Wavemaker Capabilities of the Nr.1 Basin at the Delft Shiphydromechanics Laboratory

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Summary

In December 1995 the wavemaking capabilities of the wavemaker in the No. 1 model basin of the Delft Shiphydromechanics Laboratory were assessed. Although the tests were done with the aim of obtaining data for the generation of both regular and irregular waves they were carried out with regular waves. Waves with wavelengths between 1.5 and 22 m (angular frequencies between 6.28 and 1.26 rad/s) and different heights were generated and measured at three spots in the model basin: one at 17 m from the wavemaker flap and the other two at 67 and 71 m distance..

From the measured waves the first, second and third harmonics were calculated as well as the remaining residues. This gave an indication of the spectral purity of the waves (harmonics) and were things went wrong due to breakers (increasing residues).

It was found that at a water depth of 2.2 m the wavemaker is capable of generating waves with maximum amplitudes raising from 0.05 m at ω=1.257 rad/s to .22 m at ω = 3.2 rad/s. Above that angular frequency the maximum amplitude becomes steepness limited. The maximum wave steepness that can be obtained is 0.08. This results in the maximum wave amplitude dropping to 0.15 m at ω = 4 rad/s and 0.06 m at ω = 6.28 rad/s. The achievable wave heights are summarized in figure 3.1.8. With increasing wave steepness second harmonic distortion increases to a maximum of between 15 and 20 % for the maximum wave steepness values. It was also established that the waveflap introduces extra harmonic distortion due to its non-ideal motion. Above the maximum allowable wave steepness the waves quickly become irregular. This shows in an increasing wave residue (wave signal minus the first three wave harmonics). Furthermore it results in reduced wave heights further away from the wavemaker.

Using the results a simple theoretical model for the wavemaker could be verified. This model is meant for use with a programme for the generation of irregular waves. For low frequencies and low wave steepness model and measurements agreed well. For high frequencies and high values of the wave steepness the actual wave was lower than the predicted one. Using the data an empirical correction equation was found to compensate for this deviation.

The measurements resulted in better knowledge about the capabilities of the wavemaker. The results suggest that it might be worthwhile to investigate whether a slightly modified signal to the wavemaker might result in less wavemaker induced distortion. It is possible that this would allow higher values of wave steepness to be used, thereby increasing the maximum achievable wave heights at higher frequencies.

1 Introduction

This report describes the results of limited wavemaker measurements in the number one model basin of the Delft Shiphydromechanics Laboratory at Delft University of Technology. These tests were carried out in December 1995. Aim of these tests was to characterize the wavemaker for tests with both regular and irregular waves. However, the measurements were all carried out with regular waves. Measured were the:

- wave heights that could be generated as a function of frequency and the change of wave height between points in the tank about 50 m apart
- harmonic distortion of the waves and the amount of non-harmonically related wave residues.

The report is built up as follows. Chapter two starts with a brief description of the number one model basin and more in particular the wavemaker in this basin. Following that the rationale of the tests is discussed. The chapter concludes with the details of the test programme. The bulk of the report follows in chapter three. Here the results are given and were necessary discussed. From the results a simple mathematical model (taken from [1]) for the wavemaker transfer function could be verified and refined. Finally, chapter four gives conclusions and recommendations for further work. Appendix A contains a number of tables with test results.

2 The test programme

In this chapter the test programme will be described. This description consists of three parts.

- A brief description of the model basin and its wavemaker.
- The rationale behind the different tests
- The test programme.

At the Delft Shiphydromechanics Laboratory two model basins are available for model tests. The largest of the two is the number one basin and has dimensions L x W x D of 142 x 4.22 x 2.4 m. A beach is fitted at the end of this basin to absorb the waves and so minimize wave reflections. The wavemaker in the basin is of the rotating flap type (see figure 2.1). It is 4.21 m wide and at the lower side it is pivoting at a height of 0.35 m above the tankfloor. When necessary, a second pivoting point at a height of 1.5 m above the tankfloor can be used. This is advantageous with shorter waves. At the back of the waveflap is a 2 m long flooded space. Fitted in this space is a damping system comprised of packets of glassfibre corrugated plates. This system has proven to be a very effective wideband damper. The flap is driven by a hydraulic linear motor at a height of 2.6 m above its lower pivoting point. Usable stroke of this motor is 0.6 m. The motor is controlled using a Moog servo valve and associated hydraulics and control electronics. Control signals come from either a function generator (regular waves) or a computer (for irregular waves) which is located on the model carriage.

Figure 2.1. The waveflap in the number one model basin.

The test programme was designed to measure the parameters that were listed in the introduction. However, before going into details of the programme a brief description will be given of the rationale behind the tests.

First object of the tests was the determination of the wave height generating capabilities of the wavemaker. The wave heights that can be generated with the wavemaker are at low wave frequencies limited by the maximum stroke (0.6 m) of the hydraulic linear motor. At higher frequencies the increasing wave steepness becomes the limiting factor. Beyond a certain steepness harmonic distortion increases quickly. At some point the waves become unstable, breakers develop and the waves quickly become unusable. The tests aimed to determine what the actual limits are.

An important point when measuring wave heights is to know if they change as a function of distance from the wavemaker. Experience already indicated that this wave height change is negligible for practical (= usable) wave heights and lengths. The loss mechanism under these conditions is mainly the (weak) viscous friction. However, when a wave is made too high breakers start to develop and as a consequence energy starts to leak from the wave and its harmonics to the more or less random residue of the waves in the basin. This damping is much more effective than that of the viscous friction. The result is that the amplitude of the wave and its harmonics will start to decrease. Because the energy leakage increases as a function of the length comparing the wave heights measured at two points a distance apart are a clear indicator of the point were waves become unusable due to breakers and other irregularities. Therefore, the waves were measured at distances of 17 m and 67 m from the waveflap. This allowed the investigation of the influence of distance on the wave height.

The second aim of the tests was the measurement of the harmonic distortion of the waves and the wave residues. It will probably be intuitively clear that it is hard to tell what constitutes useful regular waves. Clearly, when breakers or other non-harmonically related wave components start to occur the waves are hardly useful anymore. However, when this is not the case the harmonic distortion has to be the guideline. Harmonic distortion that is acceptable for one test may not be so for the next. One instance where low distortion is desirable is when investigating non-linear phenomena of floating constructions in regular waves. In such a case it is important that the input signal (the wave) has as little harmonic distortion as possible. This greatly facilitates the interpretation of the harmonics in the output signals. On the other hand when testing basically linear systems the harmonic distortion is often less important because the linear response can be easily extracted from the harmonic byproducts.

Harmonic distortion is caused by two error sources. First of all there are the inherent non-linear mechanisms in the waves that cause distortion, mainly a second harmonic. The value of this second harmonic can be calculated from a theoretical model [2]. A second error source is the motion of the flap. This motion is a simplification of the motion that should be generated in order to generate an as-distortion-free-as-possible wave. By measuring the harmonic distortion of the waves the results could be compared with theoretical values. Furthermore, by knowing the distortion at two points in the basin, one near the wavemaker, the second some 50 m from the first waveprobe, an idea was formed of the influence of the wavemaker.

When the waves become too high and therefore unstable this is clearly visible in the residue of the wave. This residue is defined as the root mean square (RMS) value of the difference of the wave signal and the first three harmonics. So the first three harmonics of the signal were measured and then substracted from the original signal. Hence, the residue consists of the fourth and higher harmonics of the wave plus non-harmonically related wave artefacts. In general the higher harmonics will be very small and the irregular wave artefacts will remain small until the wave starts to break. After that point the residue will grow quickly. Therefore knowing the residue gives a yardstick for the regularity of the waves.

It was the intention to verify one more point, namely the accuracy of wave lengths and of wave phase measurements. The wavelengths for a given wave frequency and water depth can be easily calculated. In the formula used for that purpose the wavelength is not dependent on the wave height. However, this formula is a simplification and in reality, the wavelength depends to a small extend on the wave height [2]. By placing two waveprobes at a distance of 4 m apart the wavelength was checked to see if the change of wavelength due to wave height differences was measurable. Also, the way wave phases are measured was checked in this way. Unfortunately, insufficient usable data was obtained to verify those points satisfactorily. The trend was that the wave height dependency of the wavelength is measurable but no results will be presented in this report.

During the tests the following parameters were measured.

- The signal fed to the wavemaker.
- The flap displacement signal.
- The wave height at 17 m from the waveflap, referred to as WP1 (Wave Probe 1).
- The wave height at 67 m from the waveflap, referred to as WP2.
- The wave height at 71 m from the waveflap, referred to as WP3.

All tests were carried out with a water depth h of 2.2 m.
Varied were the following parameters.

- Wave frequency. Five frequencies were used: 0.2, 0.4, 0.6, 0.8 and 1 Hz. This corresponded to wavelengths of: 21.85, 8.92, 4.33, 2.44 and 1.562 m.
- Displacement of waveflap. Basically three stroke settings for the hydraulic cylinders were used, namely 0.15 m, 0.3 m and 0.6 m. The last value corresponds with the maximum stroke of the hydraulic cylinder. Note that stroke means peak-peak value, hence the amplitudes are half that value, namely 0.075, 0.15 and 0.30 m. For one condition where a 0.6 m stroke proved too much, a stroke of 0.45 m was used (amplitude 0.225 m).

3 The results

The discussion of the results follows the line set out in the description of the test objectives in chapter 2. Both investigated items will be treated in a sub-chapter. We will start with the wave heights that could be generated.

3.1 Wave height capabilities

In chapter two it was already outlined that apart from breakers and other non-harmonically related residues there is no clear criterium for what constitutes a useful regular wave. This is not a problem at the low frequencies where the maximum amplitude is limited by the stroke of the hydraulic cylinder and the distortion remains low. At the higher frequencies however both harmonic and non-harmonic distortion will become problems. However, here we will only consider the measured wave heights. Wave height is for our purpose defined as the amplitude of the first harmonic of the wave signal. The 'real wave' can therefore have a higher instantaneous value due to its harmonics.

If a simple mathematical model is developed for the wave height for a given waveflap amplitude a quadratic increase is found with increasing frequency. The relationship for the maximum stroke is given by [1]:

$$\zeta_{1_{max}}(\lambda)=\frac{\pi}{\lambda}.\frac{(h-0.35)^2}{8.667}$$

with: h = water depth in m in the basin
8.667 = a constant determined by the system dimensions.
For smaller strokes of the hydraulic cylinder the wave height reduces proportionally and is thus given by

$$\zeta_1(\lambda,a_f)=\zeta_{1_{max}}(\lambda).\frac{a_f}{0.3}$$

with: a_f= amplitude in m of the waveflap motion (amplitude = stroke/2).
The formulae are given as function of wavelength λ because this automatically takes undeep water effects into account. For the test series this effect played a role for the two lowest frequencies of 0.2 Hz (λ = 22 m) and 0.4 Hz (λ = 9 m).
The only damping mechanism of the waves in this region will be the viscous friction in the water. As this is a weak effect the amplitude of the wave can be expected to be almost constant over the length of the model basin.

