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Crest-trough asymmetry of waves generated by high-speed ferries

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Abstract. The shape of waves from high-speed ferries in Tallinn Bay, the Baltic Sea, is analysed from the viewpoint of the potential asymmetry of the crest heights and trough depths. Only the waves from the first group of the wake (that usually contains the highest and longest waves) are analysed. On average, wave crests deviate from still water level 1.4 times more than the wave troughs. In extreme cases, the crest height exceeds the trough depth by up to a factor of 3. It is shown that asymmetry is an important parameter of the wakes, the values of which do not necessarily correlate with the maximum wave height in the wakes, a quantity that otherwise characterizes the basic properties of the wakes well. The results for the ratio of the crest height over the trough depth coincide with estimates made using classical cnoidal wave theory. Distribution functions of the wave asymmetry for vessels, operating in Tallinn Bay, show that the most frequent values for the ratio of the crest height over the trough depth lie between 1 and 1.6.

Key words: ship waves, fast ferries, cnoidal waves, wave asymmetry, wave measurements, Baltic Sea.

1. INTRODUCTION

Long waves in shallow water frequently exhibit non-linear characteristics. One of the simplest means for adequate description of such waves is the framework of the Korteweg–de Vries (KdV) equation, which has a rigorous periodic solution in the form of a cnoidal wave [1]. A sketch of the cnoidal wave is presented in Fig. 1. Cnoidal waves have relatively high and narrow crests and wide troughs, with the deviation from still water level at the trough being less than the elevation at the crest. Equivalently, the wave-induced water surface depression at the trough has a longer duration than the elevation at the crest.

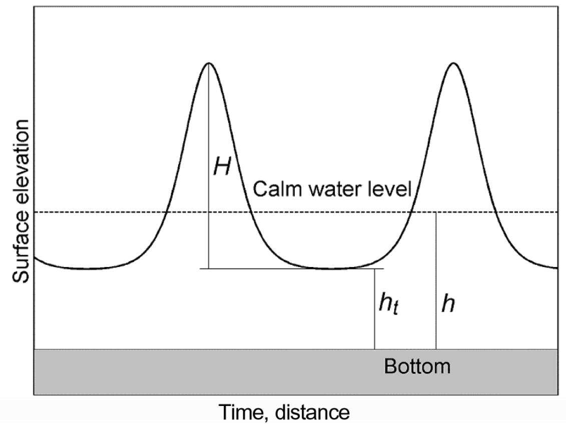

Fig. 1. Definition of a cnoidal wave.

When the wave period tends to infinity, a cnoidal wave will evolve into a solitary wave – a KdV soliton.

Waves of this type can be induced by ships. In 1844, John Scott Russell observed an '*exotic water dome*' preceding a vessel that had suddenly stopped, but had been previously moving at a small rate of acceleration in a canal of uniform depth. This phenomenon became known as Russell's wave or Russell's soliton [2], eventually leading to many studies around the world aimed at understanding and describing similar phenomena.

Solitons and other strongly non-linear disturbances of the water surface are excited relatively infrequently by ships. Typically, a moving ship generates a sequence of almost linear surface gravity waves [3]. However, in special cases, a single water elevation with a stable profile or highly non-linear wave groups mimicking solitons of different kinds can be produced [4]. Such soliton-like features were observed, for example, in [5]. In this study, wave-staff measurements of the Kelvin wake of the Coast Guard cutter *Point Brower*, showed a solitary feature, resembling the so-called envelope solitons occurring 1–4 km behind the vessel.

Specific types of ship disturbances, such as high leading waves, monochromatic packets of relatively short waves [5], solitary and cnoidal wave trains preceding a ship [6] and their associated depression areas [7], all qualitatively differ from typically occurring wind waves and from constituents of linear Kelvin wakes, and have been studied extensively during the last few decades [4]. However, very little is known about how frequently ship wakes exhibit strongly non-linear features.

Usually, non-linear effects become evident when large ships sail at relatively high speeds in shallow areas or narrow channels. Non-linear components are frequently observed in wakes of so-called fast ferries [4]. For example, the majority of waves with the longest wavelength and the largest amplitudes generated by the high-speed ferries on the Tallinn–Helsinki route in Tallinn Bay regularly show non-linear features and resemble cnoidal waves in the coastal area [8]. Another well-documented phenomenon is the extensive drawdown of the water level when a large ship sails in a narrow channel. There are many such observations from Sweden where ships frequently enter into narrow straits [9] and from Germany, where properties of waves, generated by high tonnage container merchant ships longer than 300 m have been studied [10]. Similar studies have also been done in New Zealand, where the sudden introduction of fast ferries to a coastal area caused rapid and significant changes to beaches [11,12]. High, non-linear vessel wakes are considered to be able to seriously damage the coastal environment [4,11,13].

