Analysis of Waterway Factors on the
Underkeel Clearance of Sea-going Vessels

by

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1. Introduction:

Underkeel clearance (ukc) is a significant component in design and maintenance of waterways and guarantees the ease and safety of shipping. It affects directly the load draft and the speed of sea-going vessels and thus the efficiency of waterways.

A not negligible aspect in ascertaining the vessel underkeel clearance is the vessel squat. The squat can increase the vessel’s immersion in the range of one meter and more as a function of speed, ship’s geometry and waterway conditions. Local changes in the cross sections of waterways affect the squat during a transit, like variations in the bottom structure (ripples) or the water width (river islands, mouths of tributaries, jetty plants). In river bends the draft is also increased by a heeling of the ship, due to torques by rudder actions and centrifugal forces.

2. SHIPS measurement procedure

Several approaches have been made in the past to study this phenomenon by measuring the squat of sea-going vessels in model basin or in field studies. On the basis of this data formulas were developed, which can describe the process of vessel squat quantitatively under observance of boundary conditions. The comparison of measured squat and calculated squat shows that the results of empirical formulas are often too high due to the use of static parameters and in unawareness of the exact waterway topography. The consequence for a civil engineer is an overestimation of the necessary water depth with higher costs for dredging and compensation measures. With the knowledge of the exact vessel squat the capacity of a vessel could be used better or dredging in waterways could be minimized to maintenance measures only.

The Nautical and the Survey Departments of the University of Applied Sciences in Oldenburg/Elsfleth (Germany) are developing a DGPS-based method called SHIPS (Shore Independent Precise Squat observation) (HÄRTING & REINKING)[1], which has been tested successfully in several experiments on German waterways. The novelty of this method is the application of GPS carrier phase observations on a small escort craft to represent the local water level at the vessel and avoiding the use of reference stations on shore. Instead of using a land-based station a small escort craft travels as a mobile
reference station ahead of the sea-going vessel (Fig. 2). Thus, it is possible to measure the squat of a sea-going vessel continuously during a transit. The advantage of this procedure is that the base line between the sea-going vessel and the escort craft remains short compared with land-based stations and thus the theoretical accuracy of under 5 cm is higher than other conventional procedures.

Fig. 1: Schematic representation of the SHIPS - measuring method for static conditions

Fig. 2: Schematic presentation of the SHIPS - measuring method for dynamic conditions

The principle of the procedure rests on the measurement of height differences between moving antenna positions. To prevent the measurements on the small escort craft from being perturbed by the waves of the sea-going vessel, but still representing the local water level conditions, distances are typically 300–800 m.

During a measurement four GPS receivers are used. Three are on board of the sea-going vessel. To obtain good observations it turned out that two GPS-antennas are best located at both wings of the wheel house and the third GPS-antenna on the forecastle. The fourth GPS receiver is used as a reference station on the escort craft. The height difference between the escort craft and the longitudinal centre of floatation (LCF) of the sea-going vessel can be ascertained by the determination of the coordinate differences between the individual GPS receivers on the sea-going vessel and the GPS receiver on the escort craft, taking into account the antenna positions in the vessel’s coordinate system. The three-dimensional motion of the hull, i.e. roll, pitch and yaw can also be calculated.

In addition to the information about the vessel squat the measured height differences contain influences of the waterway (waves, swell, tide effects) and of the vertical motion of the escort craft.
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S. Dunker: Analysis of Waterway Factors on the Underkeel Clearance of Sea-going Vessels (heave, its own speed-dependent squat). These influences are largely eliminated during data analysis (HÄRTING & REINKING)/[2] (GOLLENSTEDE)/[3].

Several experiments have been carried out on the Lower Weser, Outer Weser, Lower Elbe and the Kiel Canal to test and to improve the efficiency and accuracy of SHIPS since July 1999. The range of sea-going vessels includes a general purpose carrier with a displacement of about 10,000 t on Kiel Canal up to a container ship with a displacement of more than 100,000 t on the Outer Weser. The sea-going vessels were selected usually for the largest possible draft on the waterway, as well as by the possibility of a preceding inspection.