When the wave steepness increases the point is eventually reached were the waves become unsustainably steep and breakers develop. Part of the wave energy is converted into non-harmonically related disturbances. Energy is lost due to the strong damping caused by the breakers generating mechanism. As a consequence the wave height is decreasing over the length of the model basin. This is in practice not a problem because the waves are unusable anyway.

To find out what the limitations are waves were generated at five frequencies of 0.2, 0.4, 0.6,

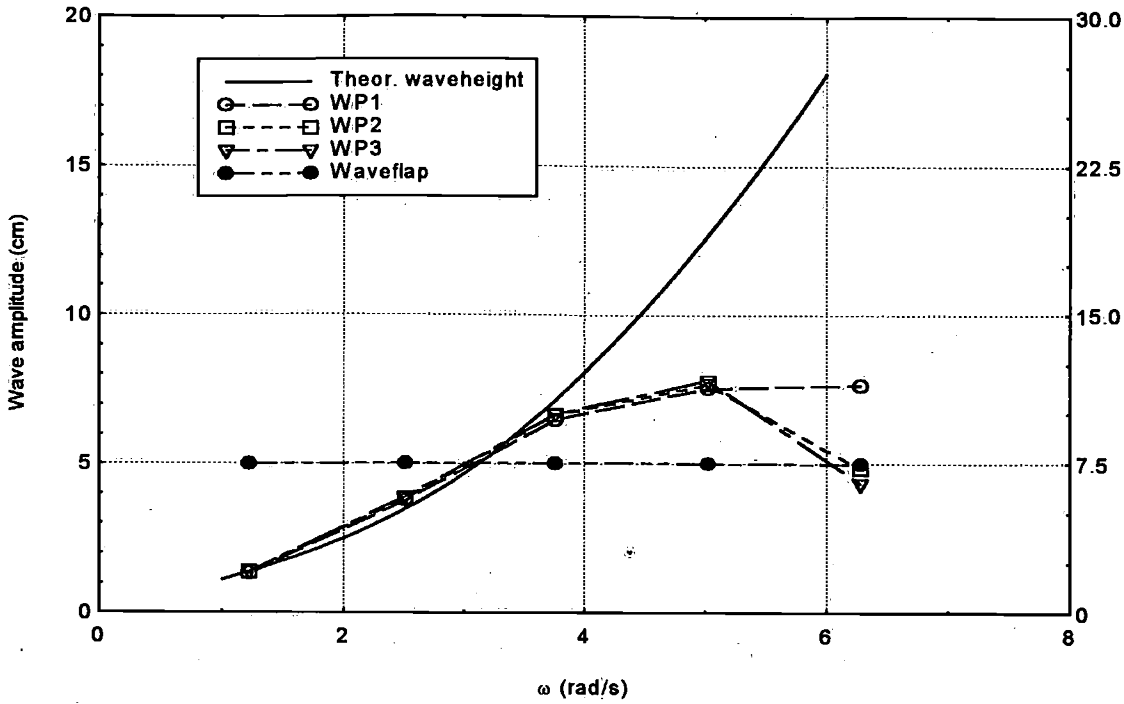

Figure 3.1.1. Wave amplitudes (first harmonics) at 0.075 m waveflap amplitude.

0.8 and 1 Hz with strokes of 0.15m, 0.3 m and 0.6 m (amplitudes are half those values).

In figure 3.1.1 the results are shown for a waveflap amplitude of 0.075 m. Also shown is the theoretical wave height calculated by the formulae given above. From the figure it becomes clear that for angular frequencies higher than 3.8 rad/s (period shorter than 1.67 s) the waves clearly no longer increased quadratically with frequency. However, up to frequencies of 5 rad/s (periods longer than 1.25 s) there was little difference of wave amplitude between the waveprobe near the wavemaker (WP1) and those 50 and 54 m further (WP2 and WP3). This means that breakers did not yet play a major role. The cause of the deviation of the quadratic behaviour is probably due to the leakage along the sides of the waveflap, especially at the bottom. This is not accounted for in the mathematical model. Onother possible reason was first thought to be the transfer of a part of the wave energy to higher harmonics. Such leakage could result in a lower first harmonic. However, the energy and amplitude of the higher harmonics are so small that this does not nearly explain the phenomena. For frequencies higher than 5 rad/s the wave height further away from the wavemaker starts to drop considerably. This is caused by breakers that start developing.

To illustrate the results three time registrations are shown in figure 3.1.2. They show the wave signal coming from waveprobes WP1 (17 m from the wavemaker) and WP2 (67 m from the wavemaker) . Registration a) is for $\omega = 3.78$ rad/s. This is still in the well-behaved region and the waves are very good. In record b) the frequency is 5.03 rad/s, the waves are still quite regular but the harmonic content is already increasing. At the highest frequency c) of 6.28 rad/s the waves near the wavemaker are still regular but have a high harmonic content. However, further along the basin breakers developed and the waves at 67 m from the wavemaker are no longer regular. From figure 3.1.1 it can be seen that the wave amplitudes at WP2 and WP3 are lower than at WP1 near the wavemaker. So the breaker induced damping is clearly discernable.

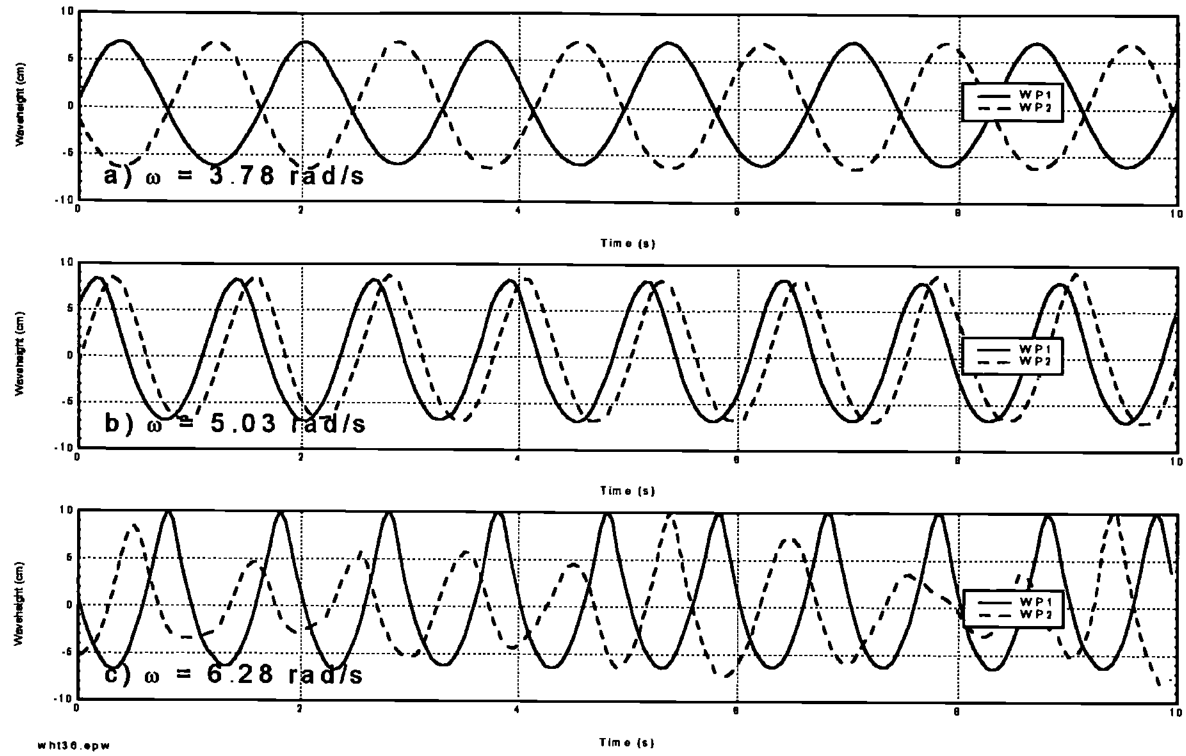

Figure 3.1.2. Time registrations of waves for freqeuencies of: a) 3.78 rad/s; b) 5.03 rad/s; and 6.28 rad/s. Amplitude of flap motion 0.075 m.

The condition with 0.15 m waveflap amplitude is shown in figure 3.1.3. The discrepancy between the results of the waveprobe near the wavemaker (WP1) and those on the carriage (WP2 and WP3) 50 m away for ω = 5.03 rad/s again indicates the existence of breakers at the

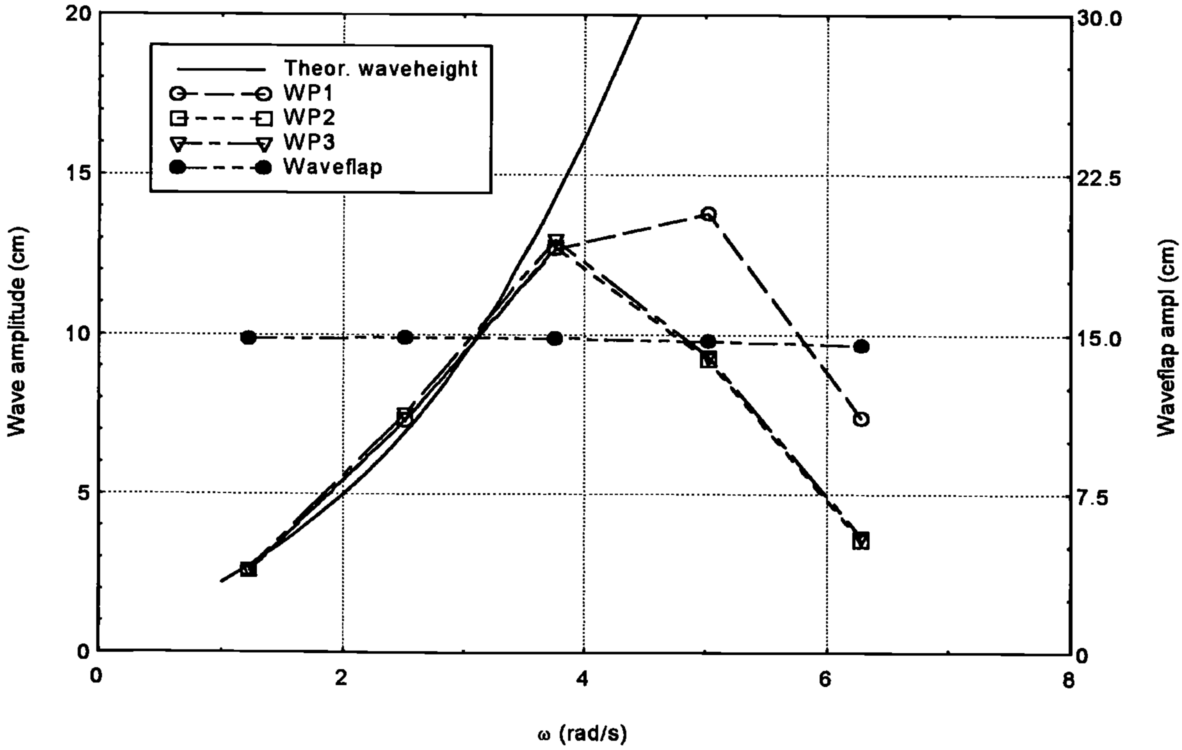

Figure 3.1.3. Generated wave heights at 0.15 m waveflap amplitude.

