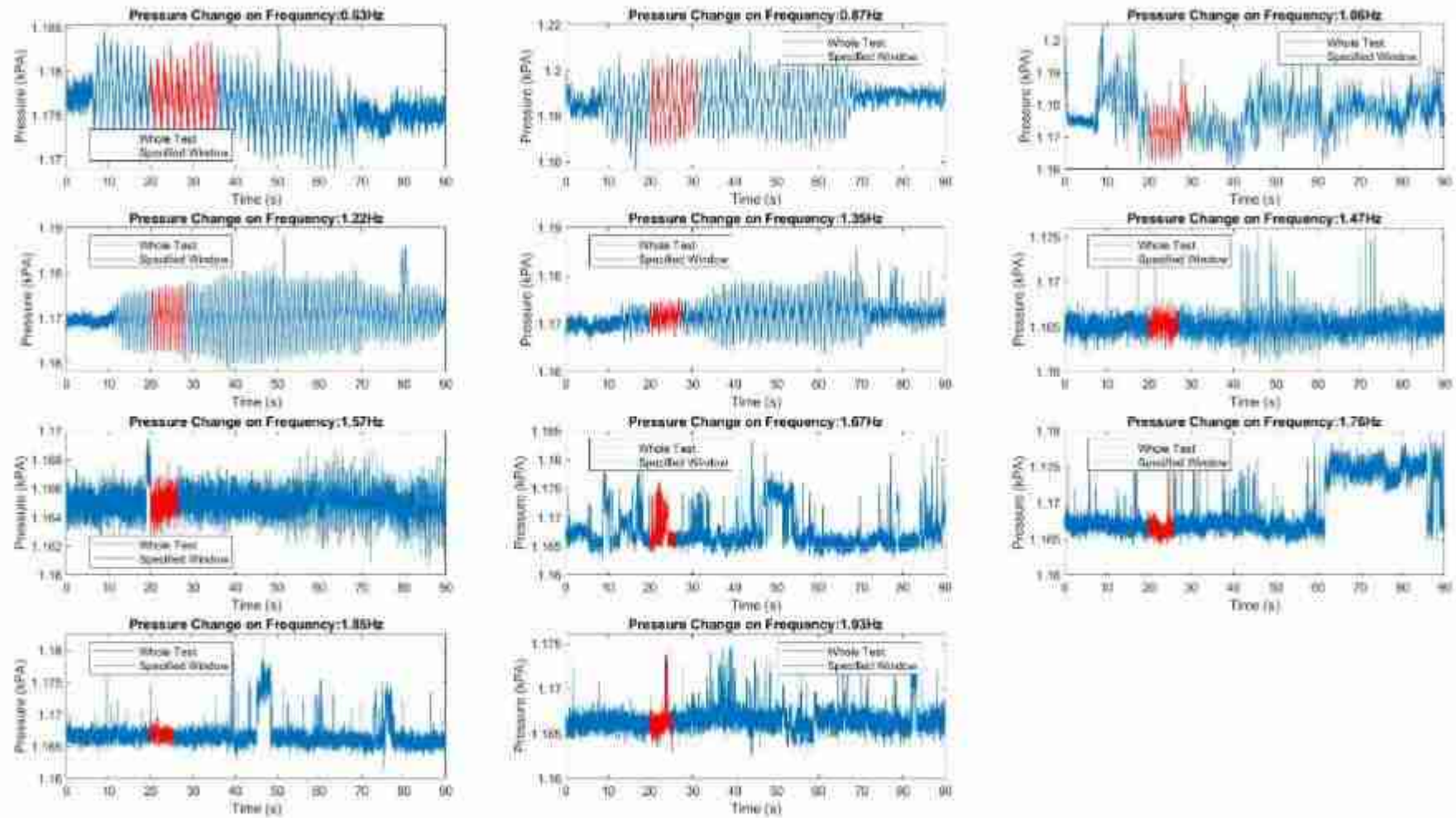


Figure -26: Pressure fluctuations: wave amplitude=0.005 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

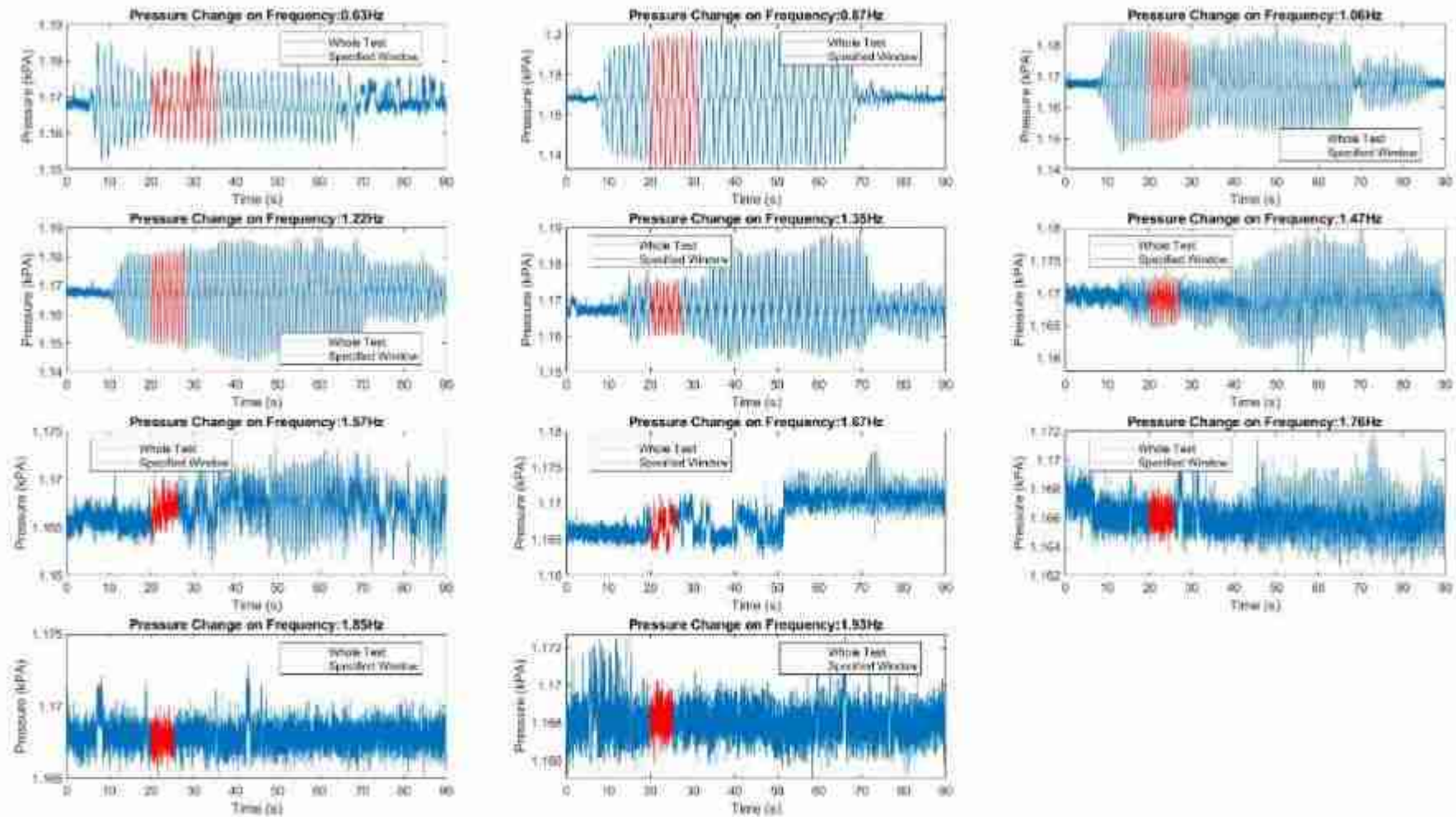


Figure 4-27: Pressure fluctuations: wave amplitude=0.010 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

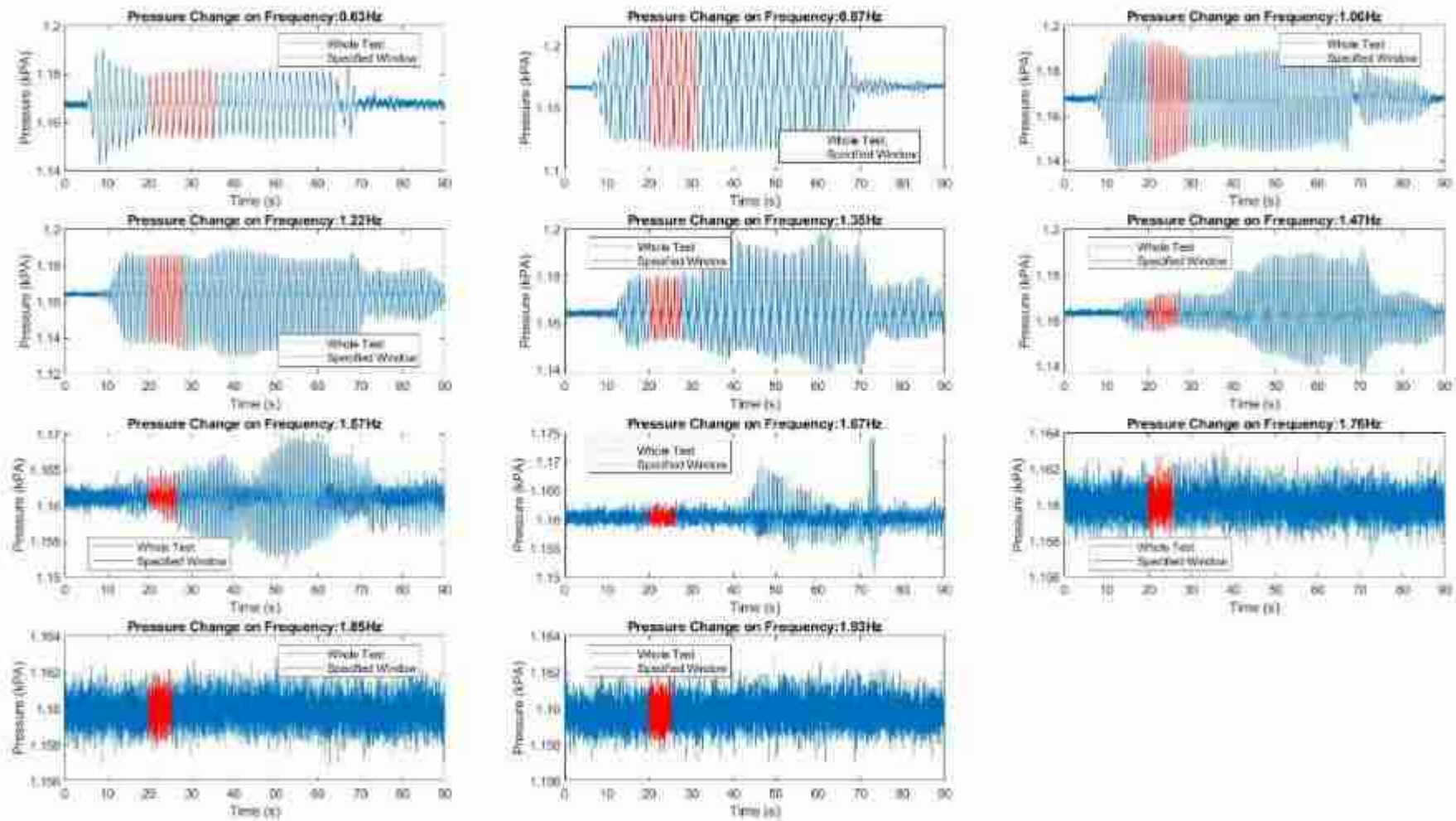


Figure 4-28: Pressure fluctuations: wave amplitude=0.015 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

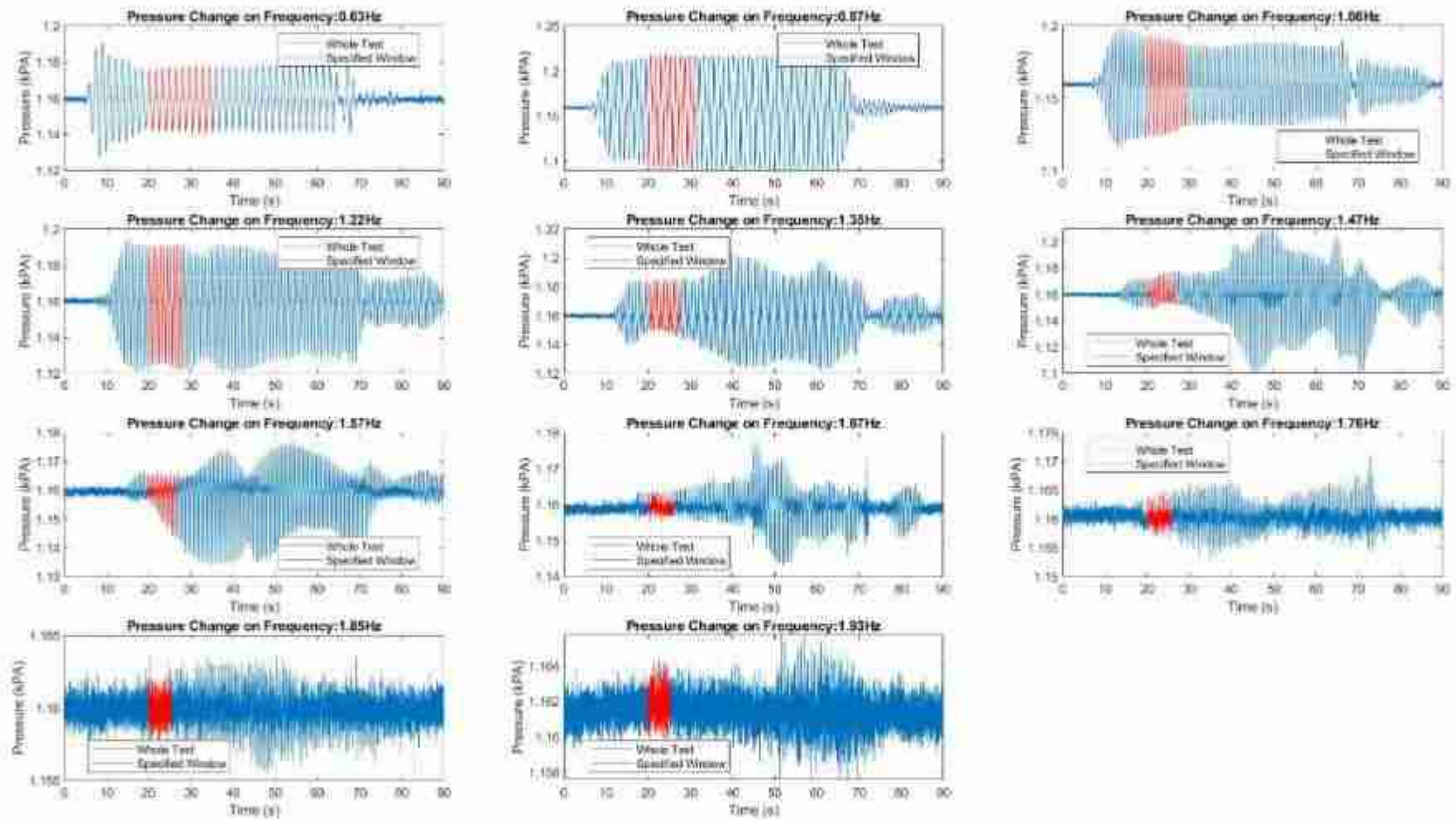


Figure 4-29: Pressure fluctuations: wave amplitude=0.02 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