One of the primary features of the appearance of non-linearity in the generation and propagation of surface waves is the potential deviation of the wave shape from the sinusoidal form. The shape of the waves is extremely important, because many properties of water particles in long linear and weakly non-linear waves (in particular, the velocity components) linearly depend on the surface displacement [1]. It has been recently demonstrated that the difference between the steepness of the wave front and its back (so-called back-front asymmetry) has substantial effect on the wave runup properties [14]. An equally important measure of the wave asymmetry is the ratio of the crest height over the trough depth (in the following called crest-trough asymmetry). This measure to some extent characterizes the excess velocities in non-linear waves compared to linear waves with the same length and height. In this study we focus on the crest-trough asymmetry only. Note that these definitions of asymmetry are not necessarily related to each other. For example, cnoidal waves are a classical example of waves with extensive crest-trough asymmetry but with no front-back asymmetry.

Although the presence of cnoidal waves in Tallinn Bay, resulting from fast ferries wakes, is well known [8], there is little research into their properties in the deeper parts of the nearshore. Their presence, through creation of unexpectedly large near-bottom velocities [8] or large impulse loads [15], may cause dangerous and environmentally damaging conditions in coastal areas not normally endangered by commonly occurring shorter, albeit higher, wind waves. Theoretically, the shape and properties of long ship waves, propagating in a shallow region with an ideal flat bottom, should match those of the corresponding solution of the KdV equation. In realistic conditions, however, the sea bottom is never perfect and precise prediction of the dynamics of waves approaching the shoreline is not possible. The aim of this study is to examine the shape of long ship waves, produced by high-speed ferries in Tallinn Bay. The research is focused on determining the asymmetry coefficients of these waves (the ratio of the crest height over the trough depth with respect to the still water surface) directly from the water surface time series in an intermediate region of the nearshore where non-linear effects become substantial but the wave profile remains smooth. The goal is to determine if possible adverse effects of long ship-generated waves can be quantified in terms of the cnoidal wave theory.

2. MEASUREMENTS AND DATA PROCESSING

The properties of ship waves in the nearshore were obtained during a field experiment during the summer of 2008 [13]. An ultrasonic echosounder (LOG_aLevel® from General Acoustics) was used for continuous water surface elevation recording at 5 Hz. The device was mounted on a heavy and stable tripod at a water depth of approximately 2.7 m, 100 m from the shore (Fig. 2). The orientation of isobaths in this area was virtually perpendicular to the crests of the largest vessel waves, which allowed for good wave transmission and minimum refraction-diffraction effects.

Most of the nearshore between the tripod and the section of the coastline between a jetty and cape Talneem in Fig. 2 contains numerous boulders and is almost non-reflective. The largest ship waves, after passing the tripod, usually propagated towards a small beach adjacent to the jetty (marked as Study Site in Fig. 2). The nearshore sediments along the line of propagation consisted of small boulders interspersed with some coarse sand, gravel, and cobbles. The beach was almost non-reflective [13]. The jetty was protected by wave-absorbing tetrapods, reducing wave reflection back towards the measurement site. The described features allowed for a relatively clean record of incoming waves. This area of the coast, which has also been the subject of several previous studies [13,16–20], was, therefore, a suitable place for measurements of vessel wave parameters.

During the entire experiment, 650 wakes from different vessels were recorded. The most interesting were waves from the classical high-speed ferries *SuperSeaCat*, *Nordic Jet*, and *Baltic Jet*, and from highly powered but otherwise conventional ferries *Tallink Star*, *SuperStar* and *SuperFast*, and *Viking XPRS* (Table 1).

An initial data evaluation was performed to identify and remove unreliable readings [13,19]. As the complete record included both wind and vessel wakes, an attempt was made to separate ship wakes from the complex signal with the use of low-pass filters. The wake records were identified for particular ships, visually and using scheduled departure times from Tallinn. Wakes from ships sailing to

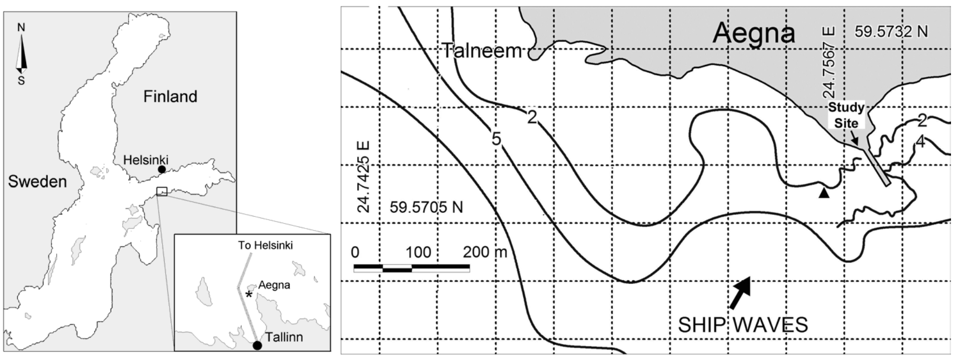

Fig. 2. The study site on the SW coast of the Aegna Island, Tallinn Bay, the Baltic Sea. The triangle shows the position of the echosounder [13].

