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A new active absorption system and its performance to linear and non-linear waves

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ABSTRACT

The present paper presents a new active absorption method for wavemakers in physical models based on digital filtering of signals from wave gauges in the nearfield. Such system is needed to maintain control of the waves when performing model tests where reflections from the models are significant. Similar systems have been described earlier, but in previous systems a causal IIR filter was applied while FIR filters were considered impossible to use. However, in the present paper it is shown that a causal FIR filter can indeed be fitted with similar or even better performance than the systems based on IIR filters. Furthermore, the existing fully linear absorption theory for gauges being flush mounted to the paddle is extended to gauges with a small gap to the paddle. Such gap can be used to compensate a large control delay in some existing setups. The performance of the new system on linear and non-linear regular waves has been tested in a new wave flume with wavemakers in both ends. Such flume is ideal for validating the theoretical performance curve and the results show excellent agreement between theory and measurements. Results for irregular waves confirm the broad banded absorption capabilities. Finally, a procedure for generating highly non-linear waves with simultaneous active absorption has been given. The results show that the superharmonics of such waves can also be well absorbed by the system.

1. Introduction

Reflected waves from structures or absorber elements in wave flumes/basins will without active absorption become re-reflected at the paddle(s) and become incident waves, cf. Fig. 1. The purpose of an active absorption system is to minimize the re-reflections at the paddle. In long flumes re-reflections can be avoided in tests with regular waves by terminating the test before re-reflections occur as done in many studies before active absorption systems became available. However, in short flumes or in irregular sea states this option is not possible or at least not practical.

Without active absorption re-reflected waves will thus contaminate the desired incident waves and especially in two ways:

1. Testing reflective structures without active absorption will with time cause built up of energy and cause deviations from the target wave field. The deviations are observed as peaks in the incident spectrum at the resonance frequencies of the facility. The problem is highly visible for highly reflective structures, but present for all reflective structures.
2. For less reflective structures the main problem is typically built up of long period longitudinal seiches in the facility especially in shallow water tests. Such seiches are observed as long free surface undulations which can be observed after the completion of a test and are fully reflected at both ends of the flume. The result of insufficient dampening of longitudinal seiches is that structures which response is highly sensitive to long waves might have very significant model effects. Examples of cases where seiches lead to unrealistic response is surf zone dynamics, floating structure response, and overtopping on structures.

In both cases active absorption is very relevant to increase the reliability and to improve the performance of the tests in wave flumes and basins, controlling spurious oscillations at different frequencies. Note that not all active absorption systems have sufficient performance in the low frequency range to actually damp seiches. Indeed some systems might even generate long waves when signals contain noise (see for example Hald and Frigaard (1997a)). Moreover, active absorption might be used to calm-down and thus decrease the settling time needed between test runs.

When active absorption is applied the reflected waves approaching the generator are absorbed by a modification to the control signal for

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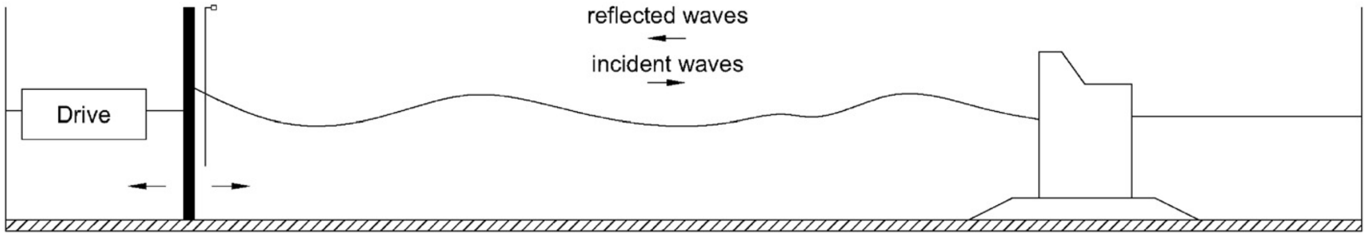

Fig. 1. Principle of an active absorption system is to modify the paddle drive signal to absorb reflected waves from structures or facility boundaries (passive absorbers).

the generator. Consequently active absorption is also sometimes called "reflection compensation" as the control signals are compensated for the reflected waves from the structures in the facility. The result is that the control of the incident waves is maintained throughout the test and the reflected waves seem to pass directly through the wavemaker.

Active absorption has been dealt with by several researches and many systems have been proposed during the last 50 years. Active absorption systems can be separated into systems based on farfield measurements (typical surface elevations and/or particle velocities) and systems based on nearfield measurements (surface elevations on the paddle faces or force on the wave board). In the following is given a review of these systems. A recent review of the available systems was also given in Schäffer and Klopman (2000).