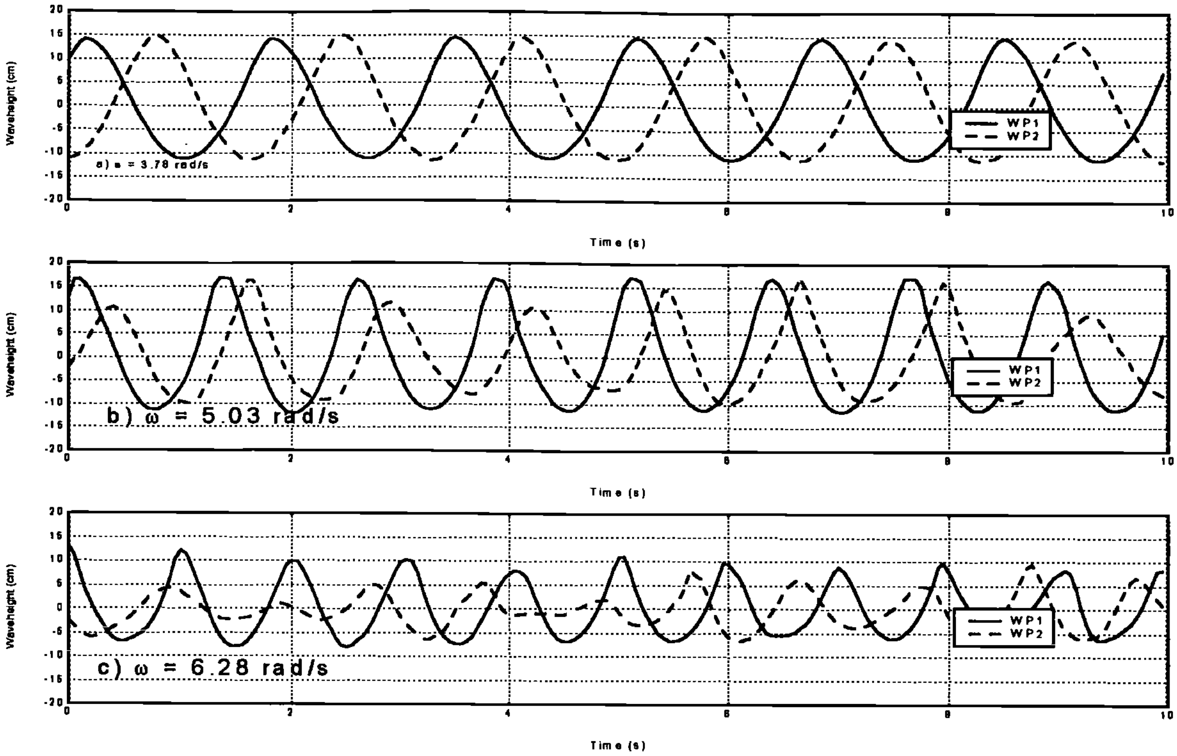

Figure 3.1.4. Time registrations of waves for frequencies of: a) 3.78 rad/s; b) 5.03 rad/s; c) 6.28 rad/s. Amplitude flap motion 0.15 m.

WP2 position. For the highest frequency both the waves at the WP1 and WP2 position suffer from breakers and therefore large irregularities. This can clearly be seen in figure 3.1.4 were time records are shown for the same frequencies as in figure 3.1.2. Due to the larger waveflap amplitude the waves are higher and therefore the harmonic distortion already becomes visible at the lowest of the three frequencies.

For the waveflap amplitude of 0.30 m the waves were usable for ω up to 2.5 rad/s (see figure 3.1.5). The waves still had the same amplitude over the length of the tank. However, beyond this frequency the waves quickly became irregular. For the next higher frequency (3.8 rad/s) in the test the waveflap amplitude was therefore reduced to 0.225 m. For this setting the wave amplitude also remained constant over the length of the tank. The two highest frequencies were not tested.

Figure 3.1.6 shows the time histories for the frequencies 1.257 rad/s, 2.51 rad/s and 3.78 rad/s. It should be realized that for the highest of these frequencies the waveflap amplitude was reduced to 0.225 m. Note that for the highest frequency the signal from WP1 clipped and was therefore unusable for the determination of harmonics. From the time registrations it can be seen that in some conditions the signal from the waveprobe near the waveflap (WP1) shows some high-frequency ripple. This is the result from water leakage between the sides of the waveflap and the model basin walls. In fact, when waves became higher and higher this caused standing waves developing in the tank transversal to the desired waves. This may also be an extra cause for the onset of irregular waves. This was however not further investigated.

Interesting as the figures so far may be, for daily use a chart showing which maximum wave heights can be generated for a given frequency without becoming unstable would be of more practical value. As was discussed before the achievable wave height at low frequencies is

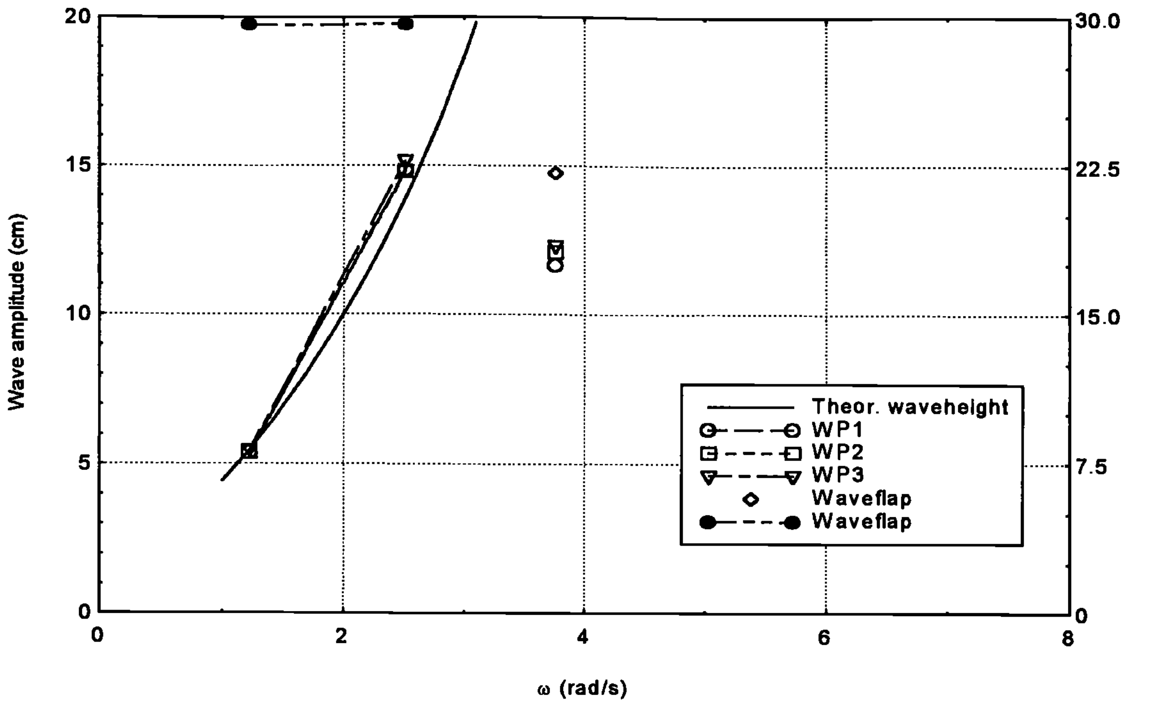

Figure 3.1.5. Generated wave heights at 0.30 m and 0.225 m waveflap amplitude.

wavemaker limited and increases quadratically with frequency for a given waveflap amplitude. For frequencies higher than about 3.5 rad/s and high amplitudes the generated amplitude is lower than predicted with the simple wavemaker model. It proved possible to obtain an experimental correction for this transfer function. This is shown in figure 3.1.7 where the ratio

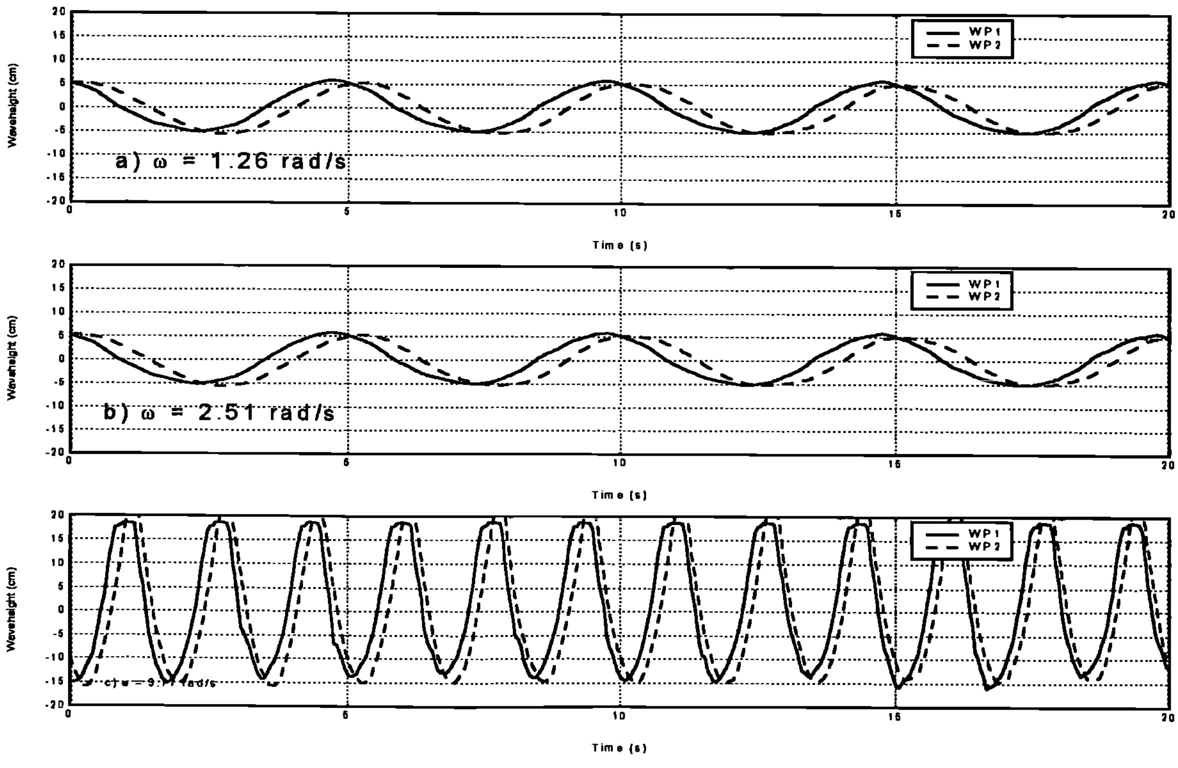

Figure 3.1.6. Time registrations for frequencies of: a) 1.257 rad/s; b) 2.51 rad/s; 3.78 rad/s. Amplitude flap motion 0.30 m for lowest two frequencies, 0.225 m for the highest one.