Table 1. Ships operating the Tallinn–Helsinki ferry route in summer 2008

Ship	Type	Length, m	Width, m	Operating speed, knots
		High-speed ferries		
SuperSeaCat	Monohull	100.3	17.1	35
Baltic Jet, Nordic Jet	Catamaran	60	16.5	36
		Conventional ferries with increased cruise speed		
Star	Monohull	186.1	27.7	27.5
Superstar	Monohull	176.9	27.6	27.5
Viking XPRS	Monohull	185	27.7	25
Superfast	Monohull	203.3	25	25.5–27.1

Tallinn and combined wakes [13,18], in which signals from two ships were superimposed, were eliminated from the analysis. Thus, the waves considered for further analysis were excited by single vessels sailing from Tallinn.

A typical wave record (Fig. 3) shows a group structure and usually consists of at least three wave groups with varying wave parameters (amplitude, period, and symmetry properties). The amplitudes of so-called precursor solitons that arrive before the highest waves are usually negligible in open sea conditions [4]. The highest waves at distances of a few kilometers from the ship lane are usually the longest waves concentrated in the first group of the wakes [16]. Their parameters can be reproduced numerically with an acceptable accuracy, and they usually cause the largest impact on the beach in terms of the wave runup [20]. They are also asymmetric with a clear prevalence of the crest height over the trough depth (Fig. 3). Waves belonging to all other groups are mostly symmetric. Waves from the first group are able to carry additional water mass to the shore [20] and therefore can have significant impact on nearshore processes.

In cases with low wind wave background, the identification of ship waves was straightforward. An elliptical low-pass filter was used to separate relatively long ship waves from wind waves on more windy days. A comparison of filtered and original data allowed for a more accurate definition of the duration of the wake and its first group (Fig. 3). On several days, however, the wave background was so strong that it was virtually impossible to filter out the wind waves. A detailed overview of the procedure is given in [13,19]. As a result, 163 wake records, collected on 15 days, were selected for the final analysis.

In contrast to the analysis of maximum and integral characteristics of the wakes in [13,19], the analysis of the wave asymmetry in terms of the ratio of the crest height over the trough depth was performed separately for each wave of the first group in each wake. An intrinsic problem with the wave data, recorded in field conditions, is that both wind and ship waves occur in the recording. Generally, wind waves cannot be removed by the standard filtering procedures because they normally suppress higher harmonics of the ship waves as well and thus distort their profiles and asymmetry properties. Therefore it is more consistent to use the non-filtered record for calculation of asymmetry properties.