Aalborg University developed earlier active absorption systems based on wave gauges or velocitymeters in the farfield (Frigaard and Christensen (1994); Christensen (1995); Hald and Frigaard (1996, 1997a, 1997b)). These systems have been used successfully for more than 20 years in different laboratories and also in numerical models. The main advantage of using farfield measurements is that the filter design is straight forward as causality issues are neglectable. The main disadvantage is that the system performance is only good for relatively linear waves that are not too long. As a consequence seiches in the flume can in many cases not be sufficiently damped. The linear assumption is giving some problems with the transformation of the waves from the farfield to the nearfield as linear wave celerity is not always good enough even though it is valid to second order for the primary component. However, waves of 3rd and higher order are amplitude dispersive (high waves travel faster) which leads to a phase error for the primary component in high waves. However, the largest problem is that in intermediate and deep water the bound super harmonics travel with very different celerity to a free wave of the same frequency. Therefore, the system might amplify high frequency energy (superharmonics) due to an accumulation of phase errors even for just mildly non-linear waves. This sets a restriction to the upper frequency the system can operate at (lowpass frequency). This phase error accumulation is avoided by using systems based on nearfield measurements as described in the following.

The pioneering work on active absorption by Milgram (1965, 1970) for replacing a passive wave absorber at the end of a flume with an active one was based on measurement of surface elevations in the nearfield. Gilbert (1978) pointed out that by adding the motion to generate the waves the Milgram system can be used as a wavemaker with simultaneous active absorption. Such approach has been followed by Kostese (1984) and Klopman et al. (1996) for linear shallow water wave assumption (long wave theory) and by Schäffer et al. (1994); Schäffer and Skourup (1996); Schäffer (2001); van Dongeren et al. (2001) for fully linear wave theory. Schäffer and Jakobsen (2003) extended the system to non-linear wave generation with simultaneous linear active absorption by splitting the control signal into a generation signal and an active absorption signal (dual mode).

Systems based on force measurements have been presented by Salter (1981); Chatry et al. (1998); Spinneken and Swan (2009) and for measurement of trust by Tanimoto et al. (1983). The advantage is that the force and trust includes partly the influence of the wave direction and that the force is an integrated property that is more robust than local measured surface elevations. The disadvantage of force based systems is that fluid on the rear side contribute significantly to the force on the paddle and thus special measures has to be taken so only the force on the front face is measured (dry-back, displacement pistons, etc.). Moreover, at high frequencies the force on the paddle is dominated by inertia forces due to evanescent modes which limit high frequency performance, cf. Schäffer and Klopman (2000). Finally, the active absorption transfer function is for a force controlled system purely noncausal (see Naito and Nakamura (1985) and Maisondieu and Clement (1993)). A noncausal filter means that the optimal active absorption correction is depending on the future which is of course unknown when the correction has to be applied. This optimal filter thus has to be replaced by a causal one where the active absorption correction is only depending on past measurements. However, making this replacement limits the effective active absorption to a much narrower band of frequencies than in the surface elevation based systems. This applies especially when the system is tuned for a fixed frequency, but seems also to apply when using an extended Kalman filter as shown in Chatry et al. (1998). Spinneken and Swan (2009) continued this work using an IIR filter, but in the physical model the reported performance was quite poor compared to wave gauge based systems.

For the systems based on nearfield surface elevations IIR filters (analog or digital) have been applied in all existing studies. Milgram (1965, 1970) gave some filter design details, but for the other cases the filter design procedure has not been provided although this is the most difficult part of the system. FIR filters were not considered possible due to the delay of half the filter length (Schäffer and Klopman (2000)). Spinneken and Swan (2009) mention the same limitation for filters for force feedback system. However, the present active absorption system is actually based on digital FIR filtering of nearfield surface elevations, proving that FIR filters can be applied. The new system is based on a similar theory as that of Schäffer and Jakobsen (2003), but the theory is extending to cases where the wave gauge might have a gap to the paddle face (see Section 2).

The present proposed active absorption system has recently been installed in more than ten facilities worldwide and has for example been in operation at Aalborg University since 2011. The system is in the present paper tested in a physical wave flume with wavemakers in both ends which was the perfect situation for validating the theoretical performance curve for both linear and non-linear regular and irregular waves. The performance of the new system will also compared to existing IIR filter based systems.

The present system was developed for wavemakers in physical models, but could just as well be applied in numerical models with moving boundaries. In fact most of above mentioned existing systems can and also have been applied in numerical models, cf. Brorsen and Frigaard (1992); Skourup and Schäffer (1997, 1998); Skourup and Bingham (1996); Troch and De Rouck (1999); Troch et al. (2000); Wellens et al. (2009); Wellens (2012); Higuera et al. (2013) and Spinneken et al. (2014). In the numerical model the