# ON THE CHARACTERISTICS OF AN ABSORBING WAVEMAKER WITH CROSS SECTION VERTICAL NEAR THE FREE SURFACE

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## ABSTRACT

**The characteristics of a plunger absorbing wavemaker are studied. In the present wave absorption system the wavemaker is controlled to absorb the incoming waves by means of digital filtering of wave elevation signal measured in front of a wavemaker. This study is focused on the influence of plunger's shape on wave absorption. Instead of the wedge-shaped plunger whose performance was investigated before, a plunger with a cross section vertical near the free surface is adopted in the system. The absorption efficiency is investigated in period 0.5sec to 1.3sec.**

**KEY WORD :** Absorbing wavemaker, FIR digital filter, absorption efficiency, cross section vertical near the free surface, wave reflection, wave absorption

## INTRODUCTION

Model tests in regular or irregular waves are carried out in a wave tank to investigate the seakeeping performance of a ship or an offshore structure. The wave tank is usually characterized as long and narrow enclosures with a wavemaker at one end. Moreover, a wave absorber such as a spending beach is installed at the end wall opposite to the wavemaker for the purpose of reducing wave reflection. Generated waves are propagated forward from a wavemaker and reach a test structure. Some waves transmit to the lee-side, and the others are reflected by the body of the test structure, are propagated back to the wavemaker and are re-reflected by the wavemaker. When the re-reflected waves arrive at the body again and the multi wave reflection starts, it is difficult to maintain the correct measurement such as the wave-induced motions and loads on the body. Considering experimental aspects such as the accuracy of measuring data, a record length and a cost of apparatus, it is important to reduce the influence of wave reflection. Thus various research and developments on an absorbing wavemaker have been continued and reported (Milgram (1970), Bessho (1973), Evans (1976), Kyozuka (1985), Kawaguchi (1986), Naito, et al.(1999)).

The active wave absorption system was introduced to the Wave Tank at National Defense Academy in 1999. The adopted plunger wavemaker acts as an active wave absorber as well as a wave generator in the system, where motions of a plunger needed for absorption are determined by means of digital filtering of wave elevation signal measured far away from a plunger. This procedure is based on the time-domain method by Frigaard et al.(1993,1994). The characteristics of the plunger wavemaker with a wedge-shaped cross section was investigated in period 0.6sec to 1.2sec (Kudo et al. (2000)). The absorption efficiency was about more than 80 %

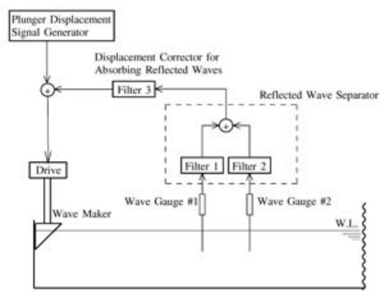


Fig. 1 Principle of absorbing wavemaker.

in case of wave absorption of incoming waves, but it was more than 70% in case of wave absorption in addition to wave generation. Though the satisfactory results were achieved from a practical viewpoint, some problems still remain for better performance. The influence of a plunger's shape is one of problems to be studied. When a wedge-shaped plunger oscillates vertically, its position to reflect incoming waves changes horizontally. This affects the plunger's motion on wave absorption, for a plunger has to generate waves in order to cancel out the waves reflected by a plunger. In the prior experimental study, the trial and error by both numerical simulations and experiments was needed in a part of filter design. This fact implies the wave reflection by a plunger has a great deal to do with the wave generation for absorption and makes the operations for wave absorption more complex. In this study, such characteristics of wave generation for absorption is called 'the characteristics of wave reflection-absorption'.

The objective of this study is to investigate the characteristics of absorbing wavemaker by using a plunger whose cross section reduces a change of a reflection position. Such a shape was determined by taking into account following two properties. First an adopted shape keeps the characteristics of wave generation which a wedge-shaped plunger has. Secondly a plumb part near still water surface is as long as possible so that the above-mentioned change due to wave reflection is considerably decreased even in heave motions. Various experiments such as the wave absorption of regular waves or transient waves, the measurement of wave exiting force or radiation force acting on a body, the continuous generation of standing waves and so on, are carried out and the satisfactory absorption efficiency is confirmed.