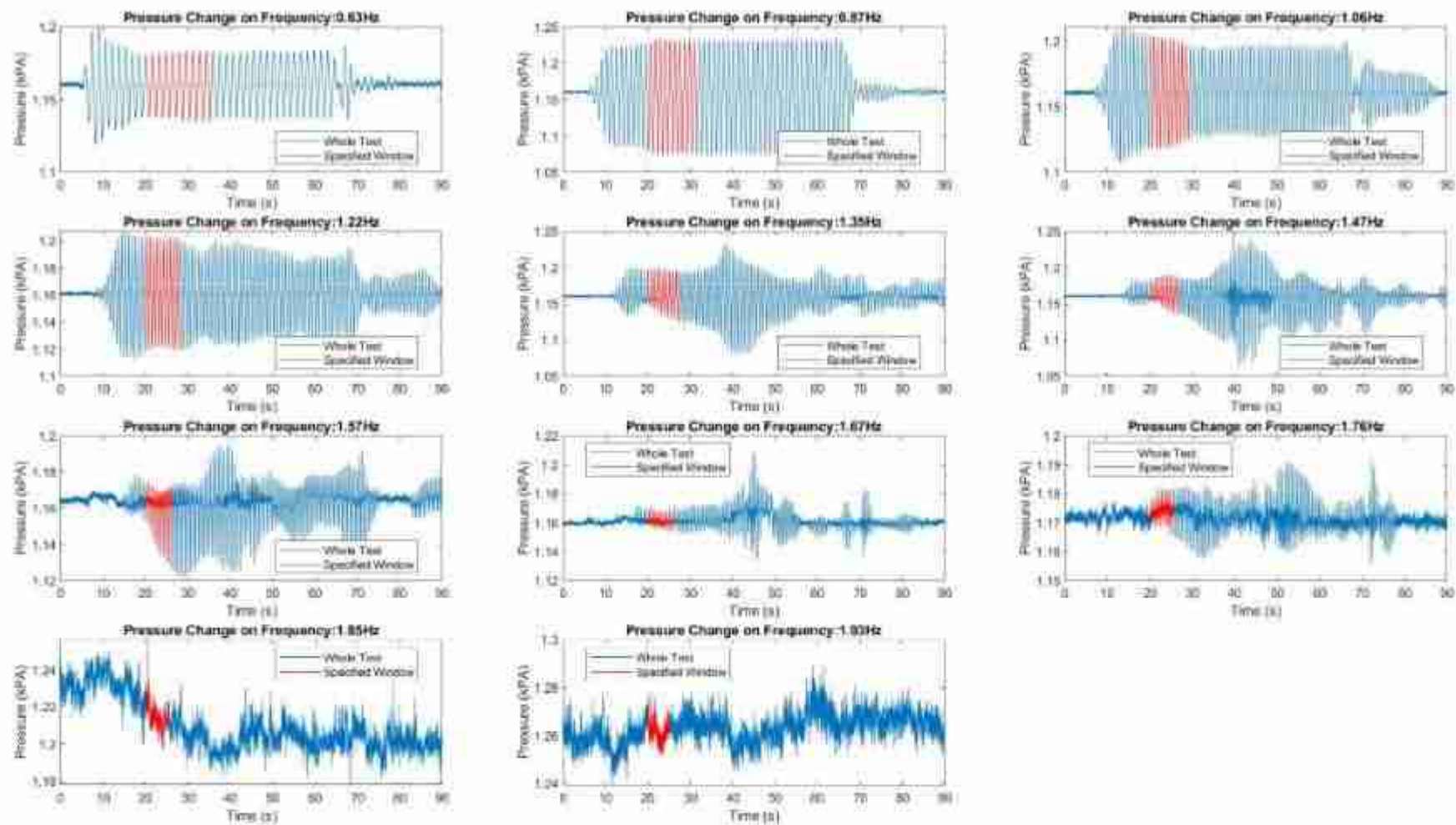


Figure 4-30: Pressure fluctuations: wave amplitude=0.025 m, wave angle=0 degree, orifice=20 mm, water depth=40 cm

Wave Angle Impact on Pressure and Discussions (Figure 4-31 to Figure 4-33)

Another vital aspect of discussion in this experimental study revolves around the influence of wave angles on Free Surface Elevation (η) and pressure fluctuations (p) within the OWC device. The distinctive characteristic of an open basin, as opposed to the commonly used flume tanks in experimental studies, is its capability to facilitate the propagation of angular waves generated by the paddles. This unique feature has provided an opportunity to assess the impact of varying wave angles on a cylindrical OWC device.

As observed in earlier chapters, the influence of wave angle had a notably limited effect on Free Surface Elevation (FSE) amplitudes. Similarly, the pressure fluctuations associated with various wave angles did not exhibit significant differences, in terms of pressure fluctuations. For instance, considering a frequency of 0.87 Hz, the maximum pressure fluctuation between consecutive waves for a perpendicular (0 degree) wave angle fell within the range of 55-65 Pa (refer to **Figure 4-27**). In comparison, waves with a 5-degree wave angle exerted a maximum pressure of 65-75 Pa on the OWC device within the same frequency (0.87 Hz) wave climate (refer to **Figure 4-31**). Likewise, the maximum pressure reached the range of 80-85 Pa for wave angles of 10 degrees and 15 degrees with other default wave conditions (refer **Figure 4-32** and **Figure 4-33**).

Consequently, it can be concluded that the impact of wave angle on pressure excitation for a cylindrical OWC device was not substantial.

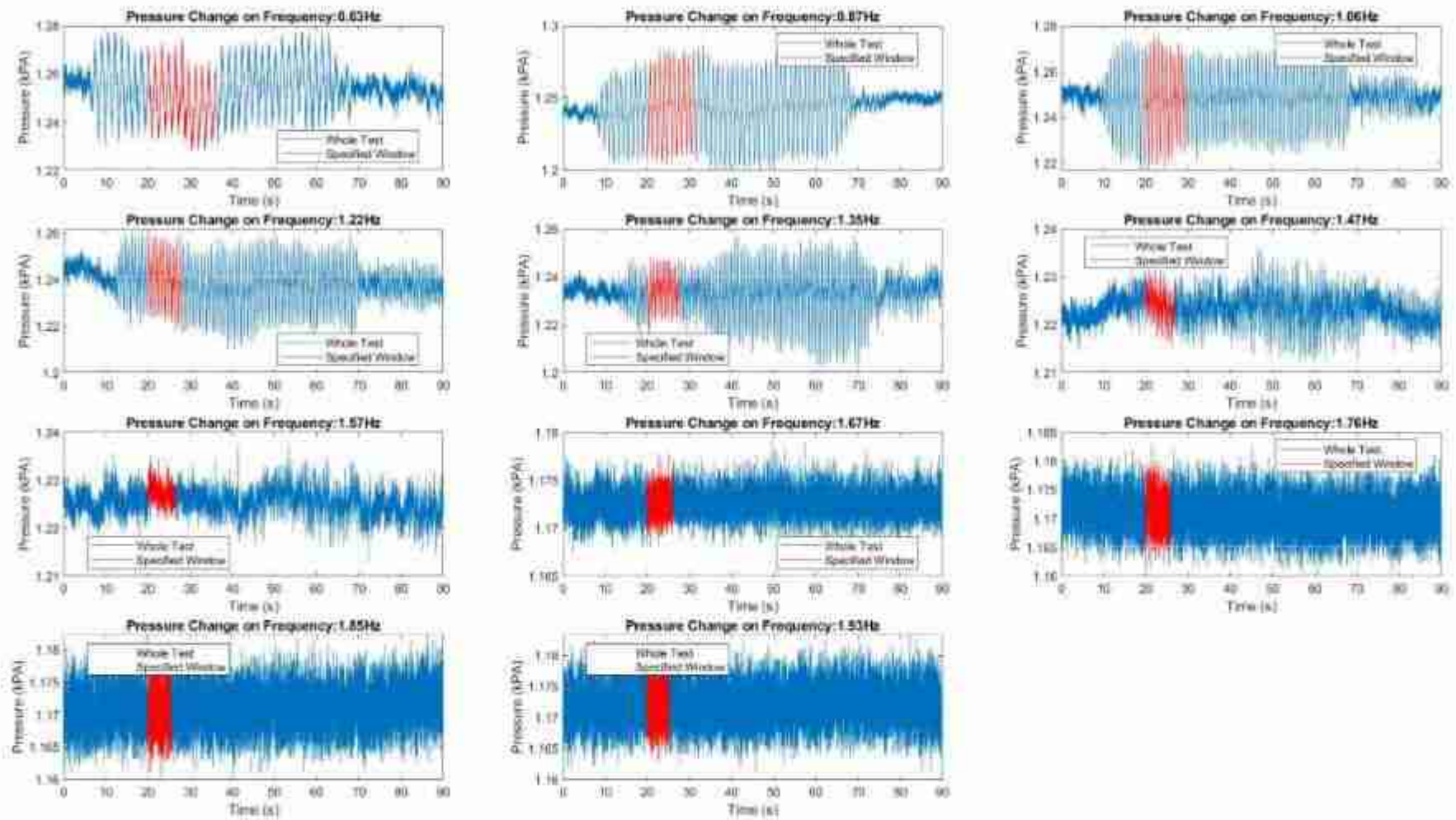


Figure 4-31: Pressure fluctuations: wave amplitude=0.01 m, wave angle=5 degrees, orifice=20 mm, water depth=40 cm

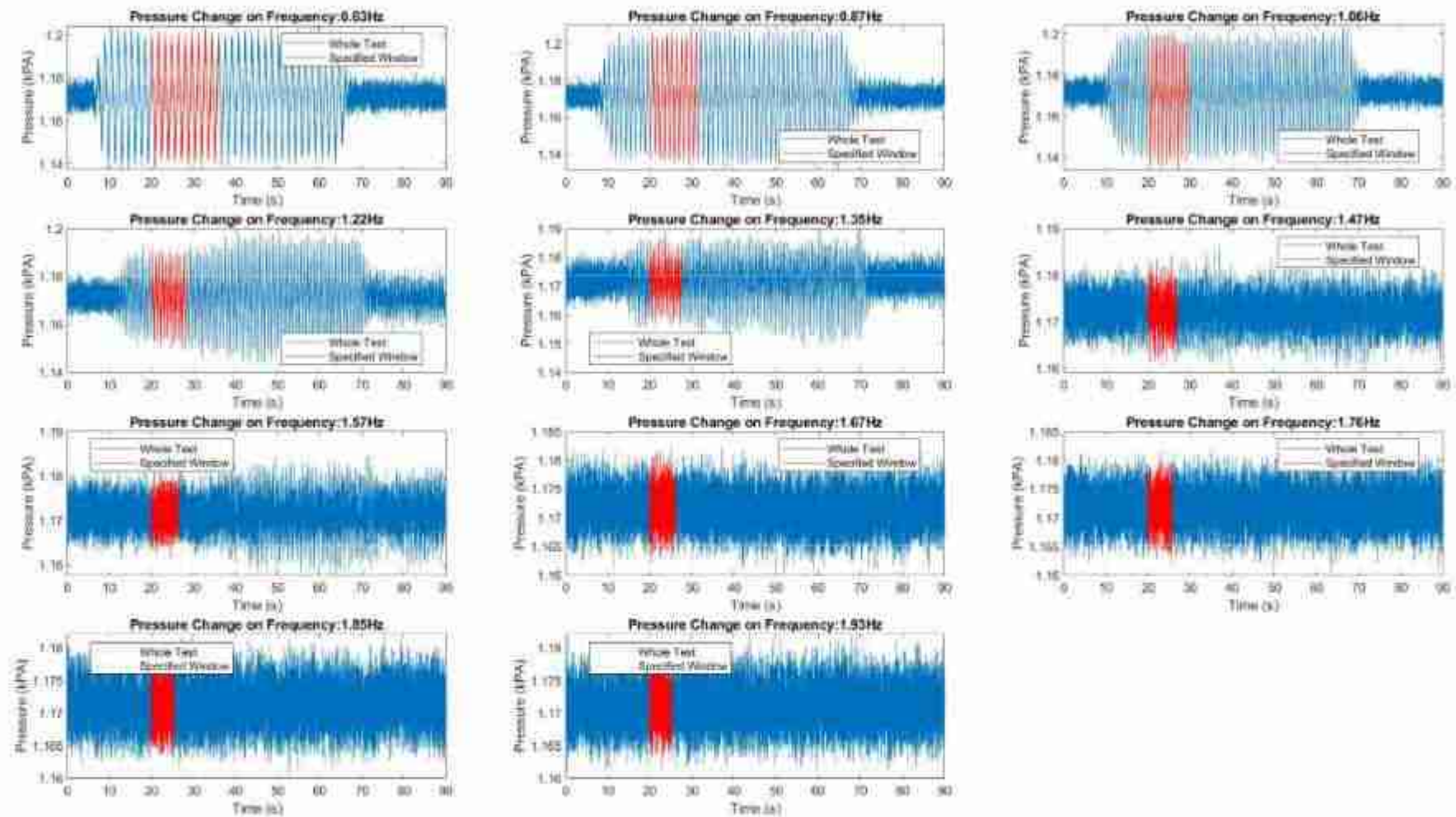


Figure 4-32: Pressure fluctuations: wave amplitude=0.01 m, wave angle=10 degrees, orifice=20 mm, water depth=40 cm