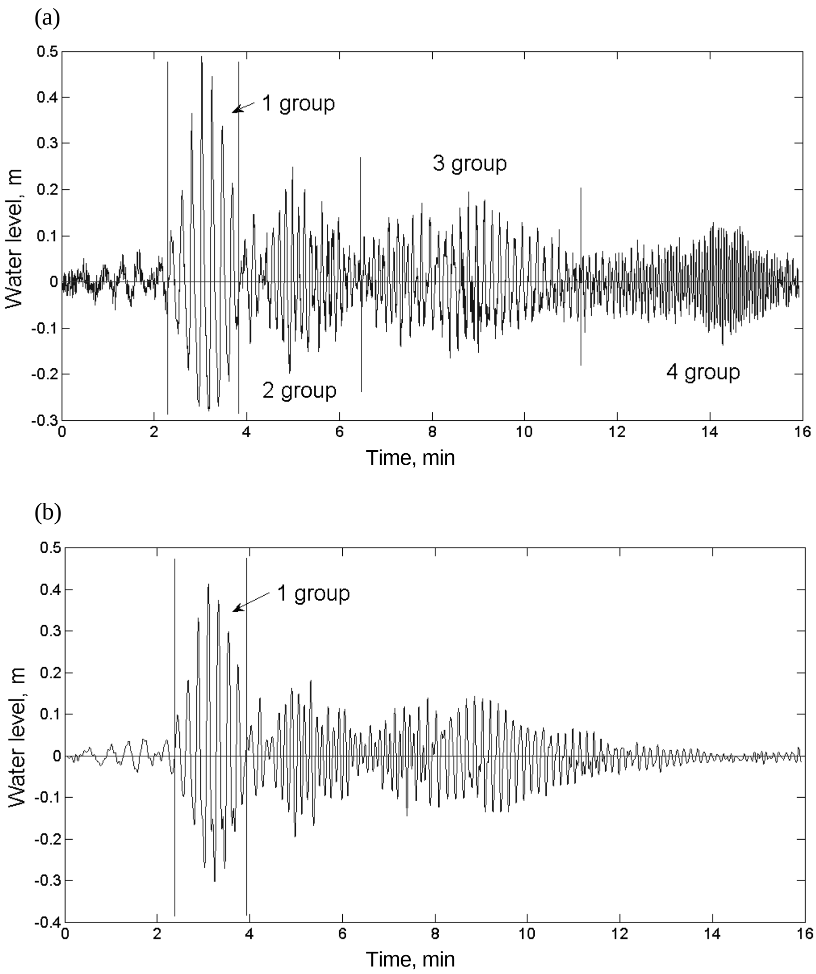

Fig. 3. Original (a) and filtered (b) record of the wake by *SuperSeaCat* on 03 July 2008 at 21:40.

Doing so leads to fairly limited changes of the resulting asymmetry coefficient when wind waves are much shorter and smaller than long ship waves. In most of the records, the typical height of wind waves was about 10%–25% from that of ship waves in question whereas the typical periods of wind and ship waves were 1–2 s and 7–15 s, respectively. It is straightforward to establish that an analysis of crest heights and trough depths of a combined field of long, relatively high waves and much shorter and lower waves would result in almost equivalent overestimation of both measures by about a half of the shorter wave height, compared to the analysis of the ideal long-wave signal. Consequently, the potential asymmetry would be certainly detected whereas the exact values of the asymmetry coefficient would be slightly underestimated. Much larger errors in establishing the length (or period) of long waves may, however, occur in the analysis of a combined wave field. Therefore it is reasonable to determine the wave amplitudes from the original (combined) record, but to find the wave periods from a filtered record.

For the listed reasons we have applied a multistep algorithm for defining the asymmetry coefficient. Initially, a low-pass elliptical filter with a relatively low cut-off frequency was used to separate single long waves from the raw data. The filtering procedure resulted, as expected, in a time shift of the filtered signal compared to the original record. The magnitude of this shift is defined by the parameters of the filter and was removed from the filtered data. The zero-crossing time instants were detected from the resulting time series. Single waves were then separated by applying both the zero-upcrossing and zero-downcrossing methods [21] to the filtered record. Finally, the crest heights, trough depths and the corresponding asymmetry coefficients for each full wave were calculated from the original, unfiltered record. As a result, 1346 waves from the first group of the selected 163 wakes, each representing a single ship, were included in the analysis.

Another non-trivial aspect in the described process is how to determine the reference water level. In order to avoid distortions of the calculated asymmetry coefficients, the mean sea level for each wake under consideration was established using a 20-min long section of wind wave recording immediately before or after the wake [13].

3. RESULTS

Comparison of the average value and standard deviation of the asymmetry coefficient, calculated through the application of zero-upcrossing and zero-downcrossing methods (Fig. 4), shows that both methods give very similar results for these parameters. This is not unexpected and shows that the highest crests and deepest troughs usually occur in sequence. This feature also indicates that the vessel waves, by nature, are more akin to regular oscillations than to

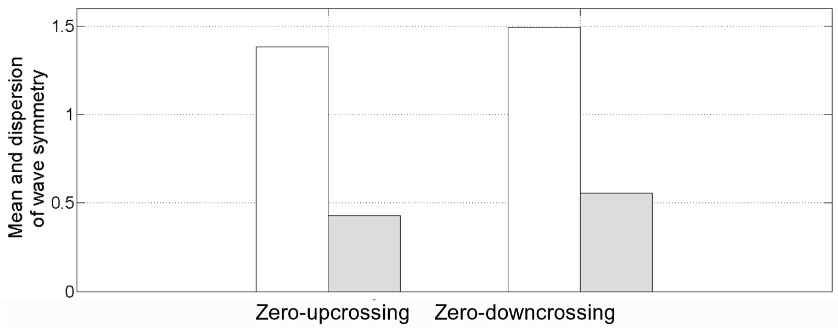

Fig. 4. Average values (white bars) and dispersion (filled bars) of the asymmetry coefficient using zero-upcrossing and zero-downcrossing methods.

freak waves (which frequently are characterized as specific sequences in which a deep trough is followed by a high, steep crest [22]).

The empirical distributions of asymmetry coefficients for different vessels (Fig. 5) show that the most frequent values for the ratio of the crest height over the trough depth lie between 1 and 1.6. The crest height, on average, exceeds the trough depth by approximately 30%–40%.

