XVII IMEKO World Congress
Metrology in the 3rd Millennium
June 22−27, 2003, Dubrovnik, Croatia

EXPERIMENTAL DETERMINATION OF WAVE PATTERN RESISTANCE OF A TRIMARAN

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Abstract − The experimental determination of wave spectra and wave resistance from measurements of the wave pattern behind a ship model while being towed in a tank received considerable attention in the sixties and seventies. The Landweber, Hogben and Baba methods of experimental determination of wave pattern resistance based on wave height measurements in several longitudinal measurement cuts have been introduced in this paper. The programme of experimental determination of wave pattern resistance has been carried out in DINMA-Trieste for a trimaran whose individual hulls are Wigley parabolic models, for the Froude number range 0.254-0.420, with a total of 12 runs. The above mentioned methods are based on identical hydrodynamic model, and a starting basis are identical analytic expressions. By experimental determination of wave pattern resistance, a comparison of the calculation results (amplitude spectrum, wave resistance, reconstructed waveforms) is given. It has been shown that all three methods are equal and that they give the same results if the criteria based on frequency content determination and resolution in frequency are respected.

Keywords: wave height measurements, wave pattern resistance, trimaran

1. INTRODUCTION

More than a century has passed since W. Froude's time and the first attempts to perform the hydrodynamic experimental researches of the ship forms, and it is still not possible to estimate reliably the total resistance of the surface ship, as an integral content of interactive effects of the water viscosity and gravitational field. During the recent four decades, special experimental methods have been developed for determination of viscous and wave pattern resistance components resulting from the measurements of the hydrodynamic elements behind the ship model.

Application of all experimental methods for determination of wave pattern resistance based on wave pattern element measurements in longitudinal cuts $y_j = \text{const.}$ is induced by the fact that experiments are performed in tanks of finite width $b = \text{const.}$

In the experimental Landweber (LFT-Landwebwer Fourier Transform), Hogben (MEM-Matrix Elements Method) and Baba (MES-Method of Equivalent Singularity) methods, it is assumed that the wave system, generated by a ship model, ideally reflects from the wall of the tank of finite width $b = \text{const.}$ Regarding that, the basic expression for all three methods is the same, and the conditions for application of the methods are the same. Apparently, the main shortcoming of the Sharma method (SLC-Sharma Longitudinal Cut), i. e. the fact that the wave pattern record length is finite and limited by the tank width, is eliminated. On the other hand, each reflection of the wave system from the tank wall has as a consequence passing through the wake. This fact breaks the basic assumption of the hydrodynamic model, i. e. that in the measurement area the fluid is inviscid and incompressible and that the flow is irrotational. Investigation of the influence of the wake on the free wave system is given in [1-6]. According to these investigations this influence can be neglected for the case of one cross of the free wave system through the wake region, that is for the case of two ideal reflections. As will be shown later, this condition, which also limits the wave pattern record length, is also very restrictive in these methods.

In order to eliminate the influence of the local wave system, the wave pattern measurements must be carried out in the region where this influence is negligible. Theoretical and experimental investigations show, see [2-4], that the influence of the local wave system is negligible in the region one half of the ship length behind the stern. This criterion applies for all four mentioned methods.

In the MES method it is possible to include the influence of the local wave system on the wave pattern resistance, what is presented in [2] and [7]. The obtained results pointed to the fact that this influence is small and can be neglected in real applications.

2. THEORETICAL BASIS OF LFT, MEM AND MES METHODS

A ship model of length L moves on the free surface at constant translatory speed c in the positive x direction, as shown in Fig. 1. The Cartesian orthogonal axes $O(x, y, z)$, attached to the ship model, form the right inertial frame of reference. The Oxy plane is a free surface at rest, and the Oxz plane is the centerplane of the ship model-tank system. The tank is of finite width b and infinite depth.

A surface ship, moving at a constant speed c, generates disturbance in the surrounding water, which is characterised by a wave system, boundary layer and wake.