The curves depicted in Fig. 3 show the squat behaviour of some measured vessels from the SHIPS measurement campaigns up to the reached maximum speed. These curves are obtained by a quadratic least-squares fit ($\Delta T = a \cdot \frac{v^2}{2 \cdot g}$) on the basis of all data of the respective measurement campaign. The data of the selected vessels are listed in table 1.
As expected the squat curves of the bulk carriers/tankers are steeper than the curves of the two selected container ships. The comparison of the block coefficients $C_B$, the ratio between displacement and the product of length between perpendiculars, breadth and draft, shows that the waterway has a further impact on the squat process. The block coefficients vary for the group of the bulk carriers and tankers between $C_B = 0.70$ for the *Polaris* and $C_B = 0.89$ for the *Weser Stahl*. Despite a block coefficient of $C_B = 0.70$ the squat curve of the 9,900 t general purpose carrier *Polaris* rises as steep as the squat curve of the 56,000 t bulk carrier *Sanko Summit* with a $C_B$ of 0.82. However, the squat of the *Polaris* was measured on the Kiel Canal, whereas the squat of the *Sanko Summit* was ascertained on the Lower Weser outward bound from the port of Brake (km 40). The influence of the waterway on the ship squat is also obvious in the curves of the two container ships *Anna Maersk* ($C_B = 0.63$) and *Hong Kong Express* ($C_B = 0.65$). Almost identical block coefficients measured on different waterways with different underkeel clearance conditions lead to different squat curves, while structural differences of the vessel hulls should be small. Consequently a comparison of different squat curves should be done always in respect to the specific waterway. The squat curve of the *Hong Kong Express* illustrates from 7,0 m/s on a steeper rise than the fitted curve could describe, because the high vessel speeds were measured only within a particular section of the Elbe, where small underkeel clearances predominate.
3. Influences of waterway factors on the ship squat

For more than hundred years the tidally influenced portion of the streams Elbe and Weser are affected by dredging, straightening, groins and other correctional measures. Since that time, all of these measures have the special purpose to allow the transit of deep drawing sea-going vessels along the Lower Elbe to the port of Hamburg and along the Lower Weser to the port of Bremen.

Since the last channel regulation measure of the Lower Weser in 1980 vessels with a draft of max. 10.7 m and 30,000 – 40,000 tdw are able to arrive at the port of Bremen using the high tide condition. The max. permitted drafts for the other ports along the Lower Weser are gradually larger, so that vessels with a draft of max. 11.0 m and 35,000 – 45,000 tdw are able to reach or leave the port of Brake and the port of Nordenham with a draft of max. 12.5 m and 60,000 - 70,000 tdw (WSA BREMEN)/[5].

The navigation channel of the Outer Weser was dredged out in 1999 to an minimum depth of 14 m under chart datum. Panmax container ships with a maximum draft of 12.6 m and Post – Panmax container ships with a maximum draft of 12.3 m are able to call at the container terminal of Bremerhaven independent of the tidal condition. Depending on tidal conditions vessels with a maximum draft of 13.5 m are able reach the container terminal (WSA BREMERHAVEN)/[6].

Incoming and outgoing container ships and/or other ship types with a Panmax-breadth of 32.2 m and a maximum draft of 12.8 m and/or Post-Panmax-container ships with a breadth > 32.2 m and a maximum draft of 12.7 m are allowed to travel on the Outer and the Lower Elbe. By utilization of the tide and in consideration of the vessel type and waterlevel condition at a specific position of the Elbe outgoing vessels with a maximum draft of 13.8 m and incoming vessels of max. 15.1 m are allowed to travel on the Elbe (WSV)/[7].

The permitted maximum draft on Kiel Canal amounts to 9.5 m for 190 m long vessels with a breadth of 27 m and/or vessels of 193 m length and 20 m breadth. For vessel with larger dimensions there exists a gradual limitation up to a maximum draft of 7.0 m for vessels of a maximum length of 235 m and a breadth of 32.5 m.