A joint distribution of the probability of occurrence of the wave asymmetry for waves with different heights and periods for the entire set of waves (Fig. 6) confirms that the most frequent value of the coefficient of asymmetry is about 1.4. As expected, waves with higher amplitudes generally have larger asymmetry coefficient values.

Interestingly, there is no evident correlation of the wave asymmetry with the wave period (Fig. 7). The entire set of waves in question contains two major groups of long waves with periods about 8 and 13 s, respectively. Within these groups, the wave asymmetry changes significantly from 1 to 2.5, but there is no clear difference in asymmetry for these groups. This feature is somewhat unexpected, because an increase of the length of an ideal cnoidal wave in water

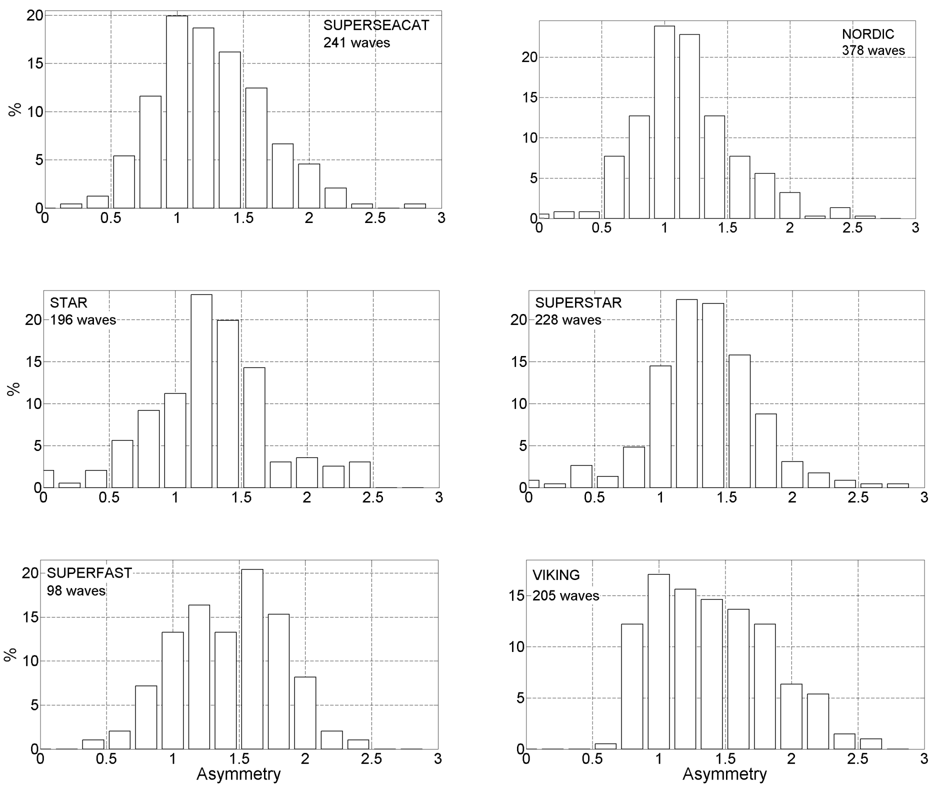

Fig. 5. Empirical distributions of the asymmetry coefficient for waves from the first group of the wake for different vessels.

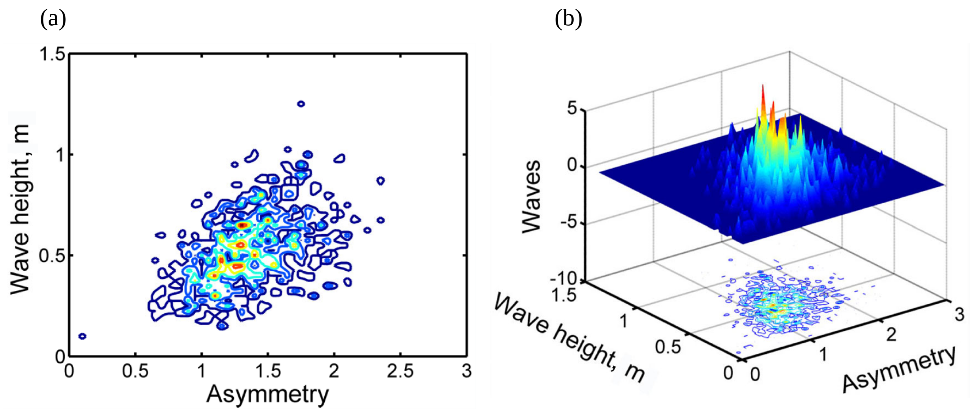

Fig. 6. Scatter diagram of the occurrence of different values of the asymmetry coefficient for waves of different heights from the first group of the wakes: contour plot (a); 3D surface plot (b).