## CONTROL OF ABSORBING WAVEMAKER

The basic idea of control for active wave absorption consists of three steps. The first step is to detect only a wave component traveling to the wavemaker. The incident wave and the reflected wave coexist in the wave field. The measurement of wave elevations by two wave gauges enables the separation of two waves. The second step is to predict the propagation of this separated wave and the plunger's motions for absorption. The third step is to superpose the additional plunger's motions obtained in the second step on the original motions for wave generation. The principle of this system is illustrated in Fig.1.

The wavemaker is driven by the servomotor which is controlled by the transformation of the positional deviation from an order to a voltage. The volts signal in proportion to rotational speed of a motor is given to a servomotor by PC through D-A converter. Considering sinusoidal motions with frequency $f$ and stroke $S$, the displacement of plunger's motions is written as follows:

$$y_0(t) = \frac{S}{2}\sin 2\pi f t. \tag{1}$$

Both separating the wave components and predicting the wave propagation and the plunger's motions for absorption can be realized by employing the Finite Impulse Response (FIR) digital filters. Using the signals $\eta_1(n)$, $\eta_2(n)$ measured on two wave gauges, we have the signal of reflected waves toward a wavemaker. These relations can be written in a form:

$$\eta_{ref.}(n) = \sum_{m=0}^{N-1} h_1(m)\,\eta_1(n-m) + \sum_{m=0}^{N-1} h_2(m)\,\eta_2(n-m)\,, \tag{2}$$

where $h_1(m)$, $h_2(m)$ are filter coefficients for the separation of wave components, and $N$ corresponds to duration. Next the signal of plunger's motions is obtained by means of digital filtering of the wave signal $\eta_{ref.}(n)$ in Eq.(2).

$$y_{abs.}(n) = \sum_{m=0}^{M-1} h_3(m)\,\eta_{ref.}(n-m)\,. \tag{3}$$

Finally, the signal to drive an absorbing wavemaker is determined as the sum of Eq.(1) and Eq.(3).

### *FILTER DESIGN FOR SEPARATING INCIDENT AND REFLECTED WAVES*

The incident wave is assumed to travel in the positive $x$-direction, and the reflected wave in the negative $x$-direction. When the incident wave and the reflected wave coexist, the wave elevation at wave gauge's position $x_j$ $(j = 1, 2)$ may be expressed as follows:

$$\begin{aligned}\eta_j(t) &= \eta_I(x_j,t) + \eta_R(x_j,t)\\ &= a_I\cos(2\pi f t - kx_j + \varepsilon_I)\\ &\quad + a_R\cos(2\pi f t + kx_j + \varepsilon_R)\,,\end{aligned} \tag{4}$$

where $\eta$ is wave elevation with wave amplitude $a$, wave number $k$ and phase $\varepsilon$. The indices $I, R$ denote the incident wave and the reflected wave, respectively.

Suppose that a linear system is introduced with input $\eta_j(t)$ and output $\eta_j^*(t)$. The amplitude ratio of output to input and the phase difference between output and input define the frequency response of this system for all frequencies. When $\beta$ represents the amplitude ratio and $\phi_j$ represents the phase difference, the output signal $\eta_j^*(t)$ is given by

$$\eta_j^*(t) = \beta a_I \cos(2\pi f t - kx_j + \varepsilon_I + \phi_j) \\ +\beta a_R \cos(2\pi f t + kx_j + \varepsilon_R + \phi_j) \ . \quad (5)$$

That is, the output signal has the form in which the amplification $\beta$ and the phase shift $\phi_j$ is imposed on the input signal. Two wave gauges are located at $x_1$, $x_2(= x_1+\Delta x)$. Assuming that the sum of two outputs agrees with the reflected wave component at $x_1$, this condition is given by

$$\eta_R(x_1, t) = \eta_1^*(t) + \eta_2^*(t)$$

$$\Leftrightarrow \begin{cases} \beta = \dfrac{1}{2\cos(k\Delta x + \frac{\pi}{2} + m\pi)} \ , \\ \phi_1 = -k\Delta x - \dfrac{\pi}{2} + 2n\pi - m\pi \ , \\ \phi_2 = \dfrac{\pi}{2} + 2n\pi + m\pi \ , \end{cases} \quad (6)$$
$$(n, m = 0, \pm 1, \pm 2, \pm 3, .....).$$