3.1. Examples from the SHIPS – measurement campaigns

As stated before a further advantage of the SHIPS procedure is that the squat of a sea-going vessel can be ascertained and evaluated for the whole transit of a vessel. Contrary to model experiments, where parameters can be controlled and changed individually, several factors affect the squat behaviour of a sea-going vessel at the same time in field studies. The following example describes the influences of locally limited parameters during the measurement of a 55,000 t bulk carrier (Weser Stahl from measurement 2) on the Lower Weser.
It is evident that the vessel squat mainly depends on the speed (approximately quadratically) of a sea-going vessel. A comparison of the squat curve and the speed curve demonstrates that they have a comparable shape (see fig. 4). It is useful to create an auxiliary tool to locate deviations of the squat curve from a pure ship speed dependence.

Fig. 4 shows the course of an inbound transit from Lower Weser-km 66 to km 10. The vessel squat versus river kilometre is represented in [m] and the speed through water in [m/s]. The correlation between vessel speed and vessel squat results in a value of about 0.74 for the whole transit and confirms the apparent impression that the squat follows primarily the speed of the sea-going vessel. However, in some portion of the Lower Weser (e.g. km 65) there are considerable deviations from the speed influenced squat curve.

Fig. 4: Lcf squat, vessel speed and ukc of a 55,000 t bulk carrier on the Lower Weser

The correlation between underkeel clearance and vessel squat results in a value of about -0.1 for the whole measurement, so that the influence of the underkeel clearance may appear negligible related to the total process of the measurement.

A square fit is calculated on the basis of all measured squat and vessel speed values to determine the speed-dependent part of the squat (see red curve in Fig. 5).
The parameter $a$ of the equation $\Delta T = a \cdot \frac{v^2}{2 \cdot g}$ results for this particular experiment in about 0.36 and varies between 0.30 and 0.39 for all measured bulk carriers. A value of about 0.02 $s^2/m$ arises when $a$ is divided by the double acceleration of gravity, which also MOES [8] has ascertained for his field studies of bulk carriers in Richards Bay (South Africa). On the assumption that the fitted curve describes the speed influence sufficiently, the deviations from this regression curve are caused by other speed-coupled influences (see Fig. 6), for example by changing underkeel clearances, changing cross section of the waterway and/or navigation manoeuvres. The correlation between vessel underkeel clearance and the difference between the measured and the fitted squat results in an improved coefficient of about -0.48 for about 12,000 data pairs. This value confirms that, apart from the speed and the speed-dependent influence of the underkeel clearance, still further influences act on the immersion behaviour of a sea-going vessel.

Because the remaining factors can only have an influence on the vessel squat in connection with the vessel speed, the graph in Fig. 6 still contains speed-dependent influences. Remarkable in this graph is
the strong rise in the section of a shallow bar at km 65 (Blexer curve). The strong oscillations of the curve from km 38 are due to bottom structures (ripples). In this last section the vessel squat rises due to a smaller water depth as well as a smaller cross section of the waterway. The cross section at km 33 amounted to about 5,750 m² and at km 30 to about 3,150 m² at the time of the measurement, corresponding to a decrease of about 45 %.

![Graph](image-url)

**Fig. 7: Vessel speed and underkeel clearance-dependent squat for a 55,000 t bulk carrier on the Lower Weser**

Fig. 7 depicts the squats of a 55,000 t bulk carrier for different vessel speeds and vessel underkeel clearances. The graphs were determined on the basis of least-squares fits for data classified according to underkeel clearance. As expected the vessel squat decreases with an increasing underkeel clearance. Because of the strong influence of the vessel speed on the squat behaviour, shorter waterway sections will be considered to emphasize the influence of other factors on the vessel underkeel clearance.