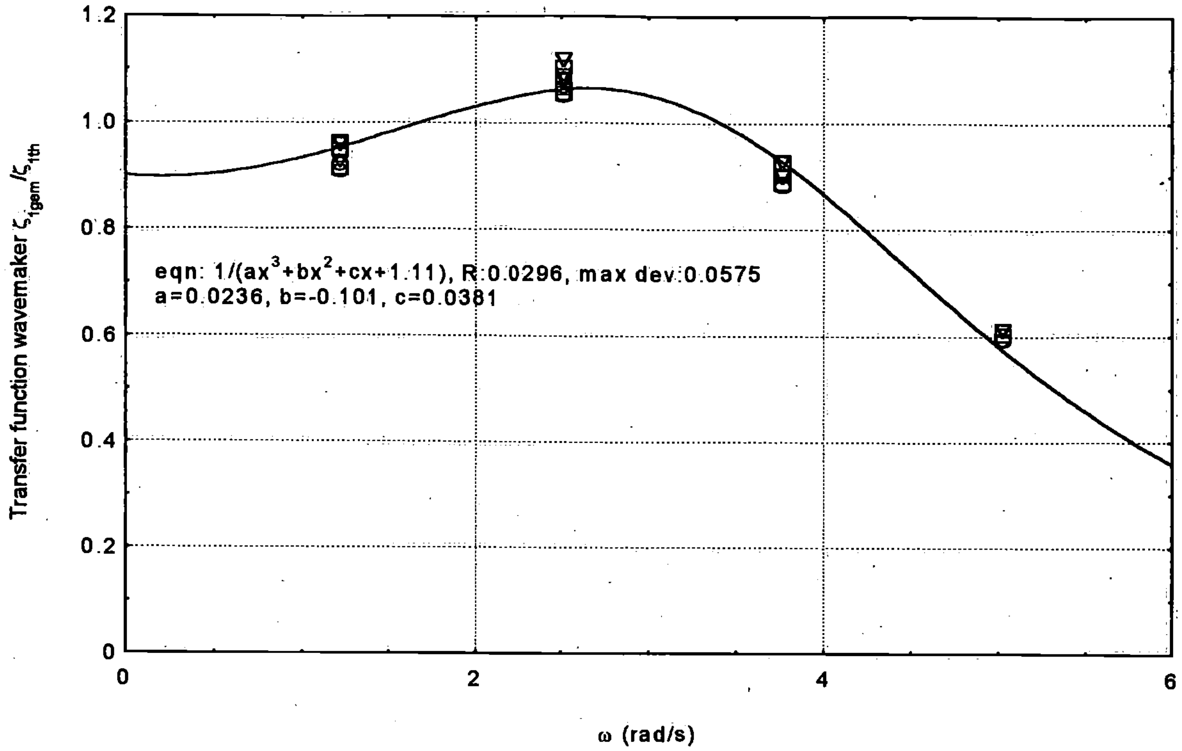

Figure 3.1.7. Correction transfer function for simple wavemaker model.

between measured and theoretical wave height are given as a function of frequency. Also shown is a function that was fitted on the data and is given by

$$H_c(\omega)=\frac{1}{.0236.\omega^3-0.101.\omega^2+.0381.\omega+1.1}$$

The equation for the wave height obtained from the model of the wavemaker transfer is given as a function of wavelength λ. However, given λ ω can be calculated and after that the correction transfer function value $H_\zeta(\omega)$. This factor can be included in the equation for the maximum waveheight achievable in the capacity limited low frequency range. This formula now becomes

$$\zeta_{1_{max}}(\lambda)=\frac{\pi}{\lambda}\cdot\frac{(h-0.35)^2}{8.667[.0236\omega(\lambda)^3-0.101\omega(\lambda)^2+0.0381\omega(\lambda)+1.1]}$$

For lower values of the hydraulic cylinder motion amplitude a_f the waveamplitude is given by

$$\zeta_1(\lambda,a_f)=\zeta_{1_{max}}(\lambda).\frac{a_f}{0.3}$$

Figure 3.1.8 shows data that was already shown in figure 3.1.1. However, instead of the theoretical value calculated with the crude wave transfer function of figure 3.1.1 the modified transfer function was used. This transfer function clearly fits the data much better.

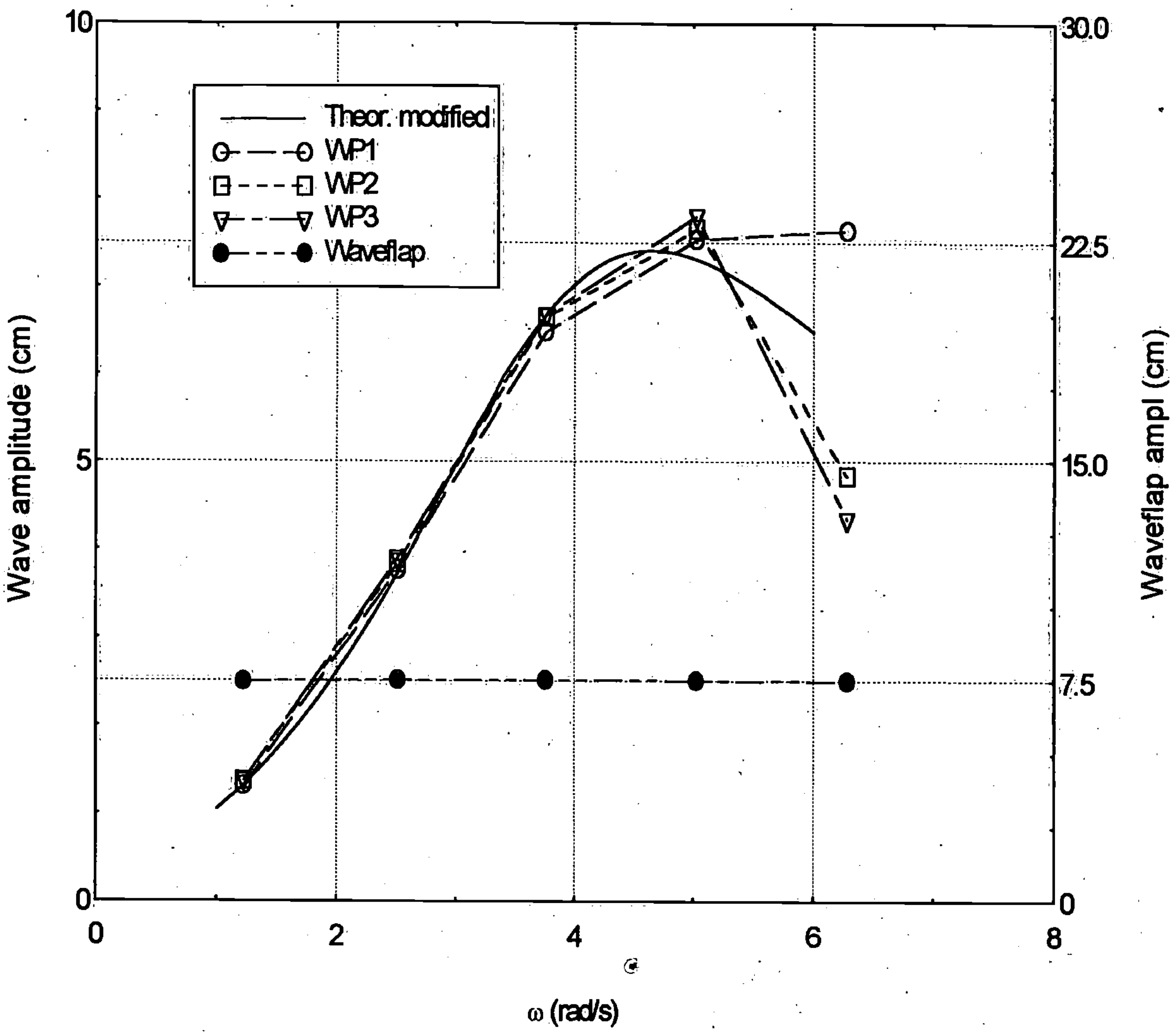

Figure 3.1.8. Comparison of theoretical waveheights calculated using the modified transfer function with measured values. Wavemaker cylinder amplitude 0.075 m.

For the higher frequency and amplitude combinations the limitation in achievable wave height becomes the wave steepness s_ζ which is defined as

$$s_\zeta = 2 * \frac{\zeta_1}{\lambda}$$

where: $\zeta 1$ = the amplitude of the first harmonic of the wave
λ = the wavelength.

Investigating the wave steepness near the onset of breakers learnt that the waves remained regular up to a steepness value of about 0.08. Above that they soon became irregular.

Using the formulae found so far the chart shown in figure 3.1.9 was generated. The (wavemaker) capacity limited curve is given for water depths of 2.2 and 2.35 m.