Thus the frequency response functions are described in analytical forms. The linear system physically means that the reflected wave is separated from the wave field by the two-point measurement of waves. The frequency response function for the input at position $x_j$ can be written as a general form:

$$H_j(f) = |H_j(f)|\, e^{i\,\phi_j(f)} \quad (j = 1, 2) \quad (7)$$

where the amplitude $|H_j(f)|$ is equal to $\beta$, and it is singular when the distance $\Delta x$ is equal to integral multiples of a half wavelength. Impulse response is obtained by the Inverse Fourier transform of Eq.(7). However, this impulse response has infinite duration and it doesn't generally satisfy the causality. Therefore the duration of impulse response is truncated finitely and a time delay by $N\Delta t/2$ has to be imposed on the design of FIR filter. Applying the Inverse Discrete Fourier transform (IDFT) to frequency response function $H_j(f)$, we have the filter coefficients as follows:

$$h_j(n) = \frac{1}{N}\sum_{m=0}^{N-1} H_j(m)\cos\left(2\pi\frac{nm}{N}\right) \quad (j = 1, 2). \quad (8)$$

It is known that the filtering effect decreases when a wave frequency to be separated is not coincident with discretized frequencies $n\Delta f$. So the tapering of the filter by a window function is applied to improve the filtering effect.

*FILTER DESIGN FOR WAVE PROPAGATION AND WAVE GENERATION*

Suppose that we introduce another linear system where an input is the reflected wave traveling to a wavemaker and an output is the plunger's motions for absorption. The frequency response function is composed by the products of characteristics of wave propagation and characteristics of wave generation for a wavemaker. By using IDFT, we can express the impulse response as follows:

$$h_3(t) = 2\int_0^\infty \frac{1}{\bar{A}(f)}\cos\{kx_1 - 2\pi f t - \theta(f)\}\, df \ , \quad (9)$$

where $\bar{A}(f)$ and $\theta(f)$ are the amplitude ratio of generated waves to plunger's motions and the phase difference between them, respectively. The discretized form of Eq.(9) leads to the filter coefficients. In this filter design, moreover, we have to take account of recovering the time delay, which is caused by using the filters for separation. The impulse response doesn't satisfy with the causality. However, even neglecting the low frequencies would provide satisfactory results practically and no problem would be caused (for example, Noito et al. (1984)). The recovery of a time delay means that some low frequencies are cut off in the impulse response, so that a small time is put ahead, namely a negative time delay is caused in the filter.

In the study by using a wedge-shaped plunger (Kudo et al.(2000)), undesirable labor occurred in this step of filter design. It was hard to determine the characteristics of wave generation for absorption only by the theoretical approach. The filter design partly based on experiments was necessary to obtain the characteristics of wave reflection-absorption. From a viewpoint that a plunger's shape is connected with the wave reflection, we had concluded that a plunger's shape with plumb surface near the free surface would be effective to avoid the labor. As it is described later, however, the trial and error by numerical simulations and experiments are still needed in filter design. We cannot but guess that the characteristics of wave generation in waves are affected by incoming waves to a plunger. This is an essential problem to be made clearer in future.

## DESIGN OF PLUNGER'S CROSS SECTION

When a wedge-shaped plunger oscillates vertically, the position of an intersection between the body and the free surface changes every moment. Its mean position may be coincident with the intersection with still

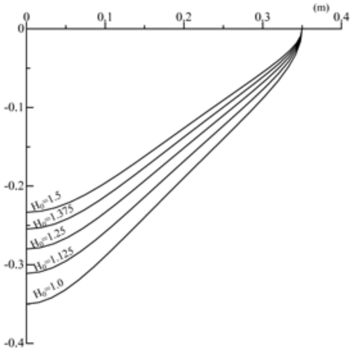


Fig. 2 Lewis form sections.

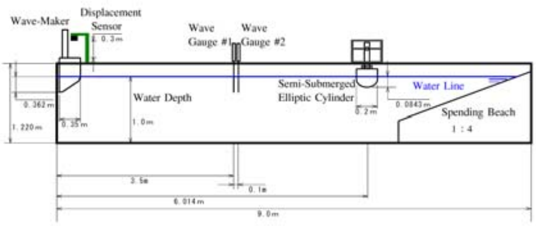


Fig. 3 Experimental set-up.

water surface. Nevertheless, the wave reflection is expected to affect the prediction of plunger's motions for wave absorption, specially in active control of phase. Assuming that the reflection of incoming waves by a moving plunger is mainly caused near the free surface, the plunger's shape with a plumb part near the free surface is expected to be effective to reduce the horizontal change of reflection positions. We adopted the Lewis form section with $H_0 = 1.0$, $\sigma = 0.6$ in some variants shown in Fig.2. It was determined by taking into account following two properties.