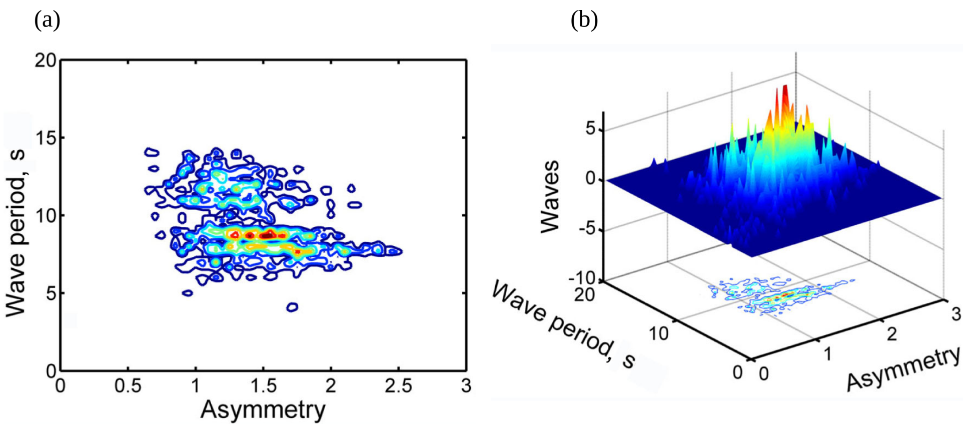

Fig. 7. Scatter diagram of the occurrence of different values of the asymmetry coefficient for waves of different periods from the first group of the wakes: contour plot (a); 3D surface plot (b).

of constant depth is accompanied by an increase of the crest height and a decrease of the trough depth. A possible explanation of this non-alignment is that the approaching waves are being shaped by a longer section of the coastal slope and that the "effective" depth, defining the wave asymmetry, is larger for longer waves. This argument is discussed in more detail below.

The analysis confirms that all the vessels generate asymmetric waves (Fig. 5). The relevant distributions have somewhat different shapes. The distributions for *Star*, *SuperStar*, *SuperSeaCat* and *Nordic Jet* and *Baltic Jet* are unimodal and have a bell-like, mostly symmetric shape resembling the normal distribution. The distribution for *SuperFast* has a bimodal shape; however, this feature may also reflect a wide distribution and an insufficient number of analysed wakes. The distribution for *Viking XPRS* is asymmetric. Both are also relatively wide. While almost all the waves excited by *Star*, *SuperStar*, *SuperSeaCat* and *Nordic Jet* and

Baltic Jet have the asymmetry coefficient well below 2, *SuperFast* and *Viking XPRS* frequently cause waves with this coefficient close to or exceeding 2. This feature is somewhat unexpected, because the distributions of the typical maximum height in wakes from these ships differ considerably [19] whereas the periods of their largest waves almost coincide. *Nordic Jet* and *Baltic Jet* demonstrate the least asymmetry. This feature may be related to the fact that these vessels are catamarans, whereas all the other vessels are monohulls.

It has been demonstrated in [19] that the distributions of the basic properties of the vessel wakes, such as the maximum wave height, total wake energy and energy flux are very similar and that the maximum wave height of the wake is an appropriate parameter to characterize the ship wakes and their variability. The above analysis, however, suggests that the asymmetry coefficient of the largest ship waves may serve as an additional useful indicator of the properties of ship wakes.

Finally, we attempt to represent the above properties of vessel waves in terms of cnoidal wave theory. The analysis below is an extension of similar research performed for a small set of ship waves near Aegna jetty in [8]. Linear wave theory, which has been widely used for the description of surface waves and their interactions, is only applicable provided the wave height is small compared to the wave length and water depth. The basic requirement $\kappa H/2 << 1,$ where $\kappa = 2\pi/L << 1$ is the wave number, L is the wave length and H is the wave height [1]), is frequently violated for ship waves in the nearshore. The length of a typical wave from a fast ferry with a period of about 10 s [13,16] is $L \ge 30\sqrt{h}$ m and therefore water with depth $h \le 10$ m can be already considered as shallow. An appropriate parameter in shallow areas is the Ursell number $U = HL^2h^{-3}$ [1]. When $U \cong 1,$ linear theory is useful, even when the condition $\kappa H/2 << 1$ is violated. For moderate Ursell numbers (up to $U \cong 75$) and $L/h < 8-10,$ various modifications of Stokes wave theory can be used [1]. The Ursell number for such a wave in the coastal area $(h \cong 3$ m) is $U \cong 100H$ where ship waves of moderate height $(H \cong 0.5$ m) correspond to $U \cong 50.$ For even longer or higher waves (that frequently occur in the study area [13,16]), or for lesser depths, Stokes wave theory is generally not applicable [1] and cnoidal wave theory is preferable.