### 3.2. Influence of the water depth on the vessel squat

The water depth is defined as the distance between the undisturbed tidal water level and the channel bottom at the position of the vessel’s longitudinal centre of flotation. It changes during a measurement due to the tide, variations in the channel bottom, wave/swells and/or wind thrust. In the SHIPS project the water depth is measured with an echo sounder of the escort craft and/or determined on the basis of data provided by the Waterway and Shipping Authorities. Fig. 8 depicts the distribution of water depths at the position of the longitudinal centre of flotation of four different vessels, measured on the Lower Weser (bulk carrier, 2), Outer Weser (container ship, 4), Lower Weser (container ship, 5) and the Kiel Canal (tanker, 7). The deviating squat curves of the two container ships with approximately
the same block coefficients in Fig. 3 can be explained at least partly by the larger water depth of 18.7 m at the Outer Weser in comparison to 17.9 m at the Lower Elbe. The mean water depth is about 1.9 m more and the mean underkeel clearance about 0.6 m more for the bulk carrier compared to the tanker.

3.2.1. Influence of the water depth on the vessel squat of a 103,000 t container ship on the Outer Weser

In October 2003 the squat behaviour of an outgoing 103,000 t container ship was measured on the Outer Weser. Escort craft was a general purpose boat of the Waterway and Shipping Authority (WSA) in Bremerhaven. Due to speed restrictions of the escort craft (after an engine overhaul), it was already overtaken at km 88 (see Fig. 9). Afterwards it followed the container ship until a distance of about 2,000 m was reached (≈ km 93) and returned then to Bremerhaven.
The section between km 80 and km 87 was selected for the evaluation, because of the almost constant vessel speed of about 8 m/s. For this condition the influence of the vessel speed on the squat behaviour is nearly constant. The underkeel clearance varies between 6.0 m and 12.0 m in this section, while the squat is observed to vary between 0.6 m and 0.8 m (see Fig. 10).

Fig. 10: Lcf squat, speed curve and ukc of a 103,000 t container ship on the Outer Weser

To determine the influence of water depth on the squat part, the measured squat was reduced by the results of the fitted relation between vessel speed and vessel squat for the previously stated conditions (red curve in Fig. 10). The graph in Fig. 11 illustrates the differences resulting from measured and fitted squat for this waterway. It is obvious that the squat reaches an asymptote of $\Delta T = 0$ with an increasing water depth for this speed range and hence the speed-dependent part of vessel squat then predominates. At the other end of the graph the data approach an asymptote, where the influence of the underkeel clearance dominates the vessel squat with falling water depth. The effect can be so pronounced that an increase of the propeller revs does not lead to an enlargement of speed, but to a further rise of the vessel squat. Intense vibrations of the vessel are characteristic for this state, as well as a tremendously changed stern wave. Mariners talk about a suction of the vessel towards the ground.
The results of the measurement represented in Fig. 11 can be described by a reciprocal square dependence on the underkeel clearance (red curve). The speed-depending influence of the underkeel clearance on the vessel squat. Neglecting the relation between cross section of the navigation channel and cross section of the vessels’ midship section, a first approximation for this special vessel on this specific waterway can be formulated as:

$$\Delta T_{UKC} = 0.253 \cdot \left(\frac{v^2}{2g} \right)^3 \frac{V}{UKC^2} \text{ in } [m]$$

With this equation the impact on the speed-dependent vessel squat can be ascertained by the vessel underkeel clearance. The correlation coefficient between underkeel clearance and measured squat amounts to 0.32 before the escort craft is overtaken by the container ship, the value for vessel speed and vessel squat results in about 0.95. The correlation between the squat differences and underkeel clearance for the regarded section results in a value of about –0.67.

### 3.2.2. Influence of small underkeel clearance conditions on the squat of a 100,000 t container ship on the Lower Elbe