- To have the characteristics of wave generation comparable with a wedge-shaped plunger.
- To have a long plumb part near still water surface on the shape.

All experiments are carried out with the body initially submerged 12mm more.

## EXPERIMENTS AND RESULTS

First we tested the characteristics in absorbing waves, which are radiated by forced sway motions of a semi-submerged elliptic cylinder and travel to the wavemaker. The schematic view of experimental apparatus is illustrated in Fig.3. Time histories of four measured data are shown in Fig.4. The sway motion's displacement of a semi-submerged elliptic cylinder and the stroke of a

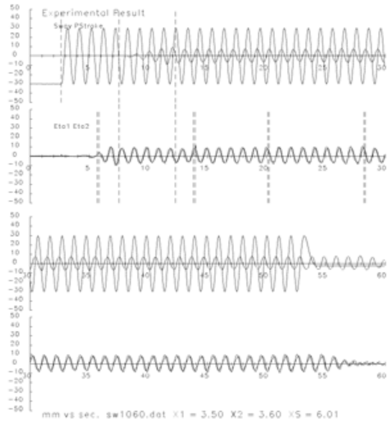

Fig. 4 Sway motion of semi-submerged elliptic cylinder, stroke of plunger and water surface elevations in control of absorbing radiated wave (T=1.019sec, S=59.1mm).

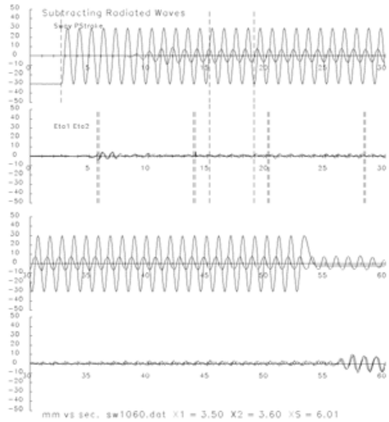

Fig. 5 Sway motion of semi-submerged elliptic cylinder, stroke of plunger and water surface elevations with radiated wave subtracted (T=1.019sec, S=59.1mm).

plunger wavemaker are shown on the 1st and 3rd lines in figure. Two water surface elevations are shown on the 2nd and 4th lines. The interference due to the wave reflection is hardly recognized and the excellent wave absorption is achieved. Using the measured data by wave gauges, we can calculate the amplitude and the phase difference about the waves traveling to the wavemaker. Then the Fourier analysis is applied to calculate a fundamental frequency component, but the data should be chosen so that the influence due to the reflected wave is not included. All experiments are conducted by the range that the prediction by a linear theory is reasonable. Subtracting the radiated wave's component from the measured wave data, we have the

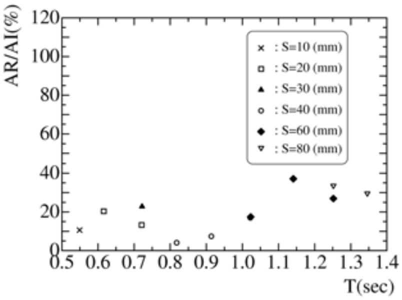


Fig. 6  Ratio of radiated wave height to reflected wave height.

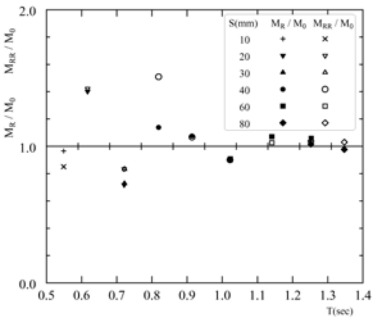

Fig. 7  Ratio of sway added mass coefficients in reflecting and re-reflecting waves.

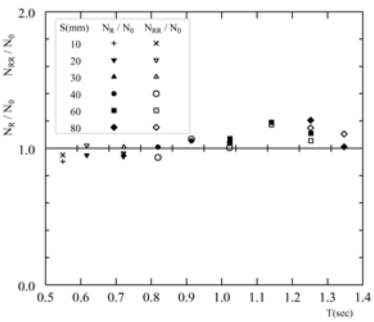

Fig. 8  Ratio of sway damping coefficients in reflecting and re-reflecting waves.

residual components including the reflected waves due to the wavemaker. These results are shown in Fig.5. The small wave components with high frequencies still remain. The component of about 2Hz seems to be mainly caused by the plunger's motions lacking for smoothness. Considering that the sampling period of controlled signals is set to 0.04sec during a wave absorption mode and the frequency of 2Hz is a lower limit in the wave absorption system targeted in the present study, it's inevitable in the present situation.