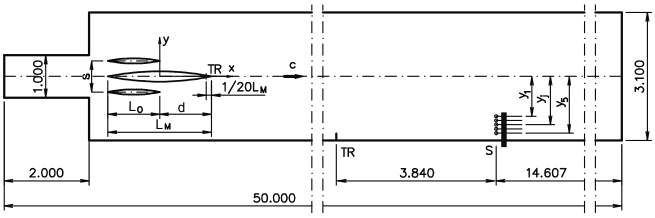

Fig. 1. Tank geometry, the position of the model in the tank, the position of the probes and trigger

The further analysis is directed towards an experimental determination of the ship model wave pattern resistance, based on analysis of the wave pattern measurements behind the model in longitudinal cuts $y_j = \text{const.}$, under the following assumptions: the fluid is incompressible and inviscid, the flow is irrotational, the linear kinematic-dynamic condition holds on the free surface, the effects of the local wave system may be neglected and the effects of the boundary layer and the wake are negligibly small.

Detailed analysis of these, together with a theoretical basis for experimental determination of the surface ship resistance components, is given in [1].

Assuming that all conditions have been met in the experimental situation, the wave height of the free wave system for the tank of the finite width b and infinite depth is given by

$$h(x,y) = \sum_{m=0}^{\infty} \varepsilon_m \left(A_m \cos k_0 l_m x + B_m \sin k_0 l_m x \right) \cos k_0 t_m y \quad , \quad (1)$$

$m = 0,1,2,...$

where

$$\varepsilon_m = \begin{cases} \frac{1}{2} & \text{for } m = 0 \\ 1 & \text{for } m = 1,2,3,... \end{cases} \quad ,$$

A_m, B_m - discrete values of free wave amplitude spectrum components,

$k_0 = \dfrac{g}{c^2}$ - fundamental wave number,

$k_0 l_m$ - discrete value of x component of the wave number,

$k_0 t_m$ - discrete value of y component of the wave number.

The intensity of wave number vector (m-th mode) is defined by the expression

$$k_m = k_0 \left(l_m^{\ 2} + t_m^{\ 2} \right)^{1/2} \quad (2)$$

and the direction of m-th mode of the wave number vector is defined by the value of the angle of propagation

$$\theta_m = \operatorname{arctg} \frac{t_m}{l_m} \quad (3)$$

Discrete values of x and y components of m-th mode of the wave number vector, normalised with the fundamental wave number k_0, are connected by the relation

$$l_m = \left[\frac{1}{2} \left(1 + \sqrt{1 + 4 t_m^{\ 2}} \right) \right]^{1/2} \quad , \quad t_m = \frac{2\pi m}{k_0 b} \quad (4)$$

Free wave amplitude spectrum is given by the expression

$$A(t_m) + \mathrm{i}\, B(t_m) \equiv A_m + \mathrm{i}\, B_m = \frac{8\pi}{bc} \frac{1 + \sqrt{1 + 4 t_m^{\ 2}}}{\sqrt{1 + 4 t_m^{\ 2}}} \; J\left((-1)^m t_m, l_m \right) \quad (5)$$

where $J\left((-1)^m t_m, l_m \right)$ represents a degenerate form of the Kochin function

$$J\left((-1)^m t_m, l_m \right) = \frac{1}{4\pi} \int_{(D)} \sigma(M') \, \mathrm{e}^{k_0 l_m^{\ 2} z' + \mathrm{i} k_0 \left[l_m x' + (-1)^m t_m y' \right]} \mathrm{d}D(M') \quad (6)$$

Substituting (5) and (6) into (1) one gets

$$h(x,y) = \frac{2}{bc} \sum_{m=0}^{\infty} \varepsilon_m \frac{1 + \sqrt{1 + 4 t_m^{\ 2}}}{\sqrt{1 + 4 t_m^{\ 2}}} \int_{(D)} \sigma(M') \mathrm{e}^{k_0 l_m^{\ 2} z'} \cdot \\ \cdot \cos k_0 l_m (x - x') \cos k_0 t_m (y - y') \, \mathrm{d}D(M') \quad (7)$$