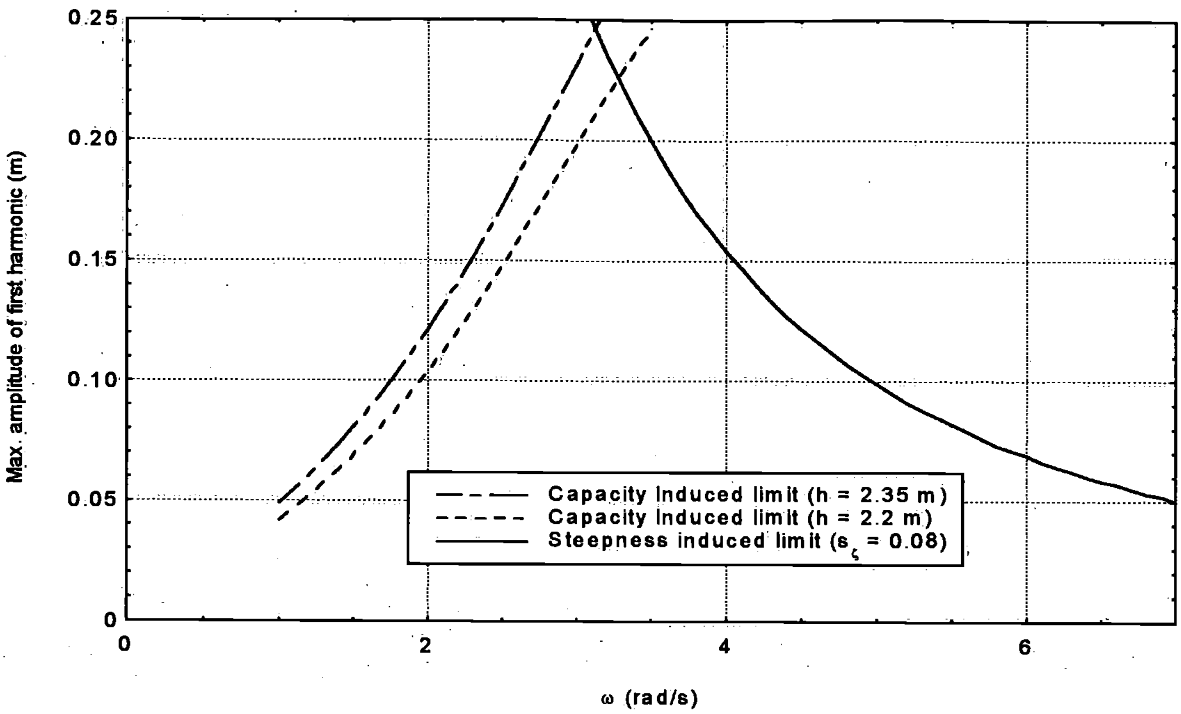

Figure 3.1.8. Achievable wave heights at water depths of 2.2 and 2.35 m. Maxima given are amplitudes of the first harmonic of the waves.

It should be realised that momentary wave heights can exceed the values given above due to the harmonic distortion of the waves. This harmonic distortion can be a problem for some tests. It would therefore be advantageous to know more the amplitudes of those harmonics. This is the subject of the next sub-chapter.

3.2 Harmonic distortion

In the previous sub-chapter it was already mentioned that the harmonic distortion of the waves becomes considerable with increasing wave height and/or frequency. In the first place this distortion is generated by physical wave mechanisms. These can not be avoided and hence form a minimum level. However, as the motion of the waveflap is non-ideal this may lead to increased harmonic distortion. These may or may not damp out further on in the tank and it is of interest to find this out. The theoretical minimum of the distortion can be calculated using the following third order Stokes representation for the instantaneous wave height. [2]

$$\zeta(x,t)=\zeta_1 \cdot \cos(k \cdot x-\omega \cdot t)+\frac{1}{2} \cdot k \cdot \zeta_1^2 \cdot \cos(2 \cdot (k \cdot x-\omega \cdot t))+\frac{3}{8} \cdot k^2 \cdot \zeta_1^3 \cdot \cos(3 \cdot (k \cdot x-\omega \cdot t))$$

From this formula it follows that the amplitude of the second harmonic is given by

$$\zeta_2=\frac{1}{2} \cdot k*\zeta_1^2=\frac{\pi}{\lambda}*\zeta_1^2$$

or, using the wave steepness s_ζ instead the amplitude can also be expressed as

$$\zeta_2 = \frac{\pi}{2}.s_\zeta.\zeta_1$$

In a similar way the equation for the third harmonic becomes

$$\zeta_3 = \frac{3}{8}.\pi^2.s_\zeta^2.\zeta_1$$

Where necessary in the sequel, theoretical values of the second and third harmonic will be calculated using the formulae given above using the measured ζ_1.

From all of the wave records of the test programme the amplitudes of the second and third harmonic were determined. The relative amplitudes from the second harmonic for the three series with different waveflap amplitude are shown in the figures 3.2.1 through 3.2.3. The relative amplitude is hereby defined as the ratio of the second harmonic and the first harmonic. The theoretical values that are also shown are the mean of the theoretical values belonging to the first harmonic of each of the three wave signals. In figure 3.2.3 only one value for WP1 data is given because the other two data points were suspect due to clipping of the signal.

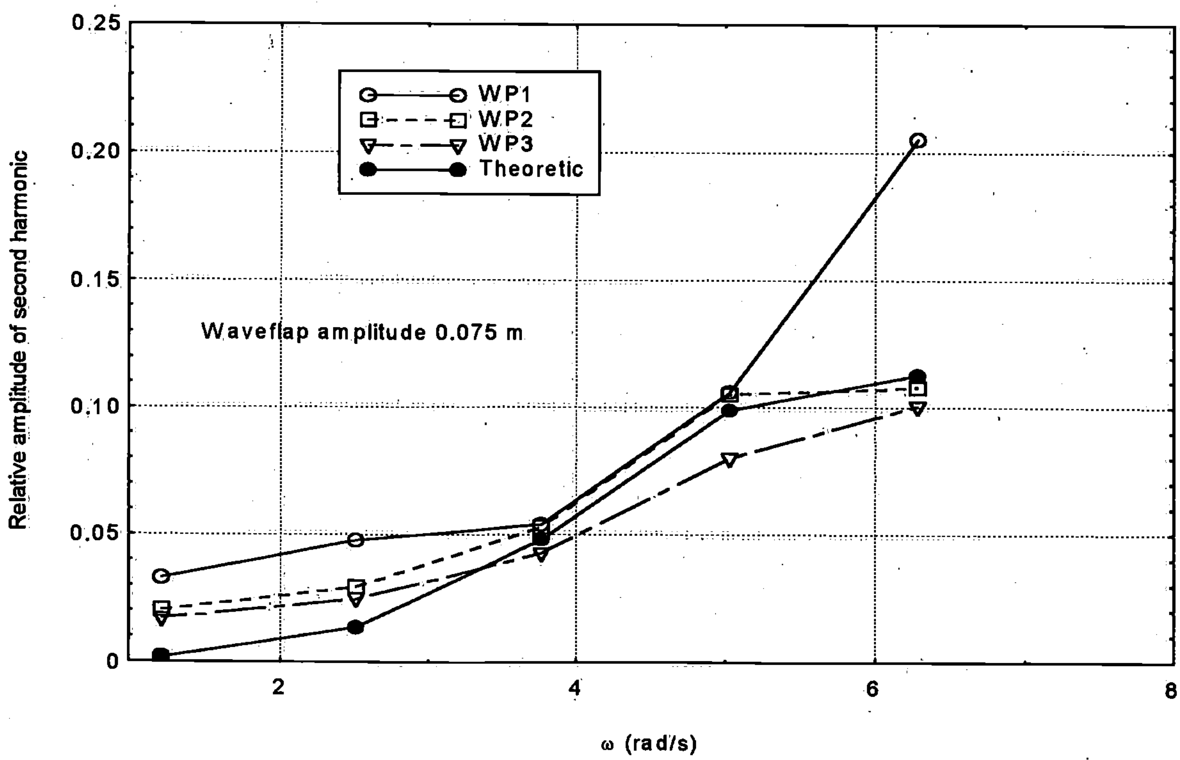

Figure 3.2.1. Relative second harmonic as a function of frequency. Waveflap amplitude 0.075 m.

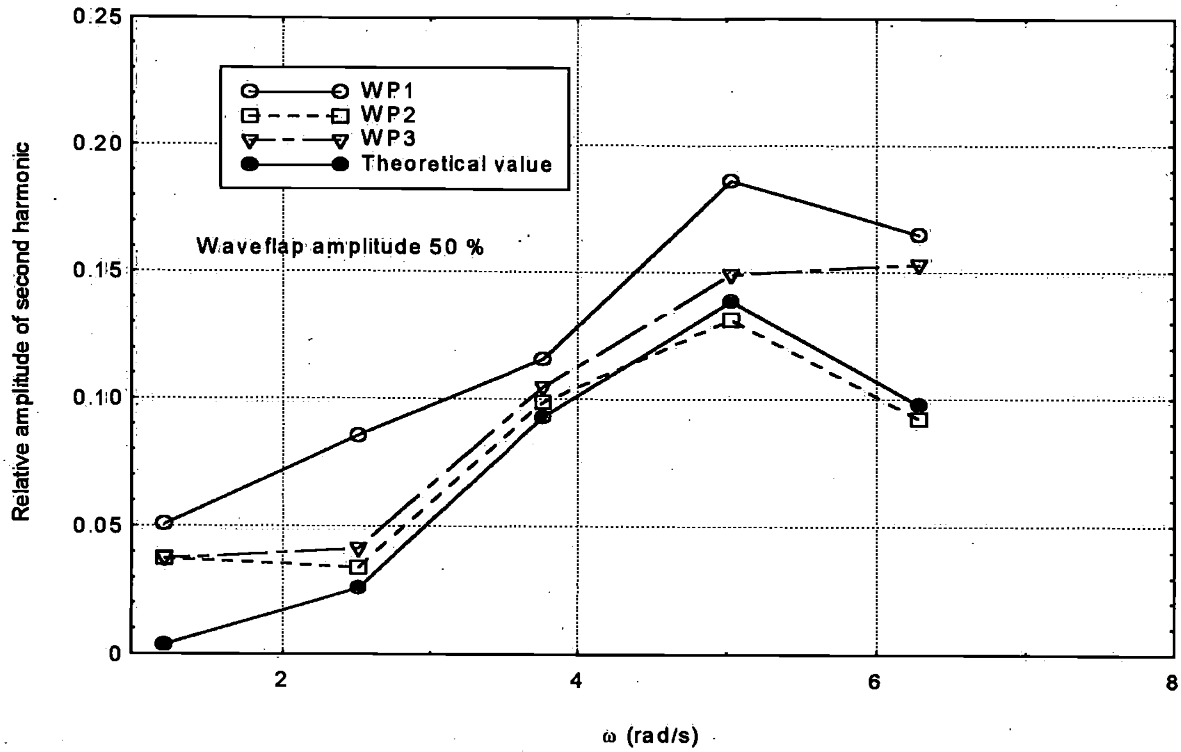

Figure 3.2.2. Relative second harmonic as a function of frequency. Waveflap amplitude 0.15 m.

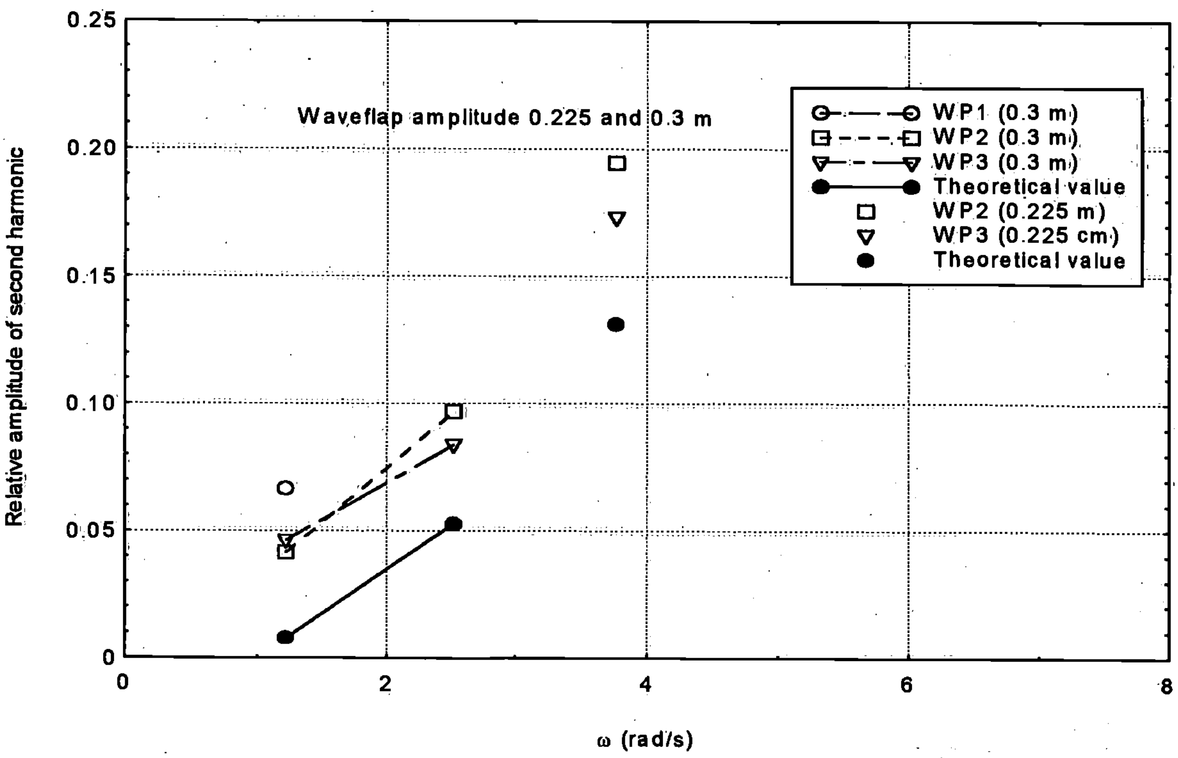

Figure 3.2.3. Relative second harmonic as a function of frequency. Waveflap amplitude 0.3 m.

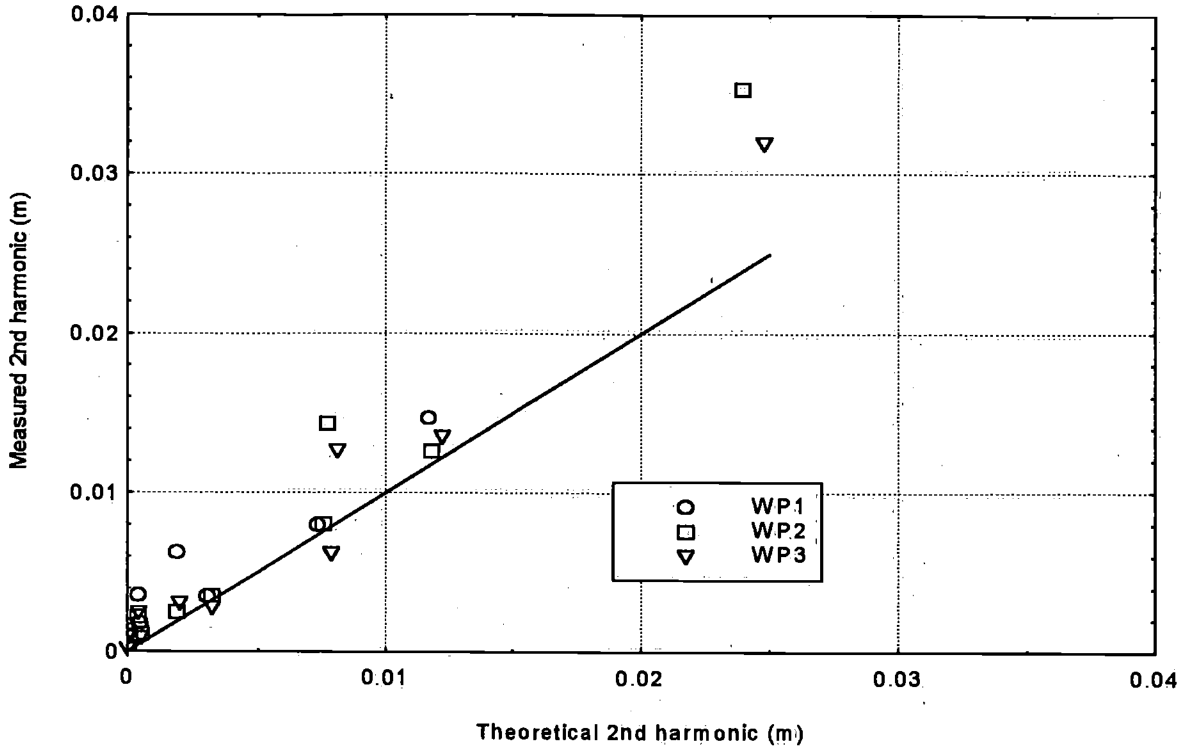

Figure 3.2.4. Measured amplitude of second harmonic as function of theoretical amplitude.

When studying the figures it becomes clear that the waves near the wavemaker show the highest amount of second harmonic distortion. This is probably due to extra harmonics generated by the non-ideal motion of the waveflap. Further away from the wavemaker the amount of second harmonic distortion decreases and is getting closer to the theoretical level (in the region were the waves are regular).

A better way of presenting the data is shown in figure 3.2.4. Here the measured relative second harmonic is given as function of the theoretical second harmonic belonging to the wave height ζ_1 of the wave. From the figure it is clear that at low theoretical values the measured values are relatively much higher. However, as the distortion remains very low this is in practice no problem. At high theoretical values the measured relative second harmonics are also about 40 to 50 % higher. However, as at these values we are approaching the point where the waves are becoming irregular effects like this can be expected.

The third harmonics can be represented in the same way as the second harmonics. Figures 3.2.5 through 3.2.7 show the normalized third harmonics as a function of frequency for the waveflap amplitudes of 0.075, 0.15 and 0.30 m respectively. Figure 3.2.8 shows the measured third harmonic as a function of theoretical third harmonic. Considering the difficulties to extract these small components from the full signal the results are very satisfactory.

Looking back at the discussion it can be concluded that the harmonic content of the waves is higher than the theoretical minimum. However, this was only to be expected and the results are in fact quite satisfactory. Noticeable is that the second and third harmonic distortion near the wavemaker are higher than further on in the model basin. This is probably due to the non-ideal motion of the wavemaker flap. It may be possible to modify the control signal to the wavemaker in such a way that the harmonic distortion is reduced. This was however not investigated.

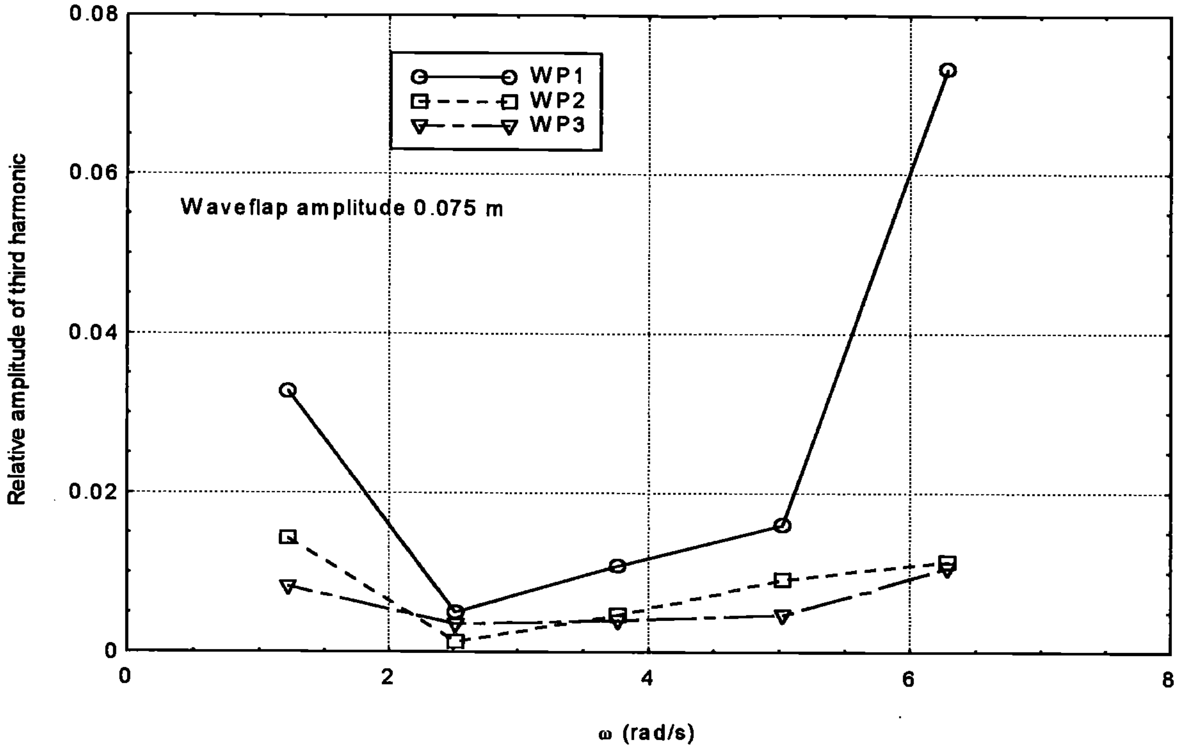

Figure 3.2.5. Relative third harmonic as function of frequency. Waveflap amplitude 0.075 m.

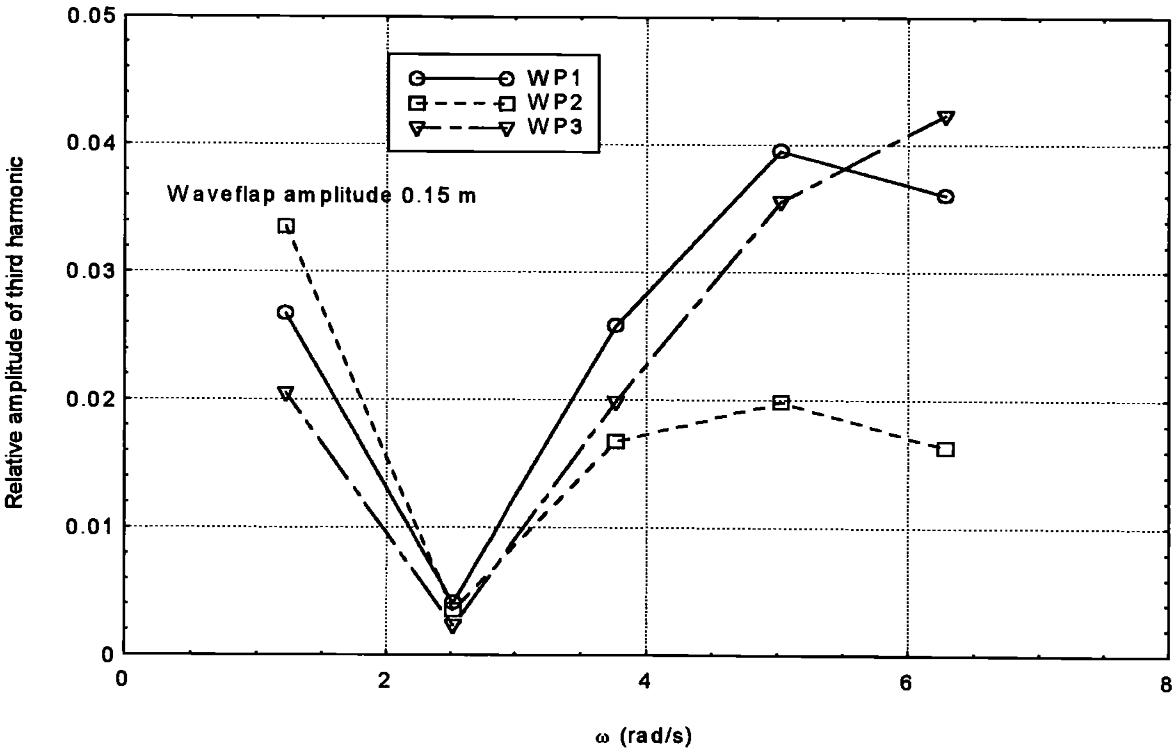

Figure 3.2.6. Relative third harmonic as function of frequency. Waveflap amplitude 0.15 m.

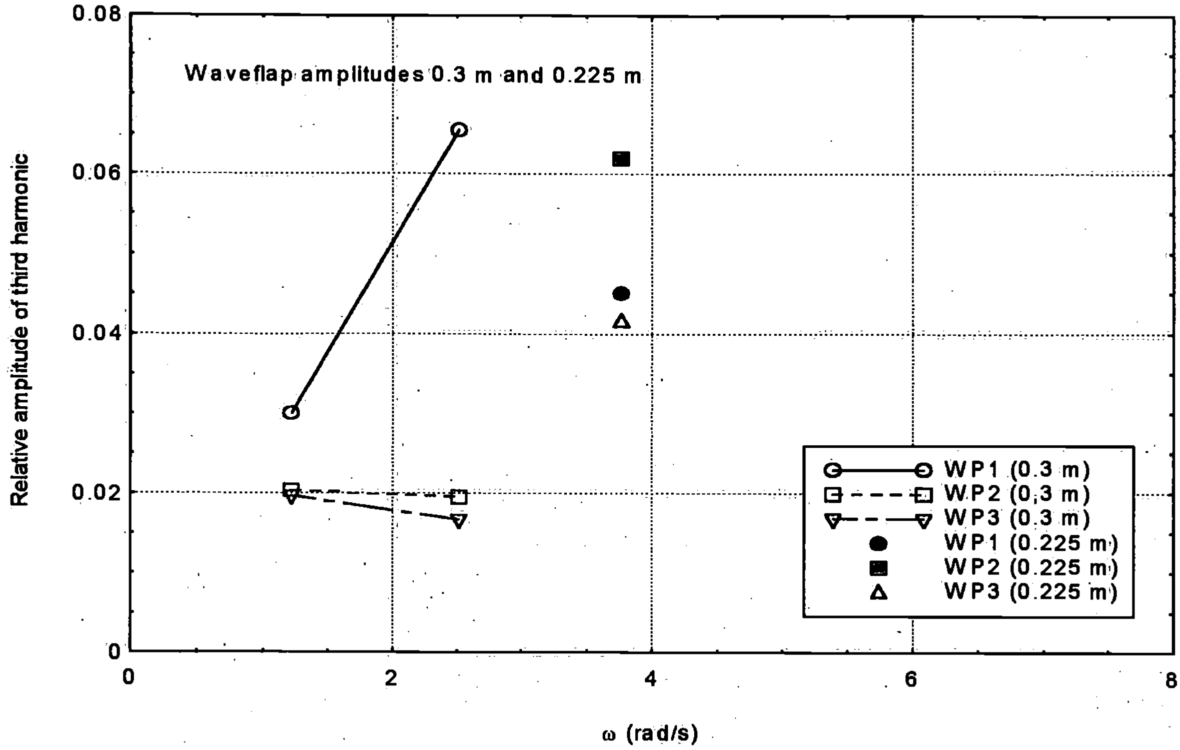

Figure 3.2.7. Relative third harmonic as function of frequency. Waveflap amplitude 0.3 m.

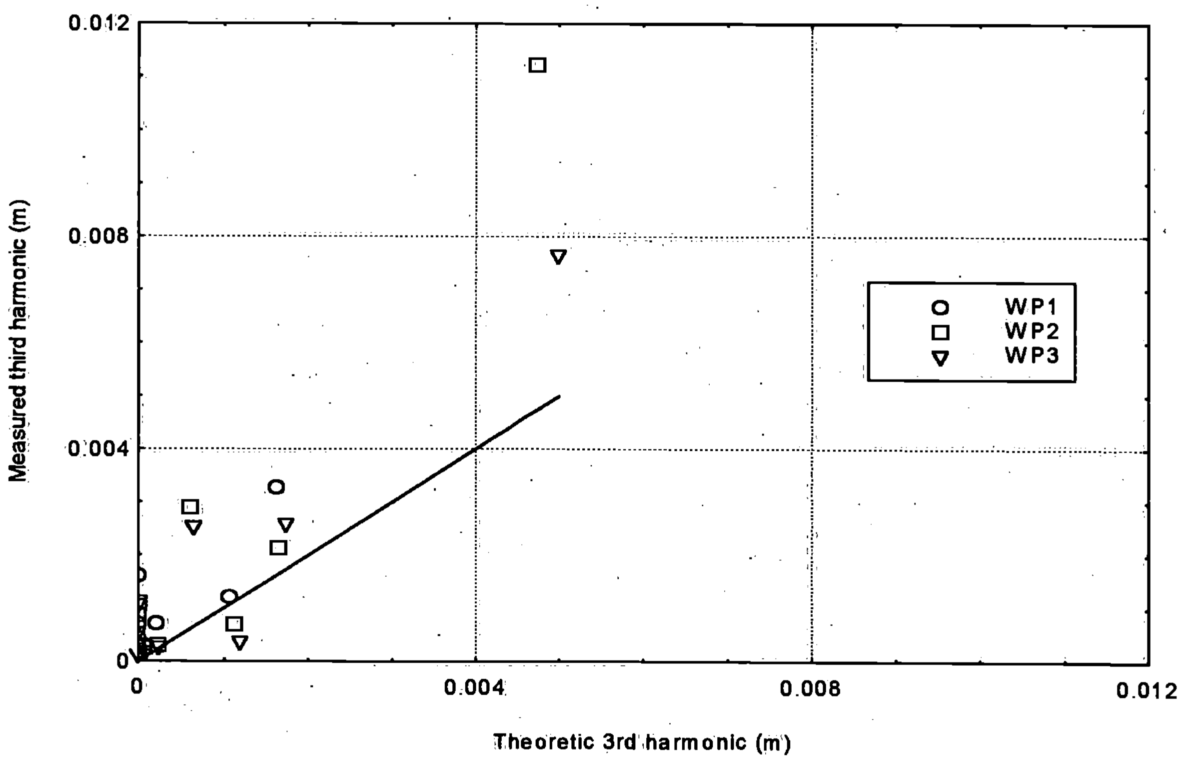

Figure 3.2.8. Measured third harmonic as function of theoretic value.

When the wave steepness becomes too high breakers will develop. As a consequence the wave height over the length of the tank will reduce. The mainly non-harmonically related signal residue will increase. The theoretical maximum wave steepness before instability occurs is about 0.14 [2]. However, in practice this value is never achieved. During the experiments a maximum usable wave steepness of about 0.08 was found. It may therefore be expected that the residues start increasing rapidly when exceeding this value.

The maximum wave steepnes of 0.08 is confirmed by the data shown in figure 3.2.9. The relative residue given in this figure is defined as the ratio of the RMS value of the residue and the RMS value of the first harmonic (0.707*ζ_1). As value for wave steepness the theoretical value is used (including frequency dependent correction) because the measured steepness is dropping quickly when the waves loose hight due to breakers. This would obscure what is happening.

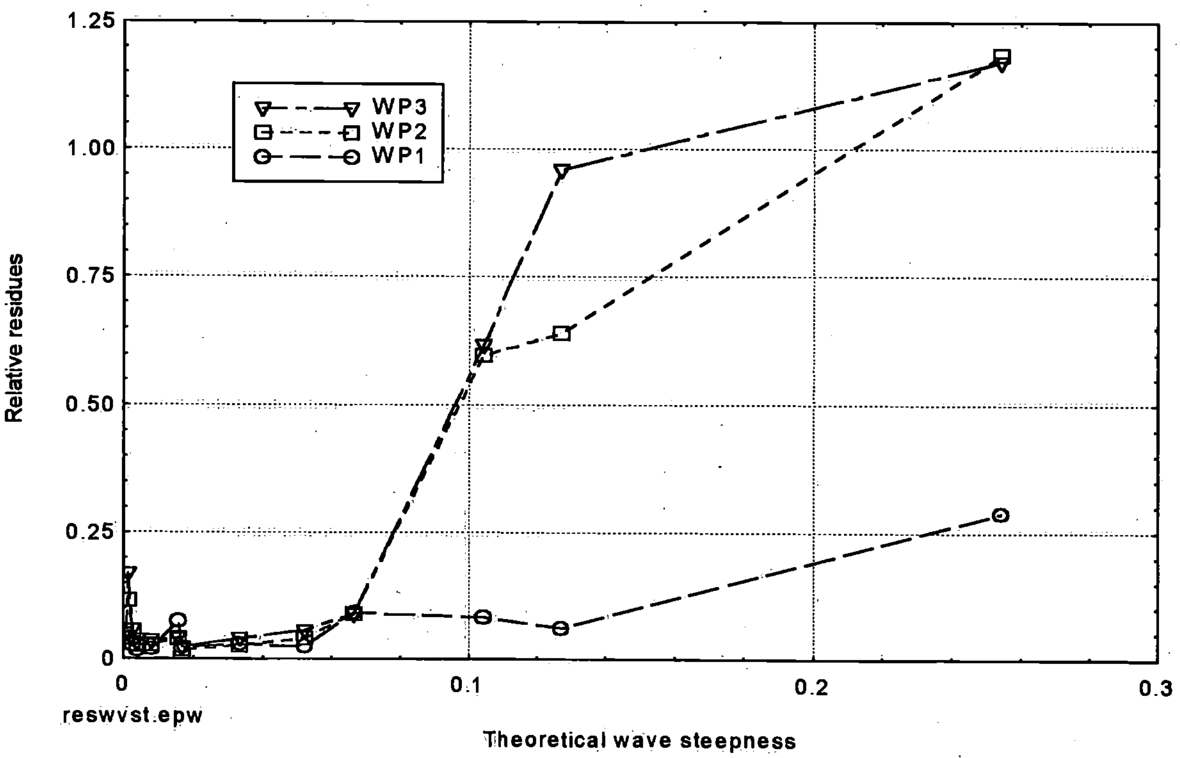

Figure 3.2.9. Relative residues as function of theoretical wave steepness.

4 Conclusions

The tests established the capabilities of the wavemaker. Insight was gained about the maximum achievable wave steepness and the equation for the calculation of maximum achievable wave heights at low frequencies was basically proven correct. A frequency correction was introduced to refine the predictions. In this frequency range the wave height also increased linearly with the amplitude of the waveflap motion. It was shown that the harmonic distortion of the waves was somewhat higher than the theoretically predicted values. However, the results were found to be satisfactory. It also became clear that the wavemaker generates more harmonics than the theoretical wave contains. When the waves move away from the wavemaker the balance is restored. This can be seen from the differences in distortion of wave probes WP1 and WP2. At shorter wavelengths and well away of the wavemaker the 2nd harmonic distortion is getting close to its theoretical value.

The results can be used for the daily use of the wavemaker during tests. Moreover, the improved mathematical model can and will be incorporated in software for the generation of irregular waves. Work on this subject has been going on for some time [1] and the verification and refinement of the mathematical model used for the wavemaker was a necessary next step. Furthermore it could be contemplated to try to reduce the second order distortion near the wavemaker by modifying the signal to the wavemaker somewhat. It is possible that this will shift the onset of residues to a higher value of the wave steepness. This would increase the wavemaker capabilities at higher frequencies.

References

[1] Ooms J. *"The Generation of Irregular Waves in the Number 1 Model Basin"* Report No. 1043-M. Delft Shiphydromechanics Laboratory, Delft, August 1996.

[2] Gerritsma J. *"Bewegingen en sturen: golven"* (in Dutch). Lecturers notes MT513. Delft Shiphydromechanics Laboratory, Delft, 1994

Appendix A Tables

				Wave amplitude				Wave steepness			
Run number	Omega	Wavelength	Waveflap ampl.	Calc. *1	WP1	WP2	WP3	Calc. *2	WP1	WP2	WP3
	rad/s	m	m	m	m	m	m				
32	1.217	21.85	0.075	0.0137	0.0131	0.0137	0.0137	0.00125	0.00120	0.00125	0.00125
34	2.513	8.92	0.075	0.0373	0.0376	0.0384	0.0390	0.00836	0.00844	0.00860	0.00873
36	3.766	4.32	0.075	0.0670	0.0648	0.0665	0.0668	0.03102	0.03001	0.03079	0.03092
38	5.027	2.44	0.075	0.0732	0.0754	0.0766	0.0781	0.05997	0.06182	0.06280	0.06402
40 *	6.283	1.562	0.075	0.0619	0.0765	0.0483	0.0434	0.07931	0.09791	0.06183	0.05551
42	1.217	21.85	0.148	0.0273	0.0258	0.0259	0.0264	0.00250	0.00236	0.00237	0.00242
44	2.513	8.92	0.148	0.0746	0.0731	0.0734	0.0753	0.01672	0.01639	0.01645	0.01689
46	3.766	4.32	0.148	0.1340	0.1267	0.1273	0.1296	0.06204	0.05868	0.05895	0.05999
48 *	5.027	2.44	0.147	0.1463	0.1379	0.0921	0.0933	0.11995	0.11305	0.07548	0.07650
50 *	6.283	1.562	0.015	0.1239	0.0740	0.0353	0.0367	0.15861	0.09472	0.04521	0.04701
52	1.217	21.85	0.296	0.0546	0.0537	0.0538	0.0546	0.00500	0.00491	0.00493	0.00500
54	2.513	8.92	0.296	0.1492	0.1484	0.1480	0.1516	0.03344	0.03327	0.03318	0.03400
56	3.766	4.32	0.221	0.2680	0.1748	0.1814	0.1846	0.12407	0.08092	0.08400	0.08548

Water depth 2.2 m
*1 calculated with frequency compensated wavemaker model.
*2 using calculated wave amplitudes.
Runnumbers followed by * denote runs were the waves became unstable

Table A1 Calculated and measured wave heights and wave steepness for all runs

			Wave amplitude				Relative second harmonic			
Run number	Omega	Wavelength	Calc. *1	WP1	WP2	WP3	Calc. *2	WP1	WP2	WP3
	rad/s	m	m	m	m	m				
32	1.217	21.85	0.0137	0.0131	0.0137	0.0137	0.00196	0.03281	0.02033	0.01694
34	2.513	8.92	0.0373	0.0376	0.0384	0.0390	0.01313	0.04762	0.02939	0.02469
36	3.766	4.32	0.0670	0.0648	0.0665	0.0668	0.04872	0.05389	0.05285	0.04256
38	5.027	2.44	0.0732	0.0754	0.0766	0.0781	0.09421	0.10588	0.10506	0.07984
40 *	6.283	1.562	0.0619	0.0765	0.0483	0.0434	0.12457	0.20522	0.10772	0.10041
42	1.217	21.85	0.0273	0.0258	0.0259	0.0264	0.00393	0.05078	0.03736	0.03743
44	2.513	8.92	0.0746	0.0731	0.0734	0.0753	0.02627	0.08543	0.03398	0.04132
46	3.766	4.32	0.1340	0.1267	0.1273	0.1296	0.09745	0.11582	0.09880	0.10474
48 *	5.027	2.44	0.1463	0.1379	0.0921	0.0933	0.18841	0.18619	0.13148	0.14922
50 *	6.283	1.562	0.1239	0.0740	0.0353	0.0367	0.24914	0.16506	0.09222	0.15311
52	1.217	21.85	0.0546	0.0537	0.0538	0.0546	0.00785	0.06658	0.04142	0.04626
54	2.513	8.92	0.1492	0.1484	0.1480	0.1516	Results unreliable			
56	3.766	4.32	0.2680	0.1748	0.1814	0.1846				

Water depth 2.2 m
*1 calculated with frequency compensated wavemaker model.
*2 using calculated wave amplitudes.
Runnumbers followed by * denote runs were the waves became unstable.

Table A2 Calculated and measured relative second harmonics.

			Wave amplitude				Relative third harmonic			
Run number	Omega	Wavelength	Calc. *1	WP1	WP2	WP3	Calc. *1	WP1	WP2	WP3
	rad/s	m	m	m	m	m				
32	1.217	21.85	0.0137	0.0131	0.0137	0.0137	0.00001	0.03273	0.01434	0.00825
34	2.513	8.92	0.0373	0.0376	0.0384	0.0390	0.00026	0.00500	0.00130	0.00352
36	3.766	4.32	0.0670	0.0648	0.0665	0.0668	0.00356	0.01086	0.00465	0.00401
38	5.027	2.44	0.0732	0.0754	0.0766	0.0781	0.01331	0.01599	0.00916	0.00466
40 *	6.283	1.562	0.0619	0.0765	0.0483	0.0434	0.02328	0.07325	0.01141	0.01061
42	1.217	21.85	0.0273	0.0258	0.0259	0.0264	0.00002	0.02673	0.03354	0.02050
44	2.513	8.92	0.0746	0.0731	0.0734	0.0753	0.00103	0.00408	0.00350	0.00232
46	3.766	4.32	0.1340	0.1267	0.1273	0.1296	0.01424	0.02582	0.01673	0.01988
48 *	5.027	2.44	0.1463	0.1379	0.0921	0.0933	0.05325	0.03953	0.01985	0.03554
50 *	6.283	1.562	0.1239	0.0740	0.0353	0.0367	0.09311	0.03605	0.01631	0.04230
52	1.217	21.85	0.0546	0.0537	0.0538	0.0546	0.00009	0.03000	0.02034	0.01963
54	2.513	8.92	0.1492	0.1484	0.1480	0.1516	Results unreliable			
56	3.766	4.32	0.2680	0.1748	0.1814	0.1846				

Water depth 2.2 m
*1 calculated with frequency compensated wavemaker model.
*2 using calculated wave amplitudes.
Runnumbers followed by * denote runs were the waves became unstable.

Table A3 Calculated and measured relative third harmonics.

			Wave amplitude				Relative wave residue *2		
Run number	Omega	Wavelength	Calc. *1	WP1	WP2	WP3	WP1	WP2	WP3
	rad/s	m	m	m	m	m			
32	1.217	21.85	0.0137	0.0131	0.0137	0.0137	0.040	0.045	0.051
34	2.513	8.92	0.0373	0.0376	0.0384	0.0390	0.017	0.026	0.038
36	3.766	4.32	0.0670	0.0648	0.0665	0.0668	0.023	0.018	0.023
38	5.027	2.44	0.0732	0.0754	0.0766	0.0781	0.025	0.041	0.057
40 *	6.283	1.562	0.0619	0.0765	0.0483	0.0434	0.062	0.640	0.959
42	1.217	21.85	0.0273	0.0258	0.0259	0.0264	0.040	0.116	0.168
44	2.513	8.92	0.0746	0.0731	0.0734	0.0753	0.019	0.028	0.037
46	3.766	4.32	0.1340	0.1267	0.1273	0.1296	0.030	0.027	0.040
48 *	5.027	2.44	0.1463	0.1379	0.0921	0.0933	0.083	0.597	0.617
50 *	6.283	1.562	0.1239	0.0740	0.0353	0.0367	0.288	1.185	1.172
52	1.217	21.85	0.0546	0.0537	0.0538	0.0546	0.027	0.055	0.057
54	2.513	8.92	0.1492	0.1484	0.1480	0.1516	0.075	0.040	0.042
56	3.766	4.32	0.2680	0.1748	0.1814	0.1846	0.092	0.089	0.088

Water depth 2.2 m
*1 calculated with frequency compensated wavemaker model.
*2 defined and calculated as (RMS value of residue)/(0.707 x wave amplitude).
Runnumbers followed by * denote runs were the waves became unstable.

Table A4 Measured relative wave residues.