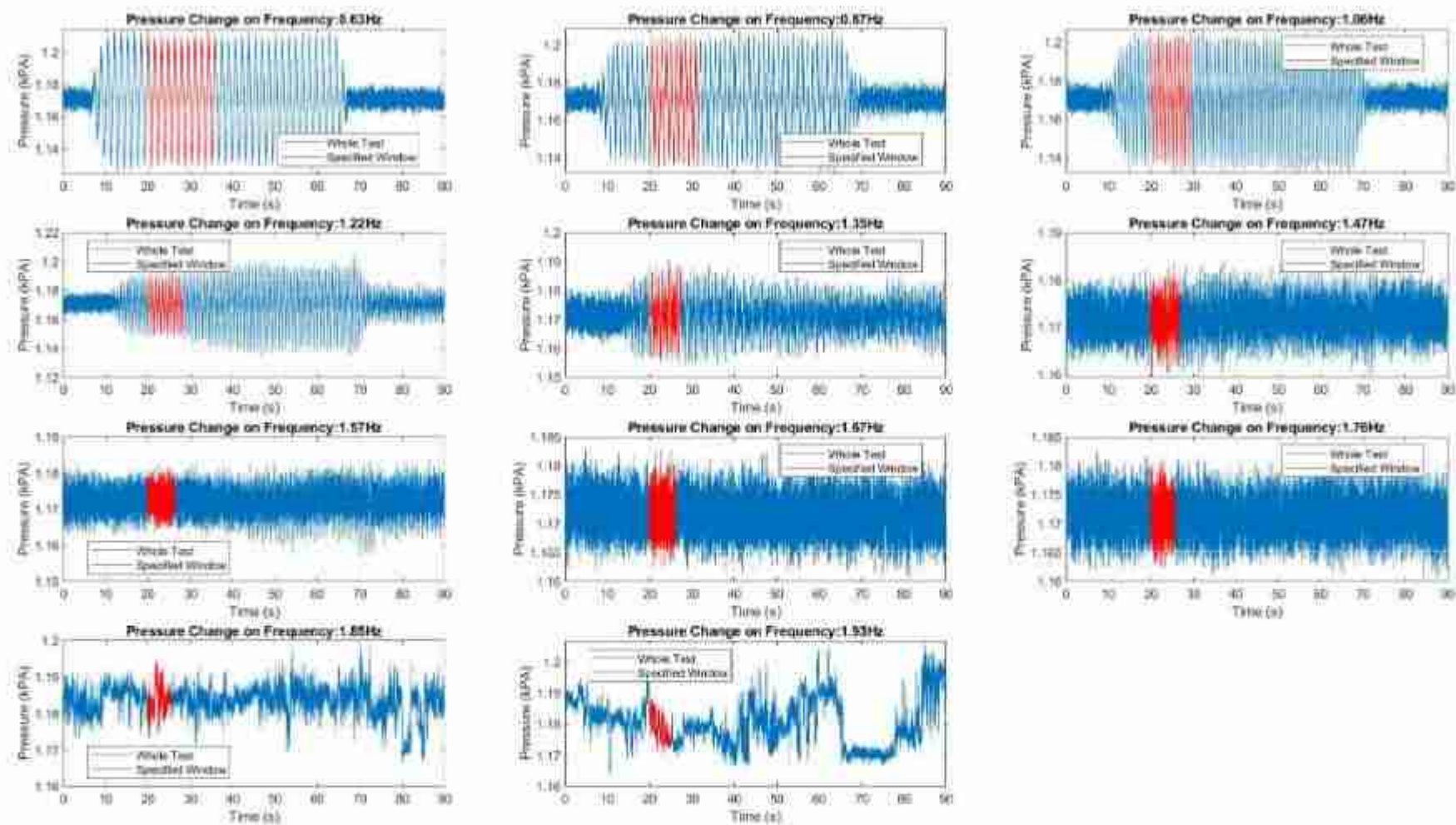


Figure 4-33: Pressure fluctuations: wave amplitude=0.01 m, wave angle=15 degrees, orifice=20 mm, water depth=40 cm

Orifice Size Impact on Pressure and Discussions (Figure 4-34 to Figure 4-37)

In Chapter 3.2.3, it is established that the size of the orifice plays a significant role in the efficiency of the OWC device. Consequently, it is crucial to investigate the impact of orifice size on pressure fluctuations to gain a comprehensive understanding of the capabilities of this cylindrical OWC chamber, which can yield valuable insights.

The analysis of pressure data for various orifice sizes revealed a notable finding: achieving consistent pressure fluctuations within the OWC device throughout all tests, regardless of orifice size, proved to be nearly impossible. Out of the forty-four tests conducted, only four exhibited uniform pressure fluctuations during the entire testing duration. This inconsistency in pressure fluctuations led to challenges in data collection quality and resulted in irregular calculations based on the available data.

Furthermore, it was observed that high-frequency wave conditions (exceeding 1.35 Hz) consistently generated minimal pressure fluctuations across all orifice sizes, resembling background, or idle pressure conditions. Conversely, low-frequency wave conditions demonstrated greater success in inducing sufficient and consistent pressure variations.

Among the five different orifice sizes studied, the most significant pressure fluctuations were observed in the cases of a 26 mm orifice (equivalent to 1.7% of the Chamber Surface Area) and a 30 mm orifice (equivalent to 2.25% of the Chamber Surface Area) when subjected to 0.87 Hz wave frequency conditions, with pressure fluctuations falling within the range of 70-90 Pa. It is important to note that no distinct pattern emerged in the pressure fluctuations across different orifice sizes, except for the

consistent satisfactory pressure fluctuations observed under 0.87 Hz wave frequency conditions within the OWC device.

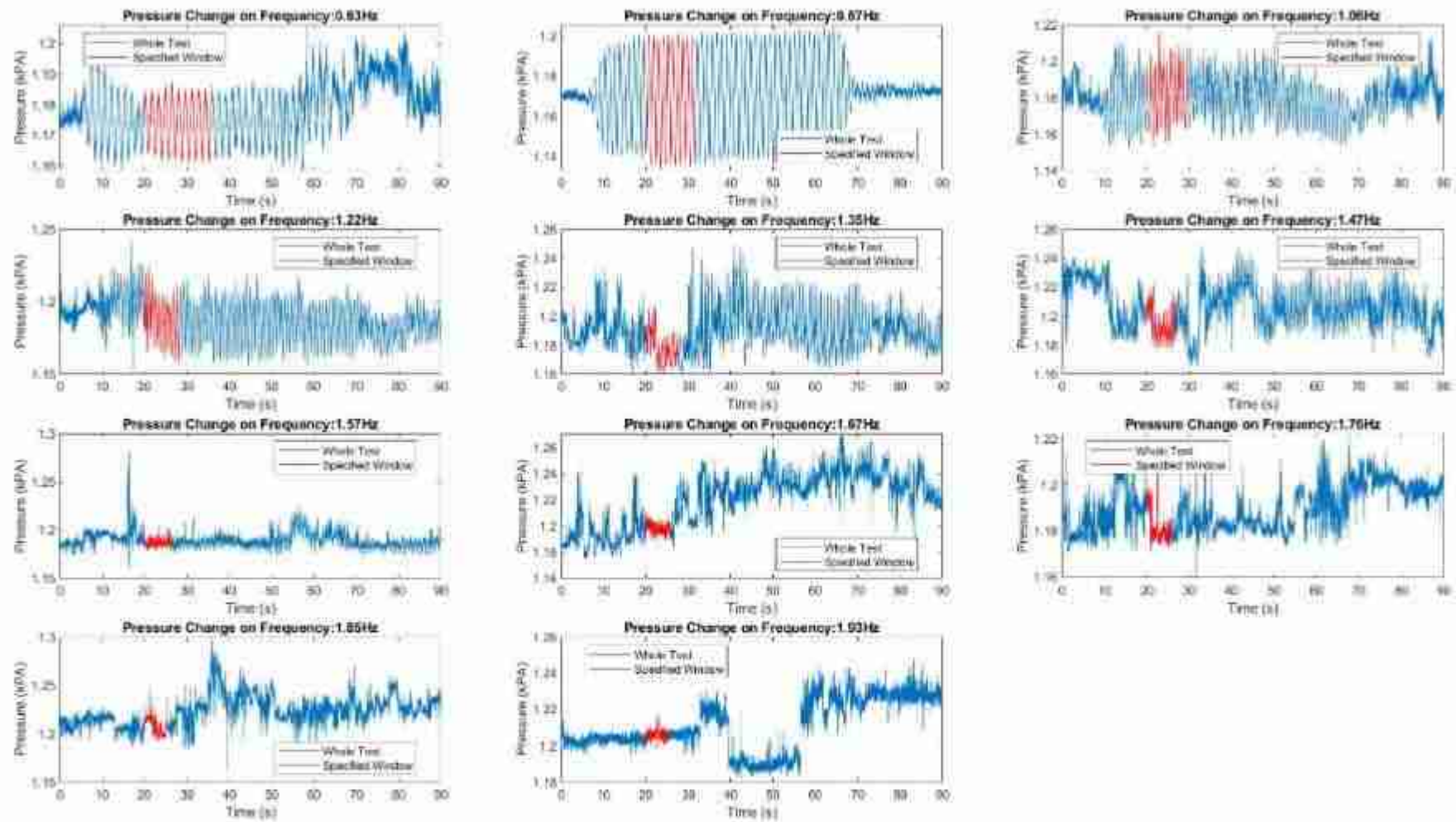


Figure 4-34: Pressure fluctuations: wave amplitude=0.01 m, wave angle=0 degrees, orifice=10 mm, water depth=40 cm

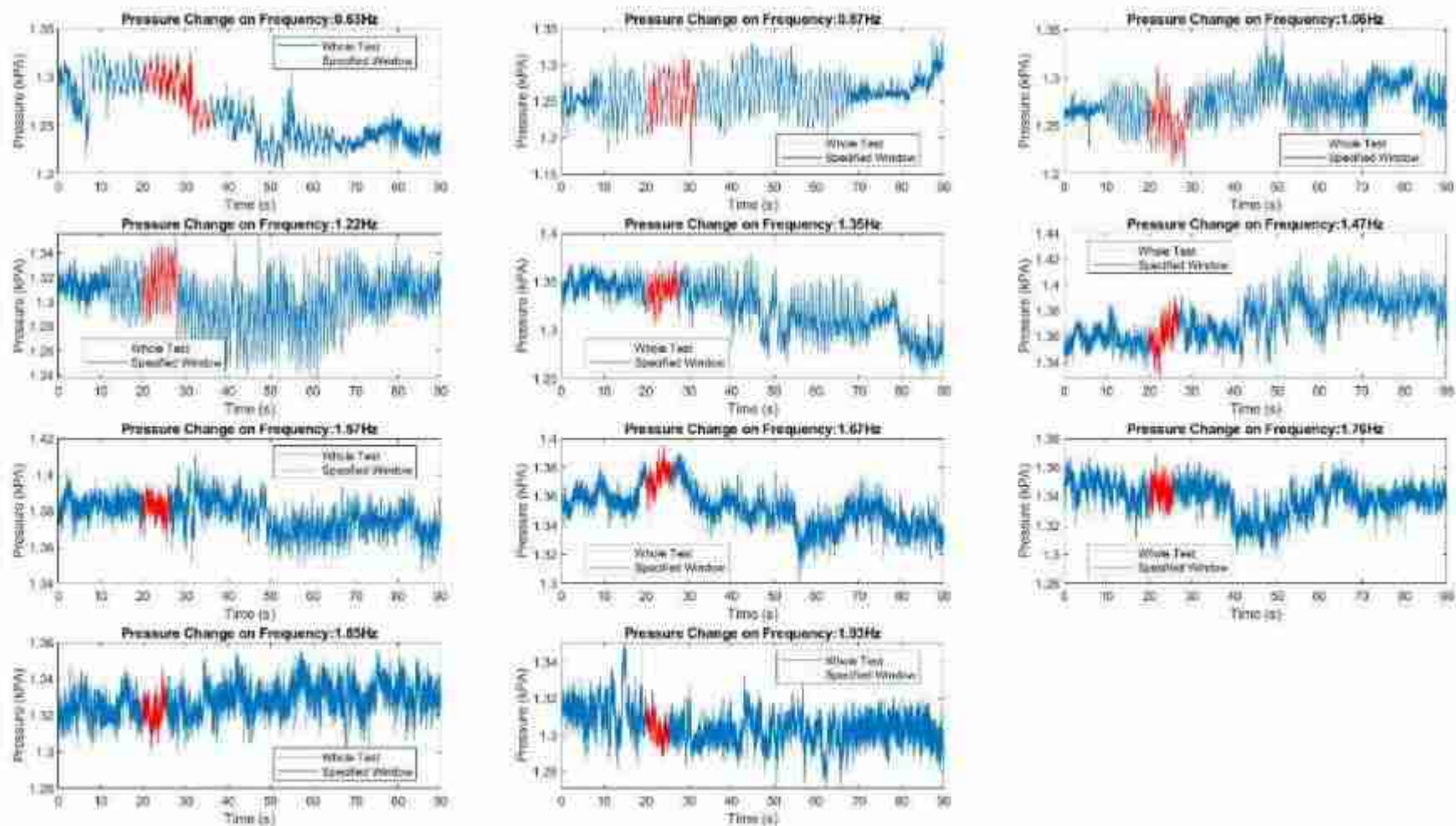


Figure 4-35: Pressure fluctuations: wave amplitude=0.01 m, wave angle=0 degrees, orifice=14 mm, water depth=40 cm