The ratio of the crest height $A_+ = H - h$ (Fig. 1) and the trough depth $A_- = h - h_t$ for an ideal cnoidal wave, propagating over an area of constant depth, can be calculated from the following equation [1]:

$$\frac{A_+}{A_-} = \frac{m}{m + E/K - 1} - 1. \qquad (1)$$

Here K and E are complete elliptic integrals of the first and second kind:

$$K(m) = \int_0^{\pi/2} \frac{\mathrm{d}u}{\sqrt{1 - m\sin^2(u)}}, \qquad E(m) = \int_0^{\pi/2} \sqrt{1 - m\sin^2(u)}\,\mathrm{d}u \qquad (2)$$

and values of the parameter $m = \sqrt{k}$ (elliptic modulus) can be found for different values of the wave height H and period T from the following relationship:

$$\frac{H}{h}\frac{gT^2}{h} = \frac{16}{3} mK^2(m) \qquad (3)$$

for the given water depth h.

When a cnoidal wave propagates over a sea area of variable depth, its parameters obviously change with changes in the water depth. The measurement site of the water surface elevation is located in a 2.7 m deep area along a coastal slope, whereas the actual water depth may vary over the typical length (~80 m) of a ship wave with a period of 10 s from about 5 to 2 m. For that reason, the water depth, estimated from Eqs. (1)–(3), systematically exceeds the actual water depth at the measurement site. The reason is that the properties of waves propagating along a coastal slope express the variations of the depth over a longer section of the slope.

However, Eqs. (1)–(3) make it possible to calculate the "effective" depth for the ship waves, the parameters of which (period, height and asymmetry coefficient) are determined at the measurement site. Figure 8 demonstrates that this "effective" depth for most of the waves in question is between 2.7 and 5 m. In this figure, the dashed lines correspond to the asymmetry coefficient of cnoidal waves with maximum and minimum periods of waves analysed for the particular ship at a water depth of 2.7 m (maximum period, the lower line) and 5 m (minimum period, the almost vertical line). As data points, representing the properties of most of the analysed waves, fit into the sector defined by these lines, it is concluded that cnoidal wave theory is a suitable framework for their description.

While data points, reflecting asymmetry of most of the ship waves, fit into the sector defined by these lines, a substantial number of waves generated by *Nordic Jet* and *Baltic Jet* do not. Moreover, waves from these sister ships frequently have the asymmetry coefficient below 1, that is, the wave troughs are systematically deeper than the crest heights. This peculiarity confirms that wave asymmetry is an important characteristic of wakes from different ships that does not necessarily correlate with the maximum wave height of the wakes. As *Nordic Jet* and *Baltic Jet* are the only catamarans among the fleet, it may be assumed that the frequent occurrence of deep troughs in the wakes is caused by the interference of wave systems, created by the two hulls.

All the waves analysed above are relatively long (Fig. 7) and thus expected to be, at least, slightly cnoidal at the location of the wave recorder. Therefore, one would expect almost all waves to show clearly expressed asymmetry with the relevant coefficient >1. There is, however, also a number of waves for monohulls with the asymmetry coefficient <1 (Figs. 5–8). While a few "anomalous" waves with an asymmetry well below 1 could be attached to the natural variability of the parameters of complex, realistic wave fields, a relatively large number of such waves is an interesting feature that deserves further consideration.