In December 2002 the squat of the 7,500 TEU container ship *Hong Kong Express* was measured with two independently operating escort crafts on the Elbe to examine the procedural accuracy of the SHIPS method. Supplementary to the escort craft of the Nautical Department a survey boat of the Waterway
and Shipping Authority in Hamburg was available. Fig. 12 depicts the squat of the container ship for the last measured section from Brunsbuettel outgoing to the Outer Elbe. A small underkeel clearance of about 3.0 m is characteristic for this section, which increases from km 704 on again. The container ship accelerates from 4.0 m/s to 7.0 m/s and consequently the squat rises from about 0.13 m to a maximum of about 1.06 m in the section between km 696 and km 701. At km 699 the curve of the measured squat rises steeper than the curve of the fitted squat. From km 701 the vessel speed of 7.0 m/s remains constant and the squat only increases. The difference between the measured and of the fitted squat reaches a maximum value of 0.46 m, corresponding to an increase of the vessel squat due to shallow underkeel clearance conditions of about 77%. The vessel speed increases again with greater water depth at km 704, and, at the same time, the squat decreases and approaches the fitted squat curve.

Fig. 12: Lcf squat, speed and ukc of a 100,000 t container ship in a shallow section of the Lower Elbe

The Froude depth number $F_n = \frac{v}{\sqrt{g \cdot d}}$, with speed through water $v$, acceleration of gravity $g$ and the undisturbed water depth $d$, is the relation between ship speed and wave velocity. Fig. 13 depicts the differences between the measured and fitted vessel squat in relation to the Froude depth number for a container ship in a shallow section of the Lower Elbe. The values increase almost linearly for a Froude depth number less than about 0.58, until, at about 0.62, the vessel squat approaches an asymptote and increases considerably for higher vessel speeds and/or smaller vessel underkeel clearance.
3.2.3. Influence of local restricted shallow water on the squat of a 55,000 t bulk carrier at Blexer curve (Lower Weser)

Fig. 14 exemplifies the influence of the water depth on the squat of an incoming bulk carrier at the Blexer Bow. First, at km 65.5 the water depth increases by about 4.0 m, but is diminished at km 65.0 by about 6.0 m. Consequently, a squat increases of about 0.15 m is observed. The squat falls with increasing underkeel clearance and vessel speed from km 63.0 on. The correlation between underkeel clearance and vessel squat results in a value of about -0.91 for this section. The influence of a larger vessel underkeel clearance compensates the impact on the squat by the vessel speed, because in spite of a higher vessel speed the squat decreases from km 63.5 on. The correlation between vessel speed and squat amounts to a value of about -0.27. The impact on the speed by a changed water depth is obvious at km 65.5.
Fig. 14: Lcf squat, ukc and speed through water of a 55,000 t bulk carrier in a section of local restricted shallow water (Lower Weser)

Fig. 15 depicts the influence of the underkeel clearance on the squat behaviour of a bulk carrier on the Lower Weser. With increasing underkeel clearance the influence of the underkeel clearance on the vessel squat tends to zero. For small underkeel clearances the water depth-dependent part of the vessel squat rises considerably. The fitted curve in Fig. 15 corresponds to a form of 1.99/UKC².

Fig. 15: Influence of underkeel clearance on the mean squat of a 55,000 t bulk carrier in the section of Blexer Bow (Lower Weser)
3.3. Influence of channel width on the squat of sea-going vessel

The width between the shores of tidally influenced channels varies with the tidal water level. The flow cross section increases also from the tide border to the estuary. Local contractions and/or expansions of the flow cross section can be found in the vicinity of river islands, jetty plants, mouths etc. So-called siding-areas in the Kiel Canal allow a passage of large sea-going vessels. The width at water level in the newer part of the Kiel Canal (km 2 to km 80) amounts to 162 m and to 90 m at the bottom. In the older portion of the Canal from km 80 on there is a width of only 102.5 m at water level and of 44 m at the bottom.

The navigation channel width of the Lower Weser between Bremen and Brake amounts to 150 m and in the section between Brake and Bremerhaven to 200 m. In the section of the Outer Weser the width of the navigation channel increases to 220 m between km 68 and km 90 and 300 m from km 90 to km 130 (WSA Bremerhaven). Within the section of the Lower and Outer Elbe the navigation channel has a nominal width of 300 m (WSV).