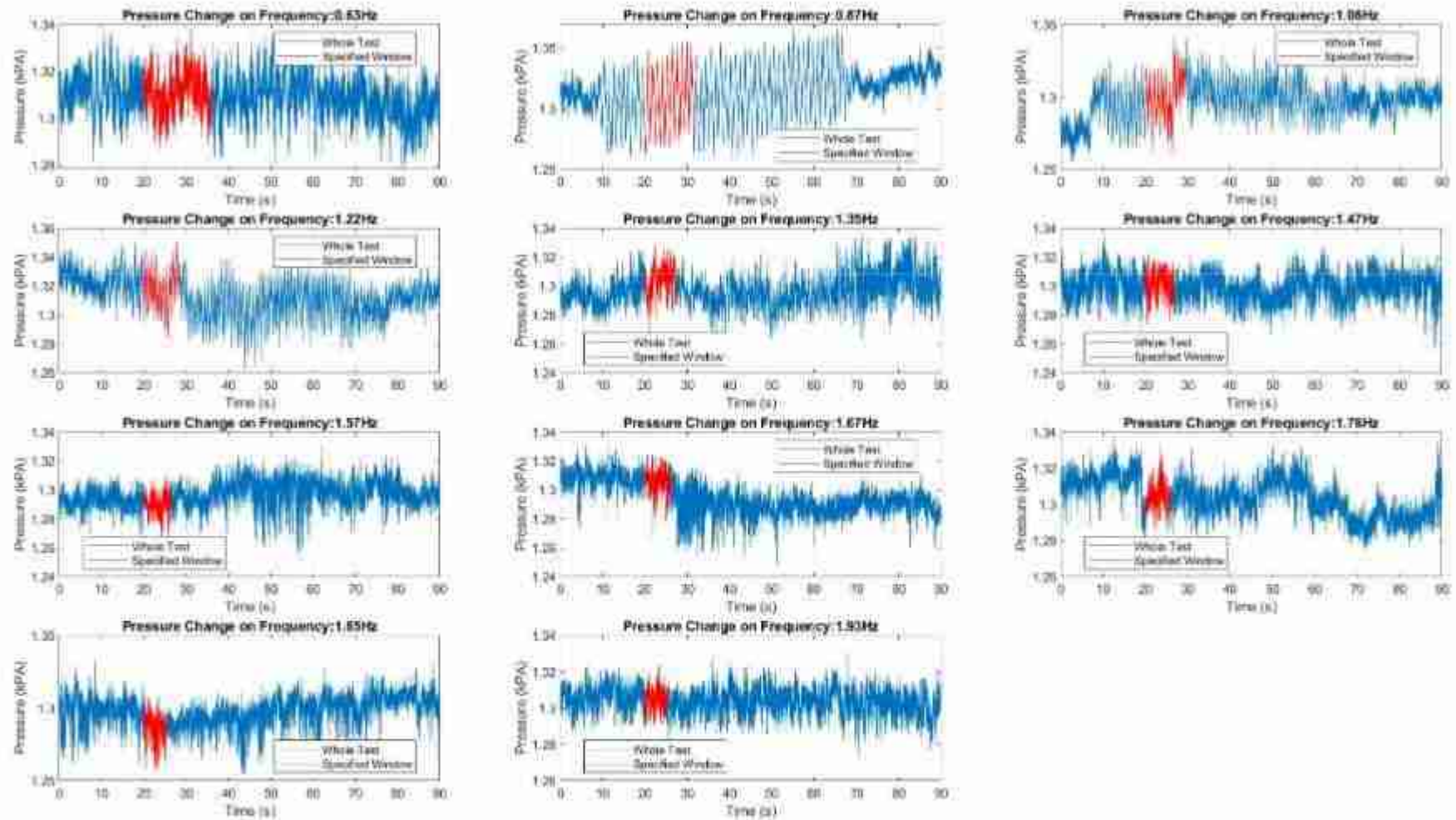


Figure 4-36: Pressure fluctuations: wave amplitude=0.01 m, wave angle=0 degrees, orifice=26 mm, water depth=40 cm

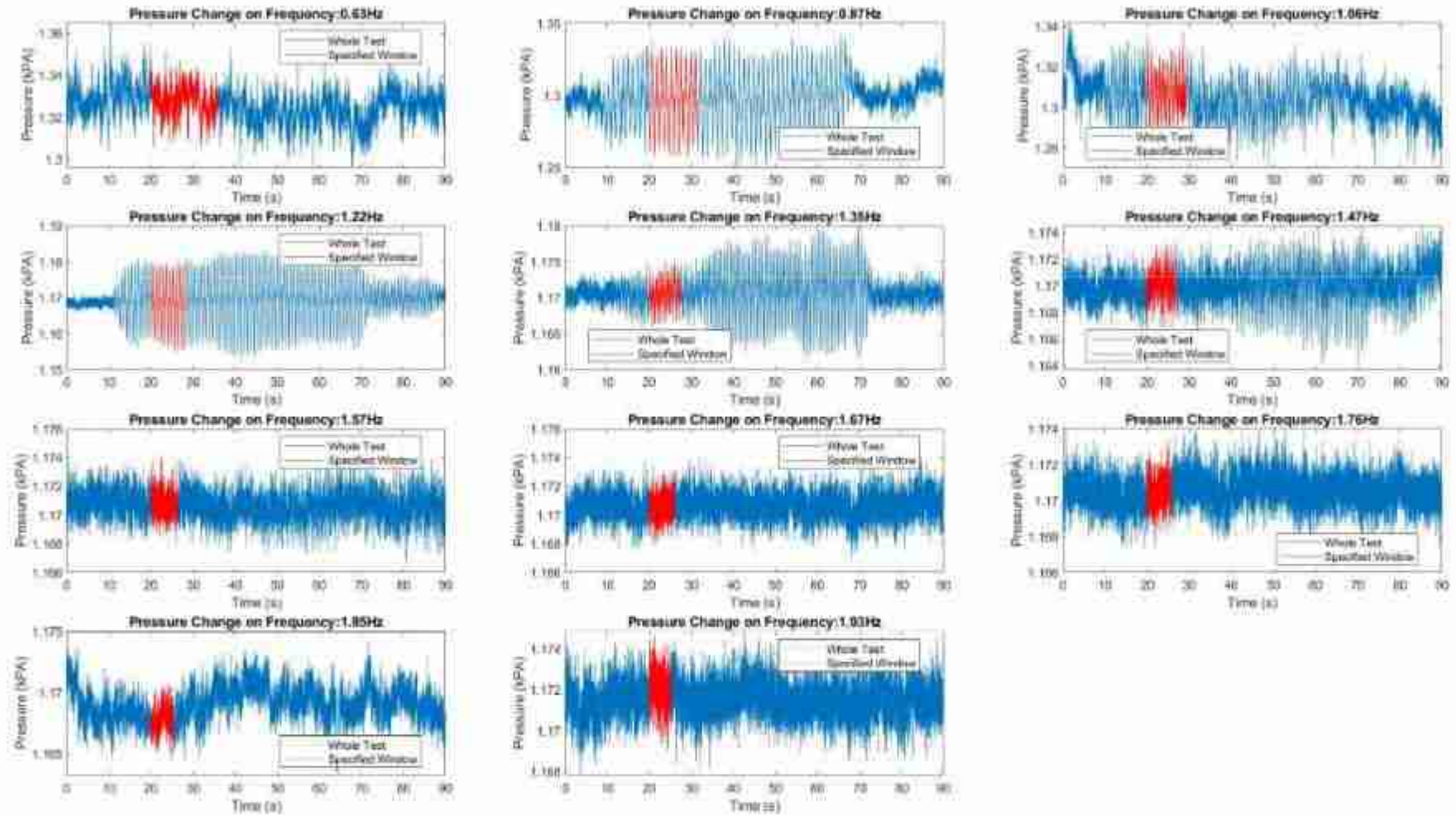


Figure 4-37: Pressure fluctuations: wave amplitude=0.01 m, wave angle=0 degrees, orifice=30 mm, water depth=40 cm

Water Depth Impact on Pressure and Discussions (Figure 4 26 to Figure 4 38)

Under the condition of a 30 cm water depth, it becomes evident that there were a higher number of pressure changes across all wave frequency wave climates, and these changes exhibited greater regularity in comparison to the conditions with a 40 cm water depth. Notably, the 30 cm water depth scenario demonstrated that high-frequency wave climates induced more consistent pressure fluctuations within the OWC, consistent with the findings in FSE results, potentially enabling the harnessing of a larger amount of wave power.

In contrast to the scenarios with a 40 cm water depth, the most effective wave frequency in this 30 cm depth condition was found to be 0.63 Hz. Under this depth, the maximum pressure fluctuation observed between consecutive waves fell within the range of 170-200 Pa, which significantly surpassed the pressure exerted in all other tests. Furthermore, the generation of pressure displayed greater regularity and predictability compared to the default scenario, indicating promising prospects for industrial applications.

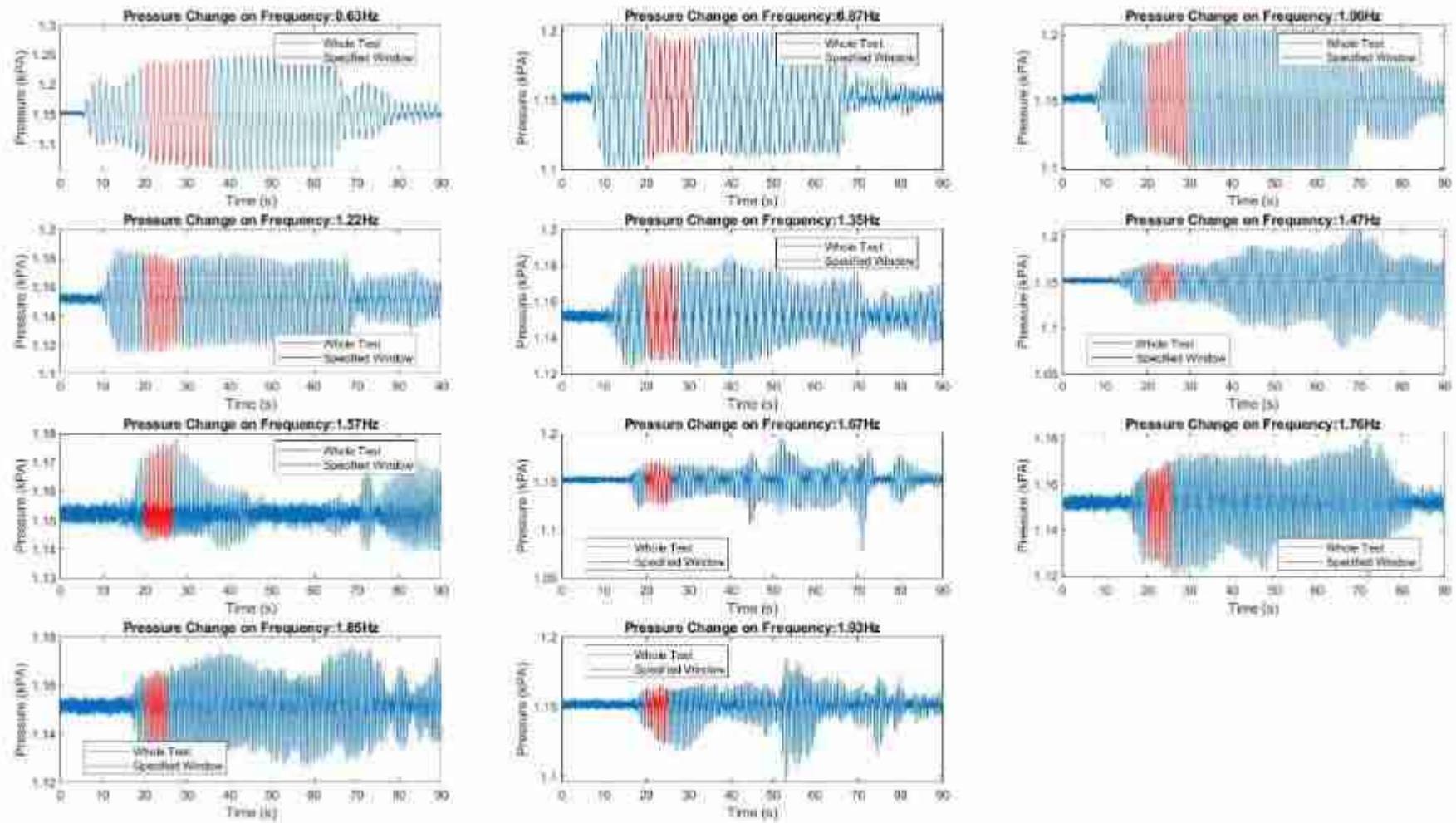


Figure 4-38: Pressure fluctuations: wave amplitude=0.01 m, wave angle=0 degrees, orifice=20 mm, water depth=30 cm

4.3 Capture Width Ratio Results and Discussions

After processing the FSE and Pressure data, capture width ratio (ε_{owc}) for a certain test set can be estimated via following the method explained in chapter 3. A total of 143 instances of capture width ratio numbers are derived by using that method. The results of capture width ratios (ε_{owc}), are classified in four different scenarios with their correspondent frequency sets. The x-axis of the graphs is showing the frequencies and the y-axis is illustrating the capture width ratios (ε_{owc}).

After analysing and checking quality of the FSE and Pressure data in MATLAB, the methodology outlined in chapter 3.3 can be employed to estimate the Capture width ratio (ε_{owc}), for a designated test dataset. A total of 143 instances of capture width ratio values are computed using this approach. The results for capture width ratios (ε_{owc}) are categorized into four distinct scenarios, each with its corresponding frequency distributions. The x-axis of the graphs displays the frequencies, while the y-axis represents the capture width ratios (ε_{owc}).

4.3.1 Capture Width Ratio Results with Wave Amplitude Variance

The wave amplitude varied tests showed that the 0.87 Hz frequency wave conditions established the most efficient setup to harness wave energy, 0.73 in numbers (see Figure Appendix 3). In any other frequency set, the capture width ratio was not higher than 0.4 (see **Figure 4-39**).

Under high-frequency wave conditions (exceeding 1.22 Hz), the OWC device exhibited limited success in the conversion of wave energy into pneumatic power, resulting in a capture width ratio consistently below 0.20. Nevertheless, in the case of a 1.57 Hz wave climate, which differed from the FSE results too, a comparatively

higher capture width ratio was observed when compared to other high-frequency wave climates. However, this performance did not reach the level achieved under 0.87 Hz frequency wave conditions.

Furthermore, it is important to highlight that there was a consistent negative correlation between wave amplitude and the capture width ratio within these test sets. For frequencies below 1.35 (with the exception of 0.63 Hz), the greatest capture width ratios were attained under conditions with a 0.005 m wave amplitude. Conversely, higher wave amplitude conditions yielded lower capture width ratios in response. This pattern aligns with the findings from the FSE analysis, where a larger FSE corresponds to a greater incident wave power, resulting in diminished capture width ratios. This is attributed to the fact that high-amplitude waves failed to generate sufficient pneumatic power within the chamber to match the incident wave power.

Overall, across all frequencies, the optimal wave amplitude among the five tested values was found to be 0.005 m. Nonetheless, the distinctions in efficiencies among these amplitudes were not considered significant.

4.3.2 Capture Width Ratio Results with Wave Angle Variance

As previously discussed in the chapters covering FSE and Pressure results, the influence of wave angles on the OWC device was found to be limited in these experiments. Similarly, the capture width ratios in the context of wave angle scenarios did not exhibit significant variations, as observed with wave amplitudes. With the exception of scenarios involving a 5-degree wave angle, the capture width ratio outcomes followed a consistent pattern. Notably, the 0.87 Hz and 1.57 Hz frequency

wave conditions appeared to be the most favourable wave conditions in these test sets (refer to **Figure 4-40**).

It would be inappropriate to assert that changes in the incoming wave angle directly correspond to changes in capture width ratios in a large scale.