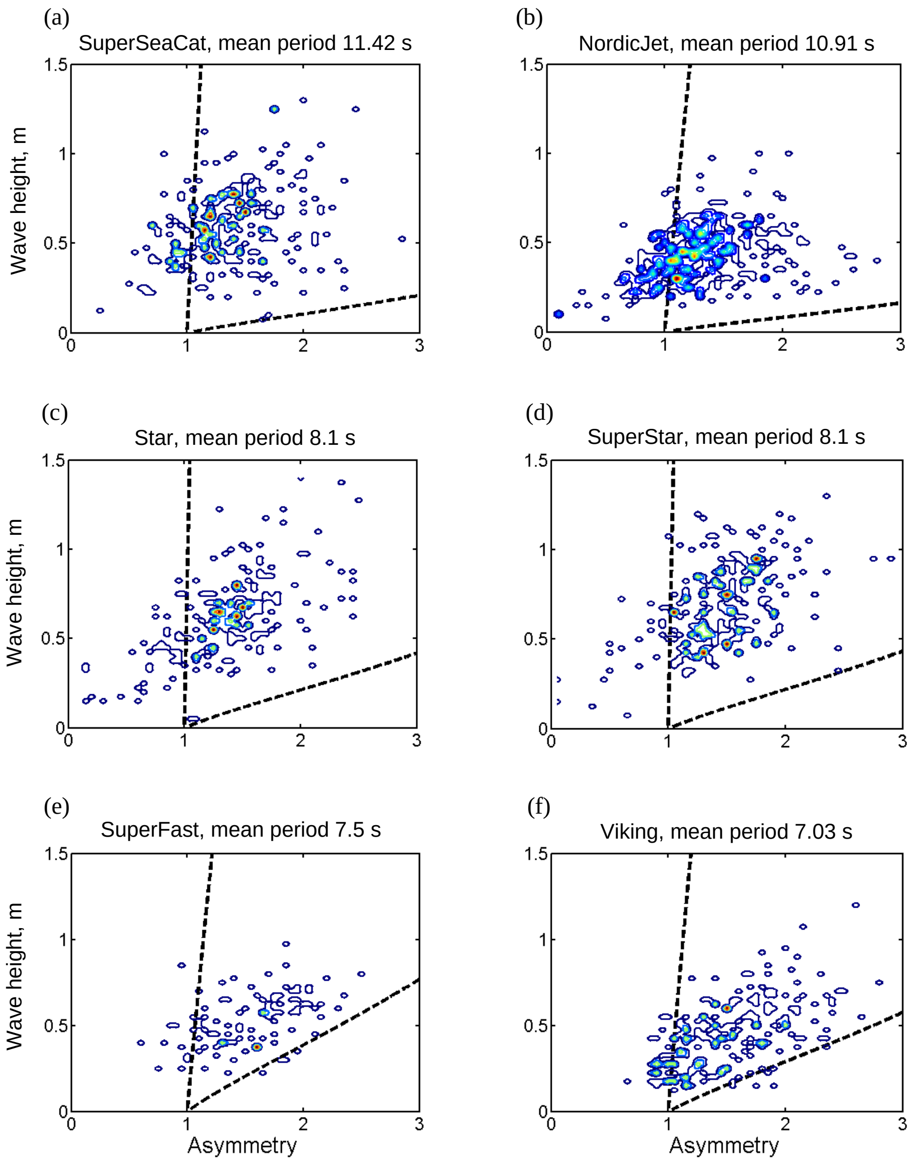

Fig. 8. The occurrence of different values of the asymmetry coefficient for waves with different height from the first group: (a) *SuperSeaCat*; maximum and minimum periods 17.2 and 3.2 s; (b) *Nordic Jet* and *Baltic Jet* (19.6 and 4.2 s); (c) *Star* (12.2 and 2 s); (d) *SuperStar* (12 and 2 s); (e) *Superfast* (9 and 4.2 s); (f) *Viking XPRS* (10.4 and 4 s).

4. CONCLUSIONS

Statistical analysis of the appearance of the first group of the longest and highest waves in wakes from fast ferries shows that the asymmetry of the waves in terms of the ratio of the crest height over the trough is an important parameter of the wakes. Its value does not necessarily correlate with the maximum wave height in the wakes, a quantity that otherwise characterizes well the basic properties of the wakes [19]. In particular, the distribution of the asymmetry may serve as a key for deciding, from the wake structure, whether the ship was a catamaran or a monohull. Although this feature has been observed only in Tallinn Bay, the Baltic Sea, it is likely to apply to other fast ferry traffic in different locations.

The presented results confirm that cnoidal wave theory is useful for the analysis and forecast of the properties and impact of waves from fast ferries in locations with an inhomogeneous bottom, as concluded in [8], based on observations of the shape of a very limited set of ship waves.

The average asymmetry coefficient for the ship waves studied is approximately 1.4. The wave crests are, therefore, about 40% higher than the water surface dropdown at the wave troughs. This value indicates a high level of non-linearity of the otherwise perfectly smooth waves in the nearshore at a depth of about 2.5–3 m and confirms the necessity of using appropriate non-linear methods to adequately describe the impact of such waves. Last but not least, the similarity of results obtained using the zero-upcrossing and zero-downcrossing methods suggests that ship waves are more similar to regular wave trains or groups than to freak waves.

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Kiirlaevalainete asümmeetriast

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On analüüsitud kiirlaevalainete asümmeetriat (mis on defineeritud laineharjade kõrguste ja lainevagude sügavuste süstemaatilise erinevusena) Tallinna lahe rannavööndis. Suhteliselt kõrged ja pikad kiirlaevalained on ligikaudu 3 m sügavuses vees tugevalt asümmeetrilised. Laineharjade kõrgus ületab lainevao sügavuse keskmiselt 1,4 korda (üksikutel juhtudel kuni 3 korda). Taoline asümmeetria on laevalainete süsteemi oluline parameeter, mille jaotus laevatüüpide lõikes üldjuhul erineb nende lainete paljusid omadusi adekvaatselt iseloomustavast kõrgeimate lainete jaotusest. On näidatud, et mõõtmiste alusel hinnatud asümmeetria kattub hästi knoidaalsete lainete teooria alusel tuletatud hinnangutega.