By using results in Fig.5, the amplitude $A_R$ of the reflected waves due to the wavemaker is calculated as well as the amplitude $A_I$ of the radiated waves due to the cylinder. The absorption efficiency of the wavemaker is shown in Fig.6 where the absorption efficiency is evaluated as the reflection coefficients, viz., a ratio of $A_R$ to $A_I$. The reflection coefficients are about less than 20 % in wave period 0.5sec to 1.0sec while a little higher in period 1.1sec to 1.3sec. This is because the accuracy of measuring data become lower. The wave height of radiated waves is too small and the wave profile is far from a sinusoidal wave. Nevertheless, in visual observations, the wave absorption is quite good in a whole range.

The reflection coefficients were evaluated by using the radiation force as well as the water surface elevation. The measured sway forces were decomposed into added mass $M$ and damping coefficients $N$. Those results are shown in Fig.7 and Fig.8. The indices 0, $R$ and $RR$ represent three kinds of states, that is, the measured data are not affected, affected by the reflection and affected by the re-reflection, respectively. The ratio of added mass coefficients are within ±20% except for 0.6sec and 0.8sec in period, and the ratio of damping coefficients are also within ±20%. As the ratio $R/0$ is almost coincident with that of $RR/0$, we can conclude that the radiated waves are almost completely absorbed by the wavemaker.

In the next experiment, the spending beach was removed and the incident waves were generated by the wavemaker. If the absorbing wavemaker acts properly, the standing wave is gradually formed in a tank due to perfect reflection at an end wall. The amplitude ratio of the reflected wave from the end wall to the incident wave is expressed as the reflection coefficients $A_R/A_I$ and that of the re-reflected wave from the wavemaker to the incident wave is expressed as the re-reflection coefficients $A_{RR}/A_I$ in Fig.9. The indices $I$, $R$, and $RR$ are a incident wave, a reflected wave and a re-reflected wave, respectively. The reflection coefficients are about 100% except for period 0.5sec. The re-reflection coefficients indicate about less than 40%. The node in the standing waves was observed at a wave gauge in period 0.9sec. Then the water surface elevation is small and the poor accuracy in measuring is anticipated. The tendency of wave absorption is a little different from that in Fig.6. This is possibly due to the above-mentioned characteristics of wave reflection-absorption.

In the following experiment, the incident waves were generated by the wavemaker and the sway forces acting on a fixed semi-submerged elliptic cylinder was measured. As for the amplitude of measured sway forces, two kinds of amplitude ratio, $F_R/F_I$ and $F_{RR}/F_I$ are shown in Fig.10. The indices about $F$ are the same as those of Fig.9. The calculated results are within ±20%

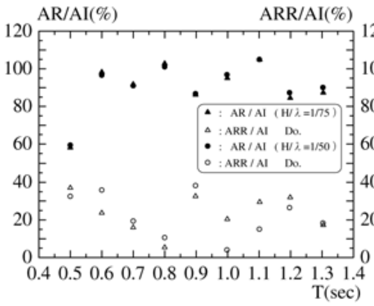


Fig. 9 Ratio of amplitudes of reflected and re-reflected waves to incident wave.

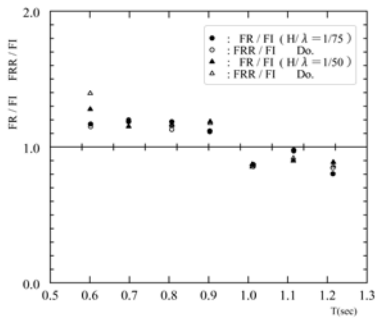


Fig. 10 Ratio of sway force of $F_R$ and $F_{RR}$ to $F_I$.

besides $T = 0.6$sec. Although more improvements are desired, satisfactory results were obtained from a practical viewpoint.

## CONCLUSIONS AND ACKNOWLEDGEMENTS

Various experiments are carried out to study the characteristics of an absorbing wavemaker with cross section vertical near the free surface. The following results are obtained.

1. It is impossible to predict the wave generation for wave absorption only by the theoretical approach based on a linear theory. (Some factors such as the nonlinearity in the wave-making problem and the effects of walls, water depth, measurement position and so on, seem to make it more complicated.)

2. The present absorbing wavemaker provides a good performance comparable with the wedge-shaped absorbing wavemaker on the wave absorption.

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