Therefore, within this set of four wave angles, it appeared that 5 and 10 degrees of wave angles exhibited the highest capture width ratios. However, additional research was deemed necessary to fully understand the impact of wave angles on a cylindrical OWC device.

4.3.3 Capture Width Ratio Results with Orifice Size Variance

The most significant outcome observed in the tests involving varied orifice sizes is the confirmation of the non-linear correlation between orifice size and capture width ratio within the scope of these experiments (Sheng et al 2012).

For OWC setups equipped with orifice sizes of 26 mm and 30 mm, it was once again evident that 0.87 Hz frequency wave conditions proved to be the most efficient, resulting in capture width ratios of 1.12 and 1.17, respectively, which were the highest among all tests (refer to Figure Appendix 3: All Incident Wave Power and Capture Width Ratio Results). Despite both of these OWC setups with 26 mm and 30 mm orifice sizes exhibiting optimal efficiency with 0.87 Hz frequency, their performance differed under 1.57 Hz frequency wave conditions. Specifically, the 26 mm orifice size setup proved to be the most efficient in this scenario, while the 30 mm setup was the least efficient under this frequency (see **Figure 4-41**).

Among the five orifice sizes examined, it is reasonable to assert that the most advantageous OWC setup, in terms of capture width ratios, was the one equipped with a 26 mm orifice size, equivalent to 1.7% of the chamber's surface area. Furthermore, the OWC setup with a 30 mm orifice size (equivalent to 2.25% of the chamber's surface area) exhibited impressive performance under low-frequency wave conditions and could be considered as a viable alternative orifice size.

4.3.4 Capture Width Ratio Results with Water Depth Variance

Among all the scenarios considered, variations in water depth had the most pronounced impact on capture width ratios (refer to **Figure 4-42**). Notably, as previously observed in the results concerning FSE and Pressures, high-frequency wave conditions displayed substantial power conversion solely within the context of a 30 cm water depth. Moreover, the wave configurations consistently exhibited regular oscillations in terms of FSE and Pressure, resulting in the establishment of a predictable and consistent pattern. Consequently, the capture width ratios achieved at this depth were exceptionally favourable, with nearly all frequency conditions yielding significantly higher values, with the exception of the 0.87 Hz frequency conditions, which were already the most effective for a 40 cm water depth (see **Figure 4-42**).

With the exception of the 0.87 Hz frequency across all wave conditions, the capture width ratios at a 30 cm water depth exceeded at least twice the capture width ratios observed at a 40 cm water depth (refer to Figure Appendix 3). Furthermore, high-frequency wave conditions (greater than 1.57 Hz) proved to be ten times more efficient with the 30 cm water depth setups compared to the 40 cm water depth setups.