3.3.1. Influence of local cross section contractions / expansions on the squat of a 55,000 t bulk carrier on the Lower Weser

Fig. 16 depicts the vessel squat, vessel speed and vessel underkeel clearance curves for the measurement 2 (Weser Stahl) in the section between km 27 and km 25 of the Lower Weser. Also the fitted squat curve and the filtered underkeel clearance are shown for a better illustration. Within this regarded section there is a widening of 180 m at km 26.3 on the western shore. The so-called Woltjenloch leads in connection with an increasing underkeel clearance, to a decrease of the vessel squat from km 26.5 on. In the vicinity of Farge the width of the Weser decreases of about 10 % due to the jetty mole of a power plant. For approximately constant conditions in vessel underkeel clearance the squat enlarges within this section by about 0.1 m at decreasing speed. From about km 25.7 the squat decreases by approximately 0.15 m due to the following larger cross section and larger underkeel clearance.
3.3.2. Influence of local changes in the Kiel Canal width (siding-areas)

The two siding-areas Groß-Nordsee and Koenigsfoerde are presented here as examples for the squat behaviour of a general purpose carrier (red curve, *Polaris*) and of a tanker (black curve, *Alsterstern*). The vessels had different drafts at the time of the measurement, as shown by the different underkeel clearance curves. For the measurement of the general purpose carrier no water depth data were available within the siding-areas, so that the nominal depth of 11 m is used there. The general purpose carrier travelled with higher speeds than the tanker and had in comparison with the tanker only 60 % of the immersed cross-section at midship’s section due to the smaller width and draft.
Fig. 17: Squat influence in the siding-areas Groß-Nordsee and Königsförde at Kiel Canal

Fig. 18 shows, for the same section, the measured squat (black) of the tanker versus the fitted squat (red) based on the measured vessel speed. The decrease of the canal cross section of about 50 %, following the siding-area Groß-Nordsee, has a stronger influence on the vessel squat than the expansion of the cross section within the siding-area.

Fig. 18: Measured and fitted squat of a 23,000 t tanker at Kiel Canal km 88 – km 75
The narrower canal cross section doubles the vessel squat of the tanker of about 0.3 m to almost 0.6 m. Although the speed rises only by 0.5 m/s (an increase of about 17%). With entry into the siding-area Koenigsfoerde the squat decreases to the initial value of 0.3 m, the width increases here nearly to twice of the old canal width. The speed increases here by about 0.5 m/s due to the squat reduction.

Fig. 19: Influence of the ship to canal cross section ratio on the squat of a 23,000 t tanker on Kiel Canal km 88 – km 75

Fig. 19 depicts the difference of the measured and the fitted squat in relation to the ratio of canal cross section and cross section at tanker’s midship section. The values approach two asymptotes, an asymptote at an Ak/As ratio of about 5.5 and the zero-line from a ratio of about Ak/As > 20 on. For a cross section ratio of less than 7, higher propeller revs would not lead to a higher ship speed, but to a considerable squat increase. The squat behaviour of the measured tanker depends for this speed range no more on the canal cross section for larger cross section ratios than 20.

3.4. Influence of waterway curves on the vessel squat

Sailing through a river bend is divided into three phases (SCHNEEKLUTH)[9]. In the first phase the ship leans to the curve inside due to the transverse forces produced by the rudder. The centrifugal forces outweigh for constant rudder position in phase II. By the transverse motion of the ship its flow resistance increases and so the rudder force is reduced with decreasing speed. In phase III the ship reaches an equilibrium between centrifugal forces, the radial part of the transverse force due to the transverse motion and the rudder force.
Fig. 20: Increasing vessel squat due to a transit through a waterway curve in the section of Stadersand (Lower Elbe)

The increase of the draft due to a transit through a waterway curve is the sum of the heeling of the vessel and the increasing of the squat due to the enlargement of the immersed vessel cross section relative to the flow cross section. Fig. 20 depicts the transit of a 100,000 t container ship (Hong Kong Express) through a curve in the section of Elbe at km 654 (Stadersand). The maximum of the drift angle amounts to about 5° and leads to an increase of the immersed ship cross section of about 60%.

The squat increases slightly about 0.02 m from the beginning of the curve at km 653.