The wave pattern resistance coefficient is given by the expression

$$C_{wp} = \frac{R_{wp}}{\frac{1}{2} \rho c^2 S} = \frac{k_0 b}{2S} \sum_{m=0}^{\infty} \varepsilon_m \frac{\sqrt{1 + 4 t_m^{\ 2}}}{1 + \sqrt{1 + 4 t_m^{\ 2}}} \left(A_m^{\ 2} + B_m^{\ 2} \right) \quad (8)$$

where

R_{wp} - wave pattern resistance,

ρ - water density,

S - ship model wetted surface area at rest.

2.1. LFT ,MEM and MES methods

The starting point of all three analysed methods is the same expression (1). The basic difference is that in the LFT method the least square method is applied to free wave amplitude spectrum, while in the MEM and MES methods the least square method is applied to wave heights.

The LFT method has originally been developed by Landweber, and it is described in [1], [4], [5], [6], [8] and [9] in detail.

The MEM method has originally been developed by Hogben and Gadd, and it is described in [1], [8], [10], [11], [12] and [13] in detail.

The MES method has originally been developed by Baba, and it is described in [1], [2], [7] and [14] in detail.

Because of the presence of the term $\cos k_0 t_m y_j$ in expressions (1) and (7), the choice of the position of longitudinal measurement cuts in the application of the LFT, MEM and MES methods should satisfy the following condition

$$4m \frac{y}{b} \neq 2k + 1 \quad , \quad k = 0, \pm 1, \pm 2, ... \quad (9)$$

2.2. Hydrodynamic model analysis

For the tank of finite width b, discrete values of x component of the wave number $k_0 l_m$ exist only in discrete points $k_0 t_m$, and they are connected by relation (4). In the wave number $k_0 t_m$, the amplitude spectrum is Fourier's and the discrete spectrum lines are equidistant with the step $2\pi/b$. In the wave number $k_0 l_m$, the amplitude spectrum is not Fourier's, and the discrete spectrum lines are not equidistant. In the space of the wave number $k_0 l_m$, the position of spectral lines is determined by the tank width b and the fundamental wave number k_0.

In expression (1) the ordinates of the free wave system are represented by the trigonometric sum of infinite number of terms of the following form

$$\begin{gathered}\left(A_m \cos k_0 l_m ct + B_m \sin k_0 l_m ct\right)\cos k_0 t_m y \quad , \\ x = ct \quad , \quad m = 0,1,2,... \end{gathered} \tag{10}$$

A set of trigonometric functions $\cos k_0 l_m ct$ and $\sin k_0 l_m ct$ is not orthogonal, from which it follows that coefficients A_m and B_m in expression (1) can not be obtained by a standard procedure of direct Fourier transformation. Free wave system $h = h(x,y)$ is not a periodic function. According to the adopted mathematical model (1), this function has not a basic (primitive, fundamental) period. The period of the *m*-th term of the series (1) is

$$T_m = \frac{2\pi}{k_0 l_m c} \tag{11}$$

and it is a function of the wave number $k_0 l_m$ with non-equidistant step in frequency region. The frequency of the *m*-th term of the series (1) amounts

$$f_m = \frac{k_0 l_m c}{2\pi} \tag{12}$$

The free wave amplitude spectrum is defined in the form

$$S_m = \left(A_m{}^2 + B_m{}^2\right)^{1/2} \quad , \quad m = 0,1,2,... \tag{13}$$

Knowing the discrete values of the free wave amplitude spectrum components A_m and B_m, all the terms of the trigonometric sum (1) are determined, in other words, the free wave system $h = h(x,y)$ is defined. The task is to determine the coefficients A_m and B_m in the trigonometric sum (1) from the wave pattern $h = h(x,y)$.

The waveform, according to [15], taken from any longitudinal measurement cut, is characterised by:

- the frequency content of the measured analogue signal,
- the total sample period of measurement (the length of the analogue signal).

Choosing (first criterion) a corresponding sample rate, the frequency content of measured waveform and the resulting spectrum are controlled. Resolution in frequency (second criterion), which is defined by the length of measured waveform, controls the accuracy of amplitude spectrum. Verification of the criteria is controlled by the reconstruction of waveform and a comparison with the measured signal.

The sample time increment of the analogue signal is defined by Shannon's sampling theorem which states that the sample rate must be more than twice the highest frequency contained in the measured signal. If f_s denotes the sampling frequency, Δt_s the sample time increment, and Δx_s the sample space increment, this criterion can be written in the following forms

$$\begin{gathered} f_s > 2 f_m = \frac{k_0 l_m c}{\pi} \quad , \quad \Delta t_s = \frac{1}{f_s} < \frac{\pi}{k_0 l_m c} \quad , \\ \Delta x_s = c \Delta t_s < \frac{\pi}{k_0 l_m} \end{gathered} \tag{14}$$

Satisfying criterion (14), the frequency content of the measured signal and the resulting spectrum is controlled.

The total sample period of measurement (the length of analogue signal) is defined by the real situation in the experiment, in other words, by limitations imposed by the mathematical model. If F_0 denotes the total record length of measured waves in one longitudinal measurement cut $y_j = \text{const.}$, then the resolution in frequency of the waveform is defined by the expression

$$\Delta f = \frac{c}{F_0} \tag{15}$$

For a sufficiently large *m*, from (4) and (12) follows

$$l_m \approx \sqrt{t_m} \tag{16}$$

and

$$\begin{aligned} \Delta f_m &= \frac{k_0 c}{2\pi} \Delta l_m \approx \frac{k_0 c}{2\pi}\left(\sqrt{t_m} - \sqrt{t_{m-1}}\right) = \\ &= \frac{1}{2}\sqrt{\frac{g}{2\pi b}} \frac{1}{\sqrt{m}} \end{aligned} \tag{17}$$

From the last relation and expression (15) one obtains

$$m \le \left(\frac{F_0}{b}\right)^2 \frac{gb}{8\pi} \frac{1}{c^2} = \frac{1}{8\pi}\left(\frac{F_0}{b}\right)^2 \frac{b}{L} \frac{1}{Fn^2} \tag{18}$$

It follows that the number of terms of the series (1), for a given tank of width b=const. and a given model speed c, is determined by record length F_0. Varying the waveform record length F_0, the frequency resolution Δf is changed, which assures the minimisation of "losses" of amplitude spectrum values and the determination of exact values.

Since the starting point of experimental determination of the ship model wave pattern resistance in a tank is the same expression (1) in the LFT, MEM and MES methods, the derived criteria for waveform analysis apply to all three methods. In the following it will be shown that the wave pattern resistance obtained by any of these three methods is the same.

It is worth mentioning that these methods do not enable the determination of ship form that is the generator of disturbance, in other words, there is no unambiguous connection amplitude spectrum-ship form.

The comparison between the LFT, MEM and MES methods will be done as well, with the application of the settled criteria.

3. EXPERIMANTAL DETERMINATION OF WAVE PATTERN RESISTANCE

This section presents the experimental determination of wave pattern resistance of the trimaran configuration which consists of standard Wigley's models with parabolic waterlines. The form of Wigley hull can be described by the analytic expression

$$\eta(x', z') = \pm \frac{B}{2}\left[1-\left(\frac{2x'}{L}\right)^2\right]\left[1-\left(\frac{z'}{T}\right)^2\right] \quad , \quad -L/2 \le x' \le L/2 , \quad -T \le z' \le 0 \tag{19}$$

The characteristic dimensions of the main hull are L_M, B_M, T_M, and the identical outriggers have characteristic dimensions L_O, B_O, T_O. The trimaran configuration is defined by the ratios d/L_M and s/L_M, where d is the distance in the longitudinal direction (the direction of motion) between the bows of the main hull and the outriggers, and s is the distance in transverse direction between the centreline planes of outriggers. The trimaran configuration with ratios $d/L_M = 0.500$ and $s/L_M = 0.4$ is adopted for the experiment, and the characteristic dimensions of individual hulls are given in Table I.

The experiments have been performed for the case of the trimaran moving in a tank with length of 50 m, width 3.1 m and depth 1.6 m, for the Froude number range 0.254-0.420, with a total of 12 runs. The Froude number is based upon the length of the main hull $Fn = c/\sqrt{gL_M}$.

The experiments have been conducted in the towing tank at the University of Trieste. The performed experiments of the trimaran configuration wave pattern resistance determination represent a part of the joint research programme of the University of Trieste and the University of Zagreb. Tank geometry with main particulars, the position of the model in the tank, the position of the probes and trigger are given in Fig. 1. All measurements have been conducted with a model free regarding trim and sinkage.

Capacitance probes of external diameter $\phi 0.75$ mm, length 220 mm, with teflon coating have been used for wave pattern measurements. The probes are mounted on a support which is vertically attached to the tank wall. The head of the support, on which this part of measurement equipment is attached, has a possibility of vertical shifting, with a possibility of reading the probe immersion depth of 0.05 mm. In this way the static calibration and cleaning of the probes is made possible. The typical disadvantage of capacitance probe, due to water absorption by the insulator with the related response variation, can be overcome by careful and frequent calibration and by avoiding probe immersion for too long times. Wave pattern measurements have been conducted in five longitudinal measurement cuts.

TABLE I. Main particulars

	Main hull	Outriggers	Total
Length L(m)	2.4384	1.2192	2.4384
Breadth B(m)	0.24384	0.12192	1.0973
Draft T(m)	0.1524	0.0762	0.1524
Displacement (kg)	40.273	5.034	50.341
Wetted surface (m^2)	0.88842	0.22210	1.33262
L/B	10.0	10.0	
B/T	1.6	1.6	
C_B	0.444	0.444	
C_P	0.666	0.666	

The trigger is placed on the position TR on the tank wall, which enables positioning and synchronising of measured waveform with respect to the model.

Analogue signals from all five probes and trigger TR are directed towards the analogue amplifier. After the conditioning/amplifying of the signals, they are recorded on the tape RACAL V-Store (8 channels, recording speed 95.2 mm/s, cut off frequency 2.5 kHz). Before and after each series of runs, the static calibration has been performed with the same measurement chain. After all runs, A/D conversion of analogue signals has been carried out with the sampling frequency of 1 kHz. Before the procedure of A/D conversion, the frequency content analysis of recorded waveforms has been done and it has been established that the measured signals do not contain frequencies higher than 100 Hz. Schematic view of measurement equipment is given in Fig. 2. In an additional procedure, the filtration of the part of fundamental data basis has been carried out passing signals through a filter of low omission of 45 Hz.

Fig. 3 shows the comparisons of the wave pattern resistance coefficient values obtained by applying the LFT, MEM and MES methods. The relative errors of the wave pattern resistance coefficient values amount to maximum 1.13% for $Fn \ge 0.270$.

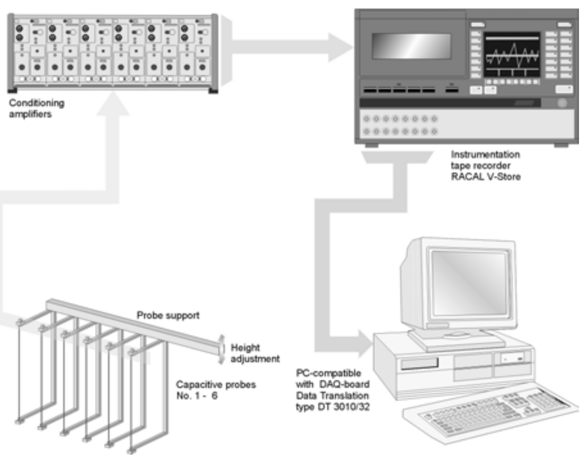

Fig. 2. Schematic view of measurement equipment

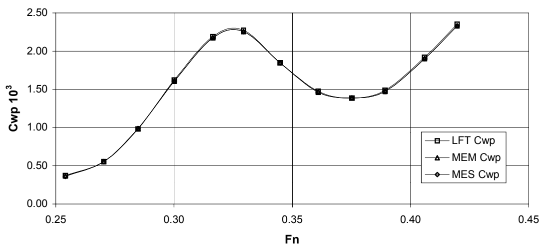

Fig. 3. The comparison of wave pattern resistance coefficients obtained by applying different methods

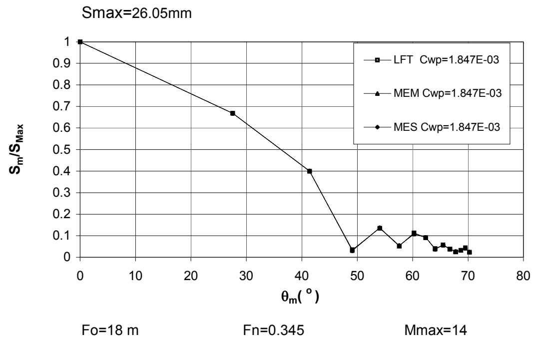

Fig. 4. Amplitude spectrum comparison

Fig. 4 represents the comparisons of amplitude spectrum values with respect to the direction angle θ_m obtained by applying all three methods for $Fn = 0.345$. Wave pattern resistance coefficient values are also given. Obtained results point to the fact that all three methods give practically identical results for amplitude spectrum values.

If we adopt the double maximum number of modes $m = 2M_{\max}$, so that all $2M_{\max}$ modes can be seen in measured waveform and that the amplitude spectrum values can be reliably determined, it is necessary, according to (18), to assure the resolution in frequency of $\Delta f = c/\sqrt{2}\,F_0$. Since the real length of waveform amounts to F_0, it is not possible to satisfy this condition. Regardless of this fact, experimental determination of wave pattern resistance has been performed applying all three methods, and results are shown in Fig. 5. The results refer to $Fn = 0.345$, the length of measured waveform being $F_0 = 18$ m, and maximum number of modes $m = 2M_{\max}$, where $M_{\max}$ is determined from criterion (18). The results obtained by applying the MEM and MES methods point again to the fact that these two methods give practically identical results for amplitude spectrum values up to the accepted maximum number of modes $2M_{\max}$. The results obtained by applying the LFT method are not real. This is a consequence of the fact that the LFT method is based on the application of direct Fourier transformation on the measured waveform taken separately from each longitudinal measurement cut, not respecting criterion (18). It is worthy to mention that the amplitude spectrum values are identical with amplitude spectrum

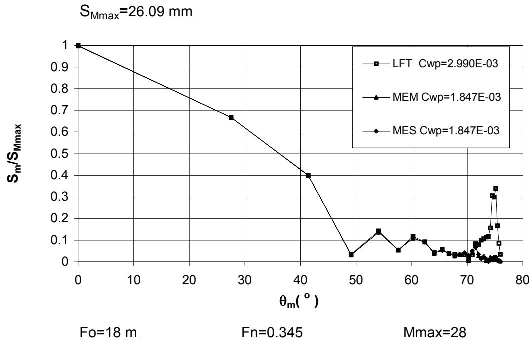

Fig. 5. Amplitude spectrum comparison for double number of modes

values obtained by applying the MEM and MES methods up to $m = M_{\max}$, that is up to the maximum number of modes defined by criterion (18). The resolution in frequency of $\Delta f = c/F_0$ is assured up to this maximum number of modes, and the amplitude spectrum values in the region $M_{\max} < m \le 2M_{\max}$ are not real (are incorrect).

One of the criteria for the method verification is a reconstruction of the waveform generated by the amplitude spectrum determined by applying one of the three methods to the measured waveform in longitudinal measurement cuts and a comparison with the measured waveform. The display of measured and reconstructed waveforms obtained by applying the MEM, MES and LFT methods to all five longitudinal measurement cuts is given in Fig. 6. Wave pattern resistance coefficient values C_{wp} are also given. The basic data concerning experimental determination of wave pattern resistance by applying the MEM, MES and LFT

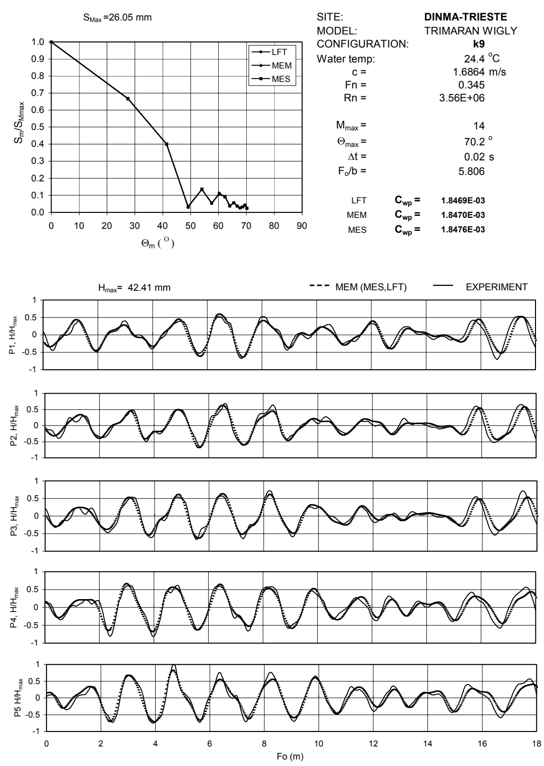

Fig. 6. Working sheet for $Fn = 0.345$

methods and a graphic display of the discrete amplitude spectrum of the free wave system as a function of the direction angle θ_m for $Fn = 0.345$ are given in the same figure. The comparison between the measured and the reconstructed waves points to the fact that agreements are very good both regarding amplitudes and phases.

4. CONCLUSION

Realisation of the programme of experimental wave pattern resistance determination has been preceded by the specification of necessary conditions, which have to be satisfied in the experiment, so that the hydrodynamic model represents the physical phenomenon accurately enough. The hydrodynamic model is based on the assumption that the fluid is incompressible and inviscid, the flow is irrotational, and the kinematic-dynamic condition on the free surface is linear.

Three methods, LFT, MEM and MES, for experimental determination of wave pattern resistance based on wave height measurements in longitudinal measurement cuts are introduced in the paper.

Maximum number of modes $M_{\max}$, which can be seen in the measured waveform depends on disposable record length, which is limited by the real situation in the experiment. In application, the MEM and MES methods are superior in comparison with the LFT method because they are less sensible to the chosen number of modes, especially for the range of higher values of the Froude number. In numerical realisation, the MES method is more complicated in comparison with the MEM method, because it contains numerical integration of unknown equivalent singularity distribution function in the application procedure, having as a consequence the impossibility of exact estimation of numerical integration.

The experimental determination of wave pattern resistance for Wigley trimaran configuration has been done for the Froude number range 0.254-0.420, with a total of 12 runs. The calculation of wave pattern resistance has been performed by applying all three methods, respecting criterion (18). Relative errors of wave pattern resistance coefficient values obtained by applying all three methods differ less than 1.13% for $0.270 \le Fn \le 0.420$. Comparison of amplitude spectrum for the same Froude number range points to the fact that all three methods are equal in application, under condition that criteria (14) and (18) are respected.

Comparison of measured and reconstructed waves for the Froude number range up to approximately 0.270, points to the fact that significant differences between the measured and the reconstructed waves exist, both regarding amplitudes and phases. For higher values of the Froude number agreements are satisfactory.

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