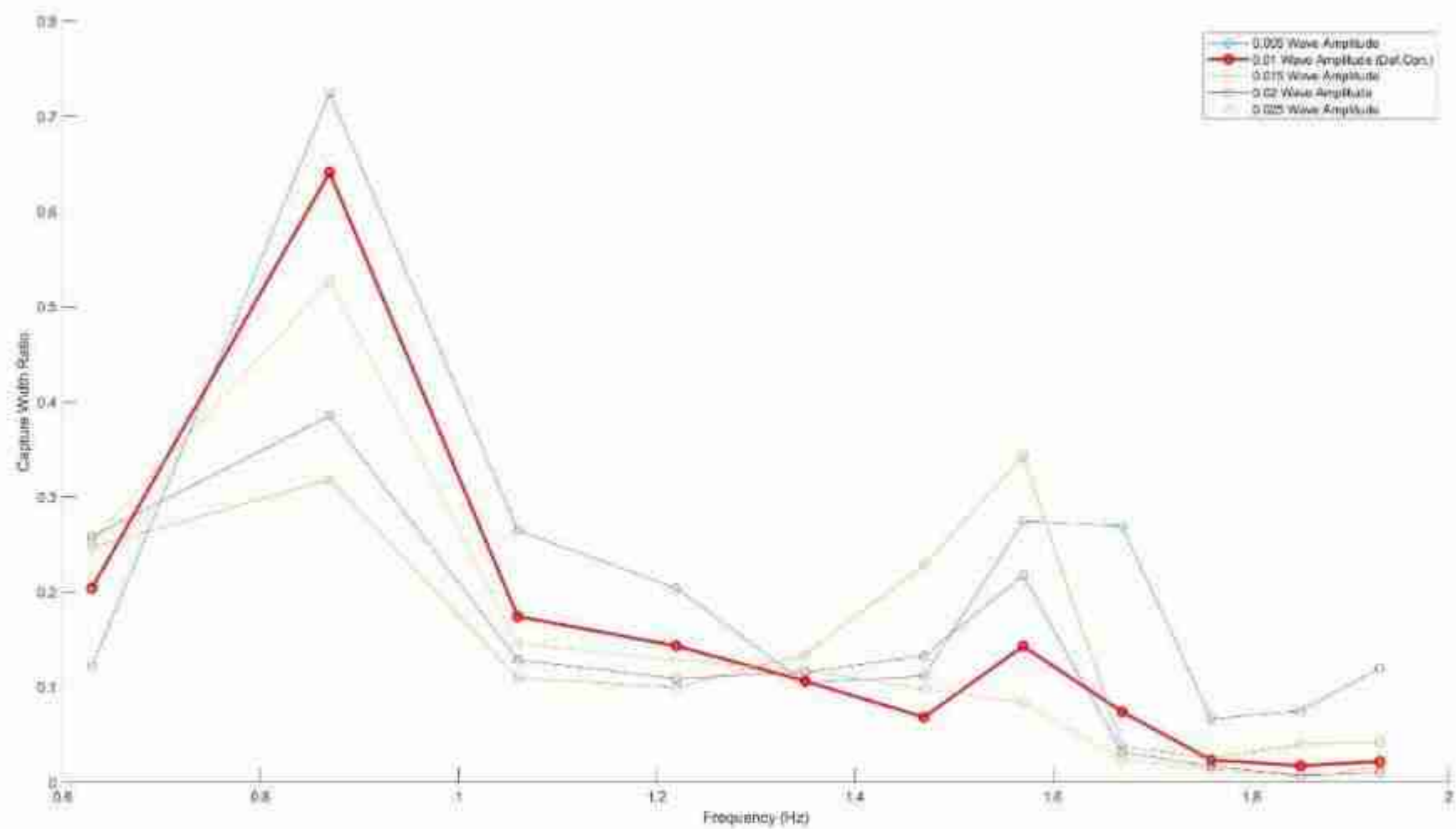


Figure 4-39: Capture width ratios to frequencies with different wave amplitudes

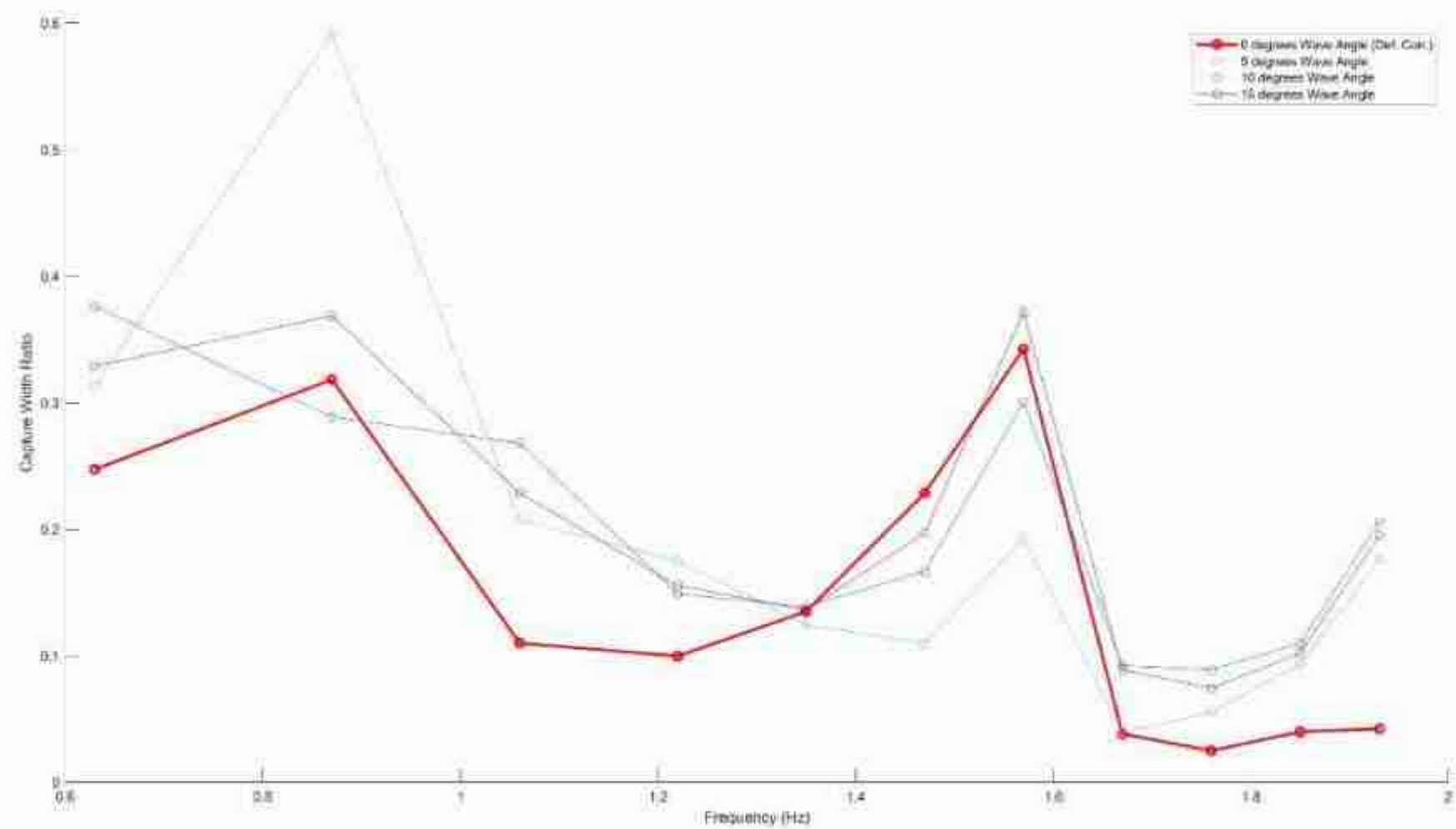


Figure 4-40: Capture width ratios to frequencies with different wave angles

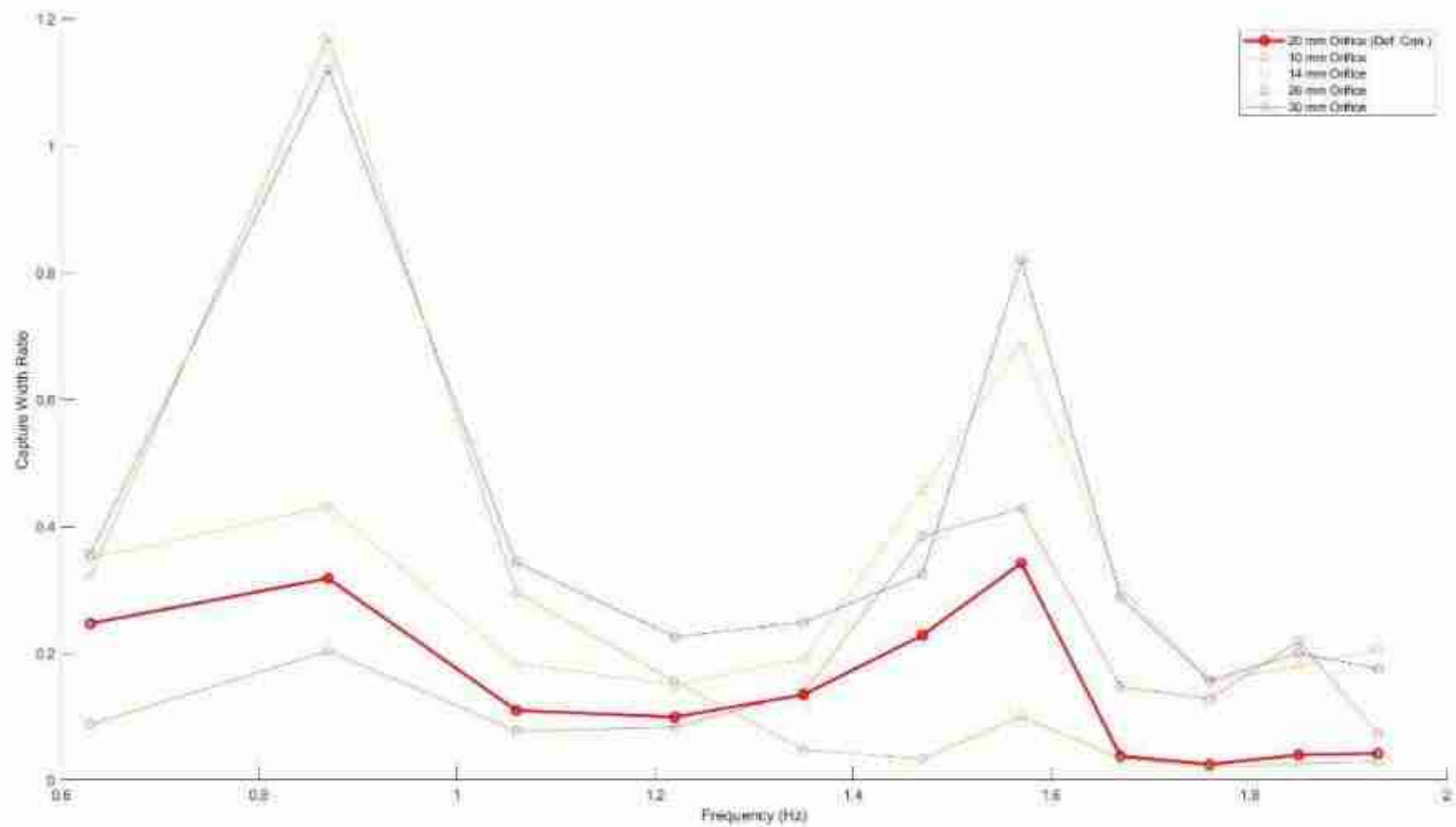


Figure 4-41: Capture width ratios to frequencies with different orifice sizes

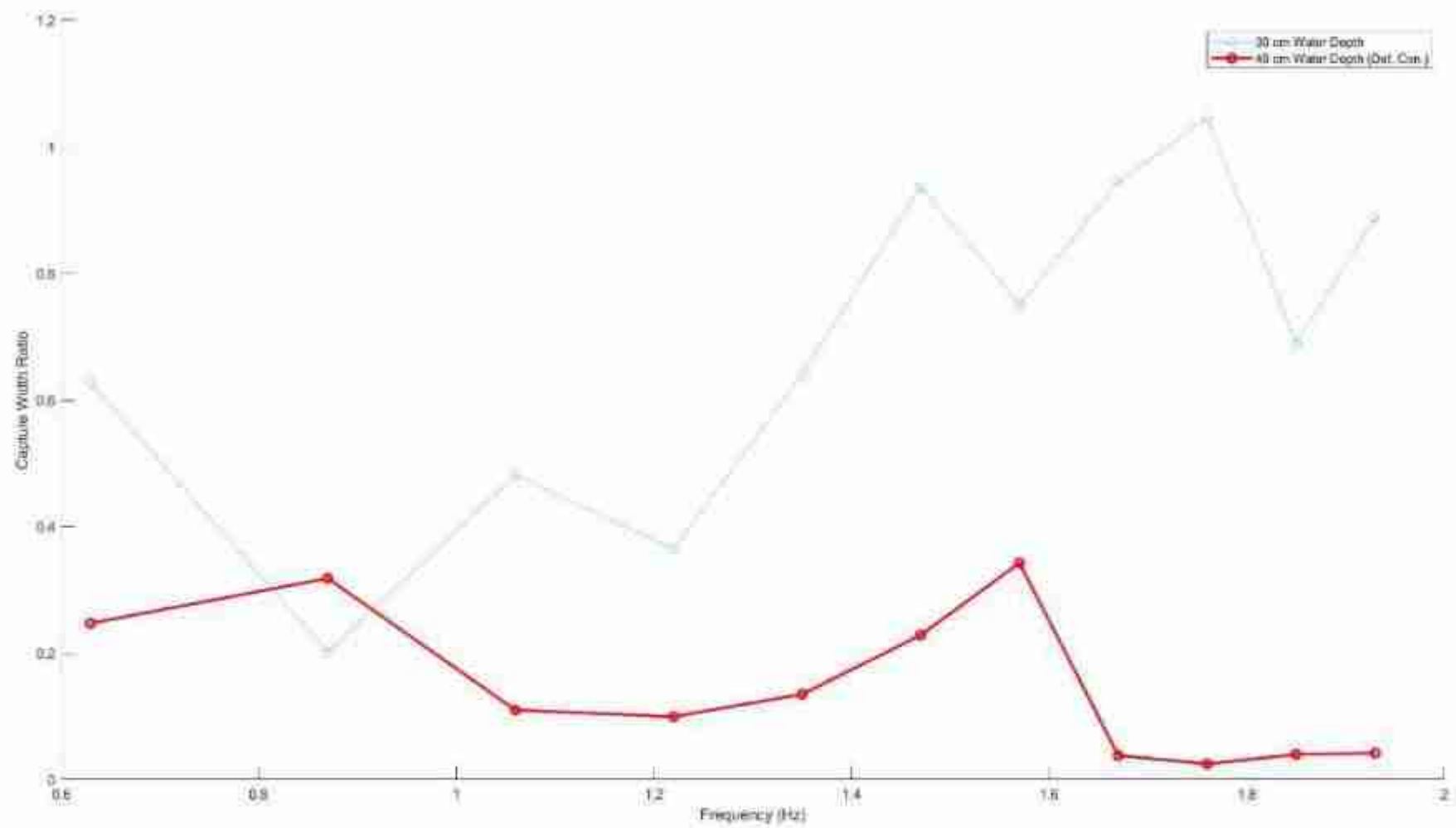


Figure 4-42: Capture width ratios to frequencies with a different water depth

4.4 General Discussions over Findings

The findings are evaluated, and following discussions are made in distinct aspects as bullet points, apart from the previous results and discussions.

- Test day observations showed that the larger wavelength wave conditions cause piston motion inside the chamber (0.63 Hz and 0.87 Hz), whereas the high frequency wave climates were mostly following irregular FSE alteration patterns inside chamber and might cause sloshing mechanisms especially with the 40 cm water depths. Having only one wave measurer inside the chamber did not give a chance to observe the piston or sloshing motion inside the chamber with a great accuracy. Hence, as a suggestion, including one or two more wave measurers inside the chamber would help test runners to comprehend this motion better.
- The findings indicated the absence of resonance phenomena within the chamber under 40 cm water depth conditions. Nonetheless, it is noteworthy that resonances have the potential to substantially enhance water motion velocity, thereby potentially leading to a more significant improvement in the efficiency of the OWC device, as observed in the 30 cm water depth scenarios. In these cases, wave amplitudes increased to more than double and triple the intended wave amplitudes.
- The experimental configuration included six wave measurement devices, with one of them positioned exclusively within the chamber, while the remaining five were located outside of the chamber. Although these five external wave probes allowed for observations of wave reflections from the breakwater, it was not the primary focus of this study. Nevertheless, the presence of multiple probes and

the remaining FSE data correspond to these wave measurers present an opportunity to explore additional wave-related effects on this OWC device integrated with a breakwater in future analyses.

- Under the influence of 1.57 Hz frequency wave conditions, the FSE within the chamber predominantly exhibited a distinctive and consistent pattern of either gradual increase or decrease throughout the tests. This phenomenon necessitates further physical investigations for a comprehensive understanding (refer to **Figure 4-1** to **Figure 4-8**).
- One of the most crucial outcomes of the Empty basin tests pertains to the overall assessment of the test setup's calibration. For the default water depth (40 cm) or corresponding (kh) values, it was observed that the target wave amplitudes could not be consistently achieved by the wave generators in numerous wave climates, whether inside or outside the chamber. In contrast, the 30 cm water depth cases successfully attained the desired target amplitudes exclusively in the empty basin tests (refer to **Figure 4-25**). This discrepancy may be attributed to a range of factors, one of which could be the submergence depth. To gain a comprehensive understanding and make definitive claims regarding the influence of submergence depth on the inability to reach the target wave amplitudes, further investigations are warranted, involving a broader range of wave setups encompassing diverse water depths and (kh) values.
- The capture width ratio is notably affected by wave amplitude. However, it is important to highlight that only under 0.87 Hz frequency wave conditions, high Capture Width Ratio values exceeding 0.30 were evident when wave amplitudes were modified. For this specific frequency, with a wavelength of

around 1.8 m (refer to Figure Appendix 1), considering a 40 cm water depth and a 0.4 m device radius (B), the ratio of the device length (B) along the wave direction to the wavelength (λ) stands at 2/9. This observation aligns with Sheng et al. (2012) findings, which suggested that the size of the device should be limited to the wavelength of the incoming wave to avoid the potential occurrence of sloshing effects inside the OWC. According to their research, if the horizontal size of the OWC device exceeds 1/4 or 1/5 of the incoming wavelength, there is a higher likelihood of initiating a sloshing motion within the chamber. This, in turn, significantly reduces the device's efficiency, particularly when dealing with smaller wavelengths and higher wave frequencies.

- The effect of wave angle was not significant on capture width ratio. The default wave conditions, and the wave angle situations are showing that up to 15 degrees of angle change does not affect the OWC device efficiencies dramatically (see **Figure 4-40**). It is unable to claim that a certain wave angle was more efficient, in terms of generating more pneumatic power than the other cases. Nonetheless, it is important to recognize that the OWC device had a cylindrical design, which could potentially limit the significance of wave angle effects. Therefore, caution should be exercised when applying the findings regarding wave angle effects from this study to a different experimental setup involving a rectangular or alternative geometry for the OWC device within a 3D testing environment. Engaging in such an approach could potentially lead to incorrect results that are lacking in precision.
- The water depth is by far the most powerful parameter to make the positive significant changes in the tests. Only conducting eleven tests with this water depth may not be convincing to reach certain conclusions. However, when it is

compared to the default water depth scenarios, ten out of eleven tests were resulted above a satisfying capture width ratio (0.36) which could not be reached any parameter set with the default depth (40 cm). Only with this water depth, significant resonances inside the chamber had been measured, which is an extremely contributing factor to the capture width ratio.

5 Conclusion

There are multiple outcomes of the tests for this experimental study. Not only the calculated parameters, but also the experimental conditions in the laboratory are significantly effective when it comes to derive OWC device efficiency. Having limited to one single cylindrical geometric design of the breakwater integrated OWC device, it was unable to observe the effects of the different chamber width, opening size at the bottom of the device, the opening ratio, and other geometric aspects of the system. Additionally, due to constraints related to laboratory conditions and the limited testing time available, it was impractical to investigate the effects of numerous parameters. However, multiple wave conditions and occurrences of resonances in different setups are noted.

In summary, based on the conducted tests, in the case of 40 cm water depth only, it can be asserted that the most economically viable wave climate for wave energy harnessing is characterized by low frequency and wave amplitude, in conjunction with the installation of a large orifice (comprising more than 1.5% of the chamber surface area) on the OWC device. This observation holds true irrespective of the angles at which the incoming waves align, up to 15 degrees relative to the perpendicular wave direction. However, the influence of water depth emerges as a crucial and promising factor in appropriately configured setups, as it has the potential to induce significant resonances, thereby enabling greater energy harnessing with high wave amplitudes and high frequency wave climates. Consequently, for a more precise evaluation of the efficiency of this OWC device in terms of water depth (h), further testing is imperative, encompassing various water depths and (kh) values while maintaining a consistent frequency set, and varying orifice sizes and wave amplitudes in conjunction with these factors.

List of References

- Boccotti, P. (2007) "Comparison between a U-OWC and a conventional OWC," *Ocean Engineering*, 34(5–6), pp. 799–805. Available at: <https://doi.org/10.1016/j.oceaneng.2006.04.005>.
- Carlo, L., Iuppa, C. and Faraci, C. (2023) "A numerical-experimental study on the hydrodynamic performance of a U-OWC wave energy converter," *Renewable Energy*, 203, pp. 89–101. Available at: <https://doi.org/10.1016/j.renene.2022.12.057>.
- Çelik, A. and Altunkaynak, A. (2019) "Experimental investigations on the performance of a fixed-oscillating water column type wave energy converter," *Energy*, 188, p. 116071. Available at: <https://doi.org/10.1016/j.energy.2019.116071>.
- Evans, D.V. (1978) "The oscillating water column wave-energy device," *Ima Journal of Applied Mathematics*, 22(4), pp. 423–433. Available at: <https://doi.org/10.1093/imamat/22.4.423>.
- Falcão, A.F.O. and Henriques, J.C.C. (2016) "Oscillating-water-column wave energy converters and air turbines: A review," *Renewable Energy*, 85, pp. 1391–1424. Available at: <https://doi.org/10.1016/j.renene.2015.07.086>.
- Heath, T. (2012) "A review of oscillating water columns," *Philosophical Transactions of the Royal Society A*, 370(1959), pp. 235–245. Available at: <https://doi.org/10.1098/rsta.2011.0164>.
- Kim, J.-S. *et al.* (2023) "Experimental study on hydrodynamic behaviour and energy conversion of multiple oscillating-water-column chamber in regular waves," *Ocean*

Engineering, 280, p. 114495. Available at:
<https://doi.org/10.1016/j.oceaneng.2023.114495>.

Li, X. *et al.* (2023) "Experimental study on the aerodynamic performance and wave energy capture efficiency of square and curved OWC wave energy conversion devices," *Sustainability*, 15(6), p. 4963. Available at:
<https://doi.org/10.3390/su15064963>.

Mahnamfar, F. and Altunkaynak, A. (2015) "OWC-Type Wave chamber optimization under series of regular waves," *Arabian Journal for Science and Engineering*, 41(4), pp. 1543–1549. Available at: <https://doi.org/10.1007/s13369-015-1691-0>.

Mahnamfar, F., Altunkaynak, A. and Abdollahzadeh moradi, Y. (2019) "Comparison of Experimental and Numerical Model Results of Oscillating Water Column System Under Regular Wave Conditions," *Iranian Journal of Science and Technology-Transactions of Civil Engineering* [Preprint]. Available at:
<https://doi.org/10.1007/s40996-019-00259-x>.

Mustapa, M.A. *et al.* (2017) "Wave energy device and breakwater integration: A review," *Renewable & Sustainable Energy Reviews*, 77, pp. 43–58. Available at:
<https://doi.org/10.1016/j.rser.2017.03.110>.

Ning, D. *et al.* (2016) "An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter," *Applied Energy*, 168, pp. 636–648. Available at:
<https://doi.org/10.1016/j.apenergy.2016.01.107>.

Ning, D. *et al.* (2020) "Experimental investigation on the hydrodynamic performance of a cylindrical dual-chamber Oscillating Water Column device," *Applied Energy*, 260, p. 114252. Available at: <https://doi.org/10.1016/j.apenergy.2019.114252>.

Orphin, J. *et al.* (2022) "Experimental investigation into laboratory effects of an OWC wave energy converter," *Renewable Energy*, 186, pp. 250–263. Available at <https://doi.org/10.1016/j.renene.2021.12.092>.

Perez-Collazo, C. *et al.* (2019) "Monopile-mounted wave energy converter for a hybrid wind-wave system," *Energy Conversion and Management*, 199, p. 111971. Available at: <https://doi.org/10.1016/j.enconman.2019.111971>.

Perez-Collazo, C., Greaves, D. and Iglesias, G. (2018) "A novel hybrid Wind-Wave energy converter for Jacket-Frame substructures," *Energies*, 11(3), p. 637. Available at: <https://doi.org/10.3390/en11030637>.

Sağlam, M., Sulukan, E. and Uyar, T. S. (2010) "WAVE ENERGY AND TECHNICAL POTENTIAL OF TURKEY," *Journal of Naval Sciences and Engineering*, 6(2), pp. 34–50. Available at: https://www.dho.edu.tr/sayfalar/02_Akademik/Egitim_Programlari/Deniz_Bilimleri_Enstitusu/Dergi/022_Mustafa_Saglam.pdf.

Sheng, W., Alcorn, R. and Lewis, A. (2014) "Assessment of primary energy conversions of oscillating water columns. II. Power take-off and validations," *Journal of Renewable and Sustainable Energy*, 6(5). Available at: <https://doi.org/10.1063/1.4896851>.

Sheng, W., Lewis, A. and Alcorn, R. (2012) *Numerical Studies of a Floating Cylindrical OWC WEC*. Available at: <https://doi.org/10.1115/omae2012-83041>.

Whittaker, T. *et al.* (1997) "THE ISLAY WAVE POWER PROJECT: AN ENGINEERING PERSPECTIVE," *Proceedings of the Institution of Civil Engineers*, 124(3), pp. 189–201. Available at: <https://doi.org/10.1680/iwtme.1997.29783>.

Zheng, S., Zhang, Y. and Iglesias, G. (2019) "Coast/breakwater-integrated OWC: A theoretical model," *Marine Structures*, 66, pp. 121–135. Available at: <https://doi.org/10.1016/j.marstruc.2019.04.001>.

Appendices

Appendix A – MATLAB Script to calculate the Capture Width Ratios

```
%% Part 1 - Initial Parameters and Data Importing

clear
close all

% OWC device physically created in coastal laboratory %
OWCDiameter = 0.4;

% Cross-sectional (surface) area of the OWC chamber %
Area=pi*OWCDiameter^2/4;

% The frequencies are decided before the experiments %
f = [0.63, 0.87, 1.06, 1.22, 1.35, 1.47, 1.57, 1.67, 1.76, 1.85, 1.93];
Periods = 1./f;

% Wave Count, in order to specify a time window %
N = input('Wave count (N):');

% The frequency of measurement of the testing device %
SamplingFrequency = 128;
Time_Step = 1/128;

% the folder where the data exist/saved %
FolderPath = './';

% listing pressure files %
PressureFileList = dir(fullfile(FolderPath, '*.lum'));

% listing free surface elevation (FSE) files %
WaveGaugeFileList = dir(fullfile(FolderPath, '*.txt'));

% Establishing required cells to store files before looping, to save time %
FSE = cell(1,143);
MeasuredPressure = cell(1,143);
BackgroundPressure = cell(1,143);

% As default 20th second of the test is selected as the initial moment of the time %
% window, tstart represents the index number of 20th second in time array %
Ts = input('Time window starting instance (Ts):');
tstart = Ts*SamplingFrequency+1;

% time window ending points for affillisted frequencies %
tend = zeros(1,11);

% The loop is extracting pressure and wave gauge data from the files %
% saved in specified folder path. Unnecessary information is removed from %
% the gauge data and rerecorded as in the end of loop %
for aa = 1:143
    PressureFileName = PressureFileList(aa).name;
    WaveGaugeFileName = WaveGaugeFileList(aa).name;
    P = importdata(PressureFileName, '\t', 15);
    W = importdata(WaveGaugeFileName, '\t', 5);
    Pressure = P.data;
    WaveGauge = W.data;
    WaveGauge(any(isnan(WaveGauge), 2), :) = [];
    if size(WaveGauge, 2) >= 7
        WaveGauge(:, 7) = [];
    end
    FSE{aa}=WaveGauge;
    MeasuredPressure{aa}=Pressure(:,2);
    Time=Pressure(:,1);
end
clear('aa');

%% Part 2 - Calculations
```

```

% Establishing required cells to store files before looping, to save time %
InsPow = cell(1,143);
TotalPower = cell(1,143);
Mean_Power = cell(1,143);

% Following loop description %
% Line 79: Estimating time window boundaries %
% Line 80: Mean value of pressure amplitudes give background pressure %
% Line 82-84: Calculating the instant and then total power %
% Line 85: Calculating mean power per single wave dividing total power to period %
for aa=1:13
    for ab=1:11
        tend(ab) = tstart+ceil(N*Periods(ab)/Time_Step);
        BackgroundPressure{(11*(aa-1)+ab)}=mean(MeasuredPressure{(11*(aa-1)+ab)}(tstart:tend(ab)));
        for ac=tstart:tend(ab)
            InsPow{(11*(aa-1)+ab)}(ac)=abs(((MeasuredPressure{(11*(aa-1)+ab)}(ac))-
            BackgroundPressure{(11*(aa-1)+ab)})*1000*Area*(FSE{(11*(aa-1)+ab)}(ac,1)-FSE{(11*(aa-1)+ab)}(ac-
            1,1))/Time_Step);
            TotalPower{(11*(aa-1)+ab)}=sum(InsPow{(11*(aa-1)+ab)});
        end
        Mean_Power{(11*(aa-1)+ab)}=(TotalPower{(11*(aa-1)+ab)}*Time_Step)/(Time(tend(ab))-Time(tstart));
    end
end

%% Part 3 - Plots and Extractions

% saving the mean power values to an external file %
% writecell(Mean_Power,'BasicCalculationPower.csv');

% Following loop saves the pressure alterations, and free surface elevation plots to desired file path
%
for ad=1:13
    figure
    % set(gcf, 'Position', get(0, 'Screensize'));
    for ae=1:11
        subplot(4,3,ae)
        plot(Time,MeasuredPressure{(11*(ad-1)+ae)})
        hold on
        plot(Time(tstart:tend(ae)),MeasuredPressure{(11*(ad-1)+ae)}(tstart:tend(ae)),'r')
        xlim([0 90])
        dynamic_title = ['Pressure Change on Frequency:', num2str(f(ae)), 'Hz'];
        title(dynamic_title);
        xlabel('Time (s)')
        ylabel('Pressure (kPa)')
        legend(['Whole Test','Specified Window'],'Location','best')
    end
    % saveas(gcf, fullfile('C:\Users\ozan_OneDrive - University of Plymouth\MSc Coastal
    Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Pressure_' num2str(ad) '.png']), 'png');
    % close(gcf);
end
%%
for af=1:13
    figure
    % set(gcf, 'Position', get(0, 'Screensize'));
    for ag=1:11
        subplot(4,3,ag)
        plot(Time(1:11517),FSE{(11*(af-1)+ag)}(:,1))
        hold on
        plot(Time(tstart:tend(ag)),FSE{(11*(af-1)+ag)}(tstart:tend(ag),1),'r');
        xlim([0 90])
        dynamic_title2 = ['FSE Change at Frequency:', num2str(f(ag)), 'Hz'];
        title(dynamic_title2)
        xlabel('Time (s)')
        ylabel('FSE (m)')
        legend(['Whole Test','Specified Window'],'Location','best')
    end
    % saveas(gcf, fullfile('C:\Users\ozan_OneDrive - University of Plymouth\MSc Coastal
    Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Free_Surface_Elevation_' num2str(af) '.png']),
    'png');
    % close(gcf);
end
%%
% Getting the data from another file to estimate Capture Width Ratio %
Filename = 'Ozan_log_updated_Extended_calculations.xlsx';

```

```

sheetname = 'TestsAndCalculationsAMPLITUDE';
dataTable = readtable(filename, 'Sheet', sheetname);
CaptureWidthRatios = table2array(dataTable(2:144,29));

% Following loops generate Capture width Ratio plots %
figure
set(gcf, 'Position', get(0, 'Screensize'));
hold on
colors = lines(5);
for ah = 1:5
    temp1 = CaptureWidthRatios(11*ah-10:11*ah);
    if ah == 2 % Check if it's the second curve
        plot(f, temp1, 'o-', 'Color', 'red', 'Linewidth', 2) % Set color to red and line width to 2
    else
        plot(f, temp1, 'o-', 'Color', colors(ah, :))
    end
end
xlabel('Frequency (Hz)')
ylabel('Capture Width Ratio')
legend({'0.005 Wave Amplitude', '0.01 Wave Amplitude (Def.Con.)', '0.015 Wave Amplitude', '0.02 Wave Amplitude', '0.025 Wave Amplitude'})
saveas(gcf, fullfile('C:\Users\oian_OneDrive - University of Plymouth\MSc Coastal Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Capture_width_ratio_1' '.png']), 'png');
hold off
%%
figure
set(gcf, 'Position', get(0, 'Screensize'));
hold on
colors = lines(8); % Predefined colors for the curves
for ah = 2
    plot(f, temp1, 'o-', 'Color', 'red', 'Linewidth', 2)
end
for ah = 6:8
    temp2 = CaptureWidthRatios(11*ah-10:11*ah);
    plot(f, temp2, 'o-', 'Color', colors(ah, :))
end
xlabel('Frequency (Hz)')
ylabel('Capture Width Ratio')
legend({'0 degrees Wave Angle (Def. Con.)', '3 degrees Wave Angle', '10 degrees Wave Angle', '15 degrees Wave Angle'})
saveas(gcf, fullfile('C:\Users\oian_OneDrive - University of Plymouth\MSc Coastal Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Capture_width_ratio_2' '.png']), 'png');
hold off
%%
figure
set(gcf, 'Position', get(0, 'Screensize'));
hold on
colors = lines(12); % Predefined colors for the curves
for ah = 2
    plot(f, temp1, 'o-', 'Color', 'red', 'Linewidth', 2)
end
for ah = 9:12
    temp3 = CaptureWidthRatios(11*ah-10:11*ah);
    plot(f, temp3, 'o-', 'Color', colors(ah, :))
end
xlabel('Frequency (Hz)')
ylabel('Capture Width Ratio')
legend({'20 mm Orifice (Def. Con.)', '10 mm Orifice', '14 mm Orifice', '28 mm Orifice', '30 mm Orifice'})
saveas(gcf, fullfile('C:\Users\oian_OneDrive - University of Plymouth\MSc Coastal Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Capture_width_ratio_3' '.png']), 'png');
hold off
%%
figure
set(gcf, 'Position', get(0, 'Screensize'));
hold on
colors = lines(13); % Predefined colors for the curves
for ah = 13
    temp4 = CaptureWidthRatios(11*ah-10:11*ah);
    plot(f, temp4, 'o-', 'Color', colors(ah, :))
end
for ah = 2
    plot(f, temp1, 'o-', 'Color', 'red', 'Linewidth', 2)
end

```

```

xlabel('Frequency (Hz)')
ylabel('Capture Width Ratio')
legend({'30 cm Water Depth','40 cm Water Depth (Def. Con.)'})
saveas(gcf, fullfile('C:\Users\osan_OneDrive - University of Plymouth\MSc Coastal Engineering\3-PROJ517-Dissertation\Matlab Figures\', ['Capture_width_ratio_4' '.png']),'png');
hold off
%% Part - 4 Cleaning

% Removing unnecessary variables %
clear('aa','ab','ac','ad','ae','af','ag','ah','ai','aj','data','filename','folderPath','loopRange');
clear('PressureFileName','sheetname','tmps','tmpa','WaveGaugeFileNames','P','W','temp4','temp3','temp2','temp1');
clear('dynamic_title','dynamic_titles');

```

Appendix B – Empty Basin FSE Fitted Curve Script

```

%% Part 1 - Initial/Default Parameters %%
clear
N = input('wave count (N):'); % wave count
Ts = input('Time Window Starting Instance (Ts):'); % Ts defines the moment of test when the
calculation starts
OrbDiameter = 0.4; % m
ChamberSurfaceArea = (OrbDiameter*OrbDiameter*pi)/4; % m2
OrificeDiameters = [0.010, 0.014, 0.020, 0.026, 0.030]; % m
OrificeArea = (OrificeDiameters.*OrificeDiameters*pi)/4; % m2
Gravity = 9.81; % m/s2
WaterDensity = 1000; % kg/m3
AirDensity = 1.2; % kg/m3
Time_Step = 0.0078125; % The specification of the test device
Frequencies = [0.63, 0.87, 1.06, 1.22, 1.35, 1.47, 1.57, 1.67, 1.76, 1.85, 1.93]; % list of
frequencies used in tests
Periods = 1./Frequencies; % inverse of frequency gives the corresponded periods
AmplitudesForEachEmptyBasinTestSet = [0.01 0.005 0.015 0.02 0.025 0.01 0.01 0.01 0.01];
SampleFrequency = 128;

%% Part 2 - Detect and Locate Measured Pressure Files %%

folderPath = './';
PressureFileList = dir(fullfile(folderPath, '*.lum')); % directory of files
DesiredNumRows = 11517;
Measured_Test_Pressures=cell(1,143);
Background_Pressures=cell(1,143);
Absolute_Pressures=cell(1,143);
for aa = 1:numel(PressureFileList)
    PressureFileName = PressureFileList(aa).name;
    PressureFilePath = fullfile(folderPath, PressureFileName);
    temporarypressuredata = dimread(PressureFilePath, '\t', 15, 0);
    if size(temporarypressuredata, 1) > DesiredNumRows % Check if the number of rows exceeds the
desired number
        temporarypressuredata = temporarypressuredata(1:DesiredNumRows, :); % Remove unnecessary rows
from pdata
    end
    Measured_Test_Pressures{aa} = temporarypressuredata(:,2);
    temparray=Measured_Test_Pressures{aa};
    Background_Pressures{aa} = mean(temparray(1:500)); % First 500 time steps are taken into
consideration to find background pressures
    Absolute_Pressures{aa}=Measured_Test_Pressures{aa}-Background_Pressures{aa};
end
Test_Time_Array = temporarypressuredata(:,1);
clear('temporarypressuredata','temparray','aa','DesiredNumRows');

%% Part 3 - Detect and Locate Gauges Surface Elevations Files, Calculate and Store Velocity Cells %%

folderPath = './';
GaugesFileList = dir(fullfile(folderPath, '*.txt'));
Tests_Gauges=cell(1,242);
for ab = 1:numel(GaugesFileList)
    GaugesFileName = GaugesFileList(ab).name;
    gdata = importdata(GaugesFileName);
    Gauges = gdata.data;
    Gauges(any(isnan(Gauges), 2), :) = [];
    if size(Gauges, 2) >= 7
        Gauges(:, 7) = [];
    end
    Tests_Gauges{ab} = Gauges;
end

%% Part 4 - Establishing Fitting Curves to Original Empty Basin FSE Gauge Data (From other Gauges) %
FittedAmplitudes=cell(1,99);
MeasuredFSE=cell(1,99);
FittedFSE=cell(1,99);
temptimearray=cell(1,11);
for ac=1:9
    for ad=1:11

```

```

    temptimestart = Ts*SampleFrequency+1; % default 10th second %
    temptimeend = temptimestart + (N*Periods(ad)/Time_Step); % Establishing time window boundaries
    temptimearray{(ad)} = Test_Time_Array(temptimestart:round(temptimeend)); % Time window
definition
    MeasuredFSE{(11*ac+ad-11)}= Tests_Gauges(143+(11*ac+ad-
11))(temptimestart:round(temptimeend),1); % Creating windowed FSE files
    sinusoidal_model = @(params, t) params(1) * cos(2 * pi * Frequencies(ad) * t + params(2)); %
The function to generate the fitting curve
    initial_guess_A = AmplitudesForEachEmptyBasinTestSet(ac); % Initial guess for amplitude
    initial_guess_phi = pi/2; % Initial guess for phase angle
    initial_params = [initial_guess_A, initial_guess_phi]; % combine initial guesses into a
parameter vector
    fitted_params = lsqcurvefit(sinusoidal_model, initial_params, temptimearray{(ad)},
MeasuredFSE{(11*ac+ad-11)}); % Perform nonlinear least squares curve fitting technique
    FittedAmplitudes{(11*ac+ad-11)}= fitted_params(1); % Generating fitted wave amplitudes
    fitted_phi = fitted_params(2);
    FittedFSE{(11*ac+ad-11)} = sinusoidal_model(fitted_params, temptimearray{(ad)}); % Generate
the predicted curve using the fitted parameters
    end
end

% Plot the original data and the fitted curves to see how well they fit, and save them in desired
folder %

for ae=1:9
    figure;
    set(gcf, 'Position', get(0, 'Screensize'));
    for af=1:11
        subplot(4,3,af)
        plot(temptimearray{af}, MeasuredFSE{(11*ae+af-11)}, 'b.', 'DisplayName', 'Original Data');
        hold on;
        plot(temptimearray{af}, FittedFSE{(11*ae+af-11)}, 'r-', 'DisplayName', 'Fitted Curve');
        xlabel('Time (s)');
        ylabel('Free Surface Elevation (m)');
        dynamic_title = ['Fitted Cosine Curve to FSE on Frequency:', num2str(Frequencies(af)), 'Hz'];
        title(dynamic_title);
        legend('Location', 'Best');
        grid on;
    end
    saveas(gcf, fullfile('C:\Users\ozan\OneDrive - University of Plymouth\MSc Coastal Engineering\3-
FROJSI7-Dissertation\Matlab Figures\', ['FSE_FSE_' num2str(ae) '.png']), 'png');
end
clear("ac","ad","ae","af")

```

Appendix C - Incident Wave Power Calculation In Excel

EQUIVALENT EMPTY BASIN TESTS			Freq. (f) (Hz)	Period (T)(s)	Ang. Freq. (w)(Hz)	Water Depth (h)(m)	Wave Number (k)(rad/m)	kh	Generated Wave Amp (A _{eb})(m)	Wave length (λ)(m)	Wave Steepness (ws)(d.less)	Wave Celerity (c) (m/s)	Group Velocity (C _g)(m/s)	Power of Wave (P _w)(W/m)	Pneumatic Power B.A P _p (W)	Calculated Wave Ratio(C _w) (d.less)
Date	Time	Empty Basin Test Name														
22062023	11:35	run155_Sine Freq=0.93Hz Amp=0.005m ang=0deg EB_40	0.63	1.59	3.96	0.40	2.24	0.89	0.0020	2.81	0.0014	1.77	1.43	0.0279	0.0014	0.1217
	11:38	run156_Sine Freq=0.97Hz Amp=0.005m ang=0deg EB_40	0.87	1.15	5.47	0.40	3.46	1.38	0.0027	1.82	0.0029	1.58	1.07	0.0376	0.0109	0.7241
	11:41	run157_Sine Freq=1.06Hz Amp=0.005m ang=0deg EB_40	1.06	0.94	6.66	0.40	4.73	1.89	0.0030	1.33	0.0046	1.41	0.82	0.0375	0.0040	0.2649
	11:45	run158_Sine Freq=1.22Hz Amp=0.005m ang=0deg EB_40	1.22	0.82	7.67	0.40	6.08	2.43	0.0034	1.03	0.0066	1.26	0.68	0.0387	0.0032	0.2039
	11:48	run159_Sine Freq=1.35Hz Amp=0.005m ang=0deg EB_40	1.35	0.74	8.48	0.40	7.37	2.95	0.0029	0.85	0.0069	1.15	0.59	0.0250	0.0010	0.1047
	11:51	run160_Sine Freq=1.47Hz Amp=0.005m ang=0deg EB_40	1.47	0.68	9.24	0.40	8.71	3.48	0.0023	0.72	0.0065	1.06	0.54	0.0144	0.0006	0.1116
	11:54	run161_Sine Freq=1.57Hz Amp=0.005m ang=0deg EB_40	1.57	0.64	9.86	0.40	9.93	3.97	0.0020	0.63	0.0065	0.99	0.50	0.0102	0.0011	0.2747
23062023	10:29	run162_Sine Freq=3.07Hz Amp=0.003m ang=0deg EB_40	1.67	0.60	10.49	0.40	11.23	4.49	0.0015	0.56	0.0053	0.93	0.47	0.0051	0.0005	0.2093
	10:32	run163_Sine Freq=1.76Hz Amp=0.005m ang=0deg EB_40	1.76	0.57	11.06	0.40	12.47	4.99	0.0018	0.50	0.0070	0.89	0.44	0.0067	0.0003	0.0666
	10:35	run164_Sine Freq=1.85Hz Amp=0.003m ang=0deg EB_40	1.85	0.54	11.62	0.40	13.77	5.51	0.0015	0.46	0.0067	0.84	0.42	0.0048	0.0001	0.0752
	10:37	run165_Sine Freq=1.83Hz Amp=0.003m ang=0deg EB_40	1.93	0.52	12.13	0.40	14.99	6.00	0.0013	0.42	0.0063	0.81	0.40	0.0035	0.0002	0.1202
22062023	14:49	run199_Sine Freq=0.93Hz Amp=0.01m ang=0deg EB_40	0.63	1.59	3.96	0.40	2.24	0.89	0.0029	2.81	0.0021	1.77	1.43	0.0600	0.0049	0.2041
	14:52	run200_Sine Freq=0.97Hz Amp=0.01m ang=0deg EB_40	0.87	1.15	5.47	0.40	3.46	1.38	0.0050	1.82	0.0055	1.58	1.07	0.1324	0.0340	0.6412
	14:55	run201_Sine Freq=1.06Hz Amp=0.01m ang=0deg EB_40	1.06	0.94	6.66	0.40	4.73	1.89	0.0066	1.33	0.0100	1.41	0.82	0.1784	0.0134	0.1743
	14:58	run202_Sine Freq=1.22Hz Amp=0.01m ang=0deg EB_40	1.22	0.82	7.67	0.40	6.08	2.43	0.0081	1.03	0.0157	1.26	0.68	0.2182	0.0125	0.1434
	15:02	run203_Sine Freq=1.35Hz Amp=0.01m ang=0deg EB_40	1.35	0.74	8.48	0.40	7.37	2.95	0.0069	0.85	0.0163	1.15	0.59	0.1406	0.0060	0.1063
	15:05	run204_Sine Freq=1.47Hz Amp=0.01m ang=0deg EB_40	1.47	0.68	9.24	0.40	8.71	3.48	0.0065	0.72	0.0180	1.06	0.54	0.1111	0.0030	0.0685
	15:09	run205_Sine Freq=1.57Hz Amp=0.01m ang=0deg EB_40	1.57	0.64	9.86	0.40	9.93	3.97	0.0054	0.63	0.0172	0.99	0.50	0.0723	0.0041	0.1431
23062023	10:39	run206_Sine Freq=1.67Hz Amp=0.01m ang=0deg EB_40	1.67	0.60	10.49	0.40	11.23	4.49	0.0036	0.56	0.0130	0.93	0.47	0.0304	0.0009	0.0741
	10:41	run207_Sine Freq=1.76Hz Amp=0.01m ang=0deg EB_40	1.76	0.57	11.06	0.40	12.47	4.99	0.0040	0.50	0.0157	0.89	0.44	0.0342	0.0003	0.0734
	10:44	run208_Sine Freq=1.85Hz Amp=0.01m ang=0deg EB_40	1.85	0.54	11.62	0.40	13.77	5.51	0.0034	0.46	0.0149	0.84	0.42	0.0240	0.0002	0.0175
	10:47	run209_Sine Freq=1.83Hz Amp=0.01m ang=0deg EB_40	1.93	0.52	12.13	0.40	14.99	6.00	0.0032	0.42	0.0151	0.81	0.40	0.0198	0.0002	0.0218

Figure Appendix 1: The Wave Parameters and Calculation of Incident Wave Power

[illegible]

Figure Appendix 2: Dispersion Relation Sheet to find Wave Number

$$\omega^2 = gk \tanh(kh) \quad (9)$$

Wave numbers are estimated for 2 water depths

Appendix D – Risk Assessment Forms

Assessment Ref. No.		Activity Assessed	An Experimental Study on Wave Power Absorption from a Breakwater Integrated Oscillating Water Column			
Assessment Date	26/01/2023	Faculty / Directorate	School of Engineering, Computing and Mathematics			
Assessor	Ozan Aydin	School / Service	School of Engineering, Computing and Mathematics			
Version No.	1	Additional individuals involved in developing the RA				
Signature of Assessor		Signature of Academic Supervisor / Approver				

Risk Score Matrix						Risk Score and Description				
Likelihood	Severity					Risk Score	Risk Level	Category	Description	
	Insignificant	Minor	Moderate	Major	Fatal					
	Very Unlikely	1 Green	2 Green	3 Green	4 Green	5 Amber	1 – 4	Low	Acceptable	No further actions needed
	Unlikely	2 Green	4 Green	6 Amber	8 Amber	10 Red	5 – 9	Medium	Tolerable/Adequate	Should be reviewed to ensure that there is nothing else that can be done
	Possible	3 Green	6 Amber	9 Amber	12 Red	15 Red	10 – 15	High	Undesirable	Immediately review current control measures, and where appropriate decide on further actions
	Likely	4 Green	8 Amber	12 Red	16 Red	20 Red	16 – 25	Very High	Unacceptable	Stop activity and make immediate improvements
Almost Certain	5 Amber	10 Red	15 Red	20 Red	25 Red	<i>Likelihood (L) x Severity (S) = Risk Score (RS)</i>				

What is/are the hazard(s) involved with the activity being undertaken?	Who might be harmed and how?	What are you already doing to control the risk?	Risk Score with current controls in place			What further action is necessary? (Add these actions to the action plan below)	Target Risk Score Likelihood x Severity = Risk Score		
			L	S	RS		L	S	RS
General Lab use	Anyone in the laboratory	All lab users must have completed a lab induction and read and follow the rules set out in the "Health and Safety Procedures for COAST" document.	3 - Possible	1 - Insignificant	3 - Low Risk	Lab induction to be scheduled with a technician.	3 - Possible	1 - Insignificant	3 - Low Risk
Use of Tools and Machines	All users. Cuts & Bruises	Induction on machines use has been given from one of the technicians.	1 - Very Unlikely	3 - Moderate	3 - Low Risk	None	1 - Very Unlikely	3 - Moderate	3 - Low Risk

Manual Handling :	All users. Cuts & Bruise, Trapped Fingers.	Control measures in place. Induction.	1 - Very Unlikely	1 - Insignificant	1 - Low Risk	None	1 - Very Unlikely	1 - Insignificant	1 - Low Risk
Spillages.	All users. Slip hazard if water exits the tanks.	A spilled water to be mopped up immediately and wet floor signs placed around the area.	1 - Very Unlikely	1 - Insignificant	1 - Low Risk	None	1 - Very Unlikely	1 - Insignificant	1 - Low Risk
Wet Hands	All users. Skin irritation from chlorinated water.	Wash hands and arms if they come into contact with the water.	3 - Possible	1 - Insignificant	1 - Low Risk	None	3 - Possible	1 - Insignificant	1 - Low Risk
Use of Ocean Basin Gantry	Those on the gantry crossing the beam in the center. Head collision.	Brightly colored impact absorbing material has been deployed.	1 - Very Unlikely	1 - Insignificant	1 - Low Risk	None	1 - Very Unlikely	1 - Insignificant	1 - Low Risk
Use of glue and silicon	All users. Skin irritation.	Use protective gloves.	4 - Likely	1 - Insignificant	4 - Low Risk	None	4 - Likely	1 - Insignificant	4 - Low Risk
			Choose an item.	Choose an item.	Choose an item.		Choose an item.	Choose an item.	Choose an item.
			Choose an item.	Choose an item.	Choose an item.		Choose an item.	Choose an item.	Choose an item.
			Choose an item.	Choose an item.	Choose an item.		Choose an item.	Choose an item.	Choose an item.
			Choose an item.	Choose an item.	Choose an item.		Choose an item.	Choose an item.	Choose an item.

Refer to scoring matrix and likelihood / severity descriptors

Action Plan and Monitoring

This section should be completed by the Risk Assessor and discussed with Manager / Academic Supervisor.

This section should be completed by the Manager / Academic Supervisor for monitor and review.

Hazard	Action required	Action assigned to	Target date	Date Completed

Review

When reviewing this risk assessment remember to move completed actions into the 'what are you already doing.' column, as these actions should be in place by the time you review the risk assessment. You should review your risk assessment periodically **and** if circumstances change, which means it is no longer valid (e.g. following an incident in the workplace or if there are any significant changes; such as new work equipment, work activities, personnel, environment, legislation or guidance etc.)

Likelihood Descriptors

Likelihood of injury / harm	Examples	Score
Very unlikely	Good control measures are in place. Controls do not rely on a person using them (i.e. personal compliance with safety rules). Controls are very unlikely to break down. People are very rarely in this area or very rarely engage in this activity.	1
Unlikely	Reasonable control measures are in place, but they do rely on a person using them (going room for human error). Controls unlikely to breakdown. People are not often in this area / do not often engage in this activity.	2

Severity Descriptors

Severity of injury / harm	Examples	Score
Insignificant	None or very insignificant injuries, health effects, damage or disruption to work. Short-term and/or localized environmental harm.	1
Minor	Cuts bruises, mild skin irritations, mild headaches and pains requiring minor first aid treatment. Minor property damage or disruption to work. Notable contributor to environmental harm.	2

Possible	Inadequate controls are in place, or likely to breakdown if not maintained. Controls rely on personal compliance. People are sometimes in this area or sometimes engage in this activity and situations sometimes arise from this activity.	3
Likely	Poor controls in place. Heavy reliance on personal compliance (lots of room for human error). People are often in this area / engage in this activity on a regular basis / situation often arise from this activity.	4
Almost certain	No controls in place where there should be, exposure to the hazard is <u>expected</u> to occur in most circumstances. The activity is considered such <u>high risk</u> that it will certainly lead to injuries.	5

Moderate	More serious injuries or ill-health requiring time off work or a hospital visit for example burns sprains, strains, short term musculoskeletal disorders, cut requiring stitches, back injuries, fractures to fingers and toes. Short term absence relating to physical or mental health issues. More serious property damage or disruption. A significant contributor to environmental harm.	3
Major	Broken limbs, amputations, long-term health problems or longer absence. Acute illness requiring medical treatment. Loss of consciousness, serious electric shock, loss of sight. Major property damage, major disruption to work. A major contributor to significant environmental harm.	4
Fatal	Injury or ill-health which leads to death either at the time, soon after the incident, or eventually, as in the case of certain occupational diseases, such as asbestos-related cancers. Catastrophic business losses. The major contributor to significant environmental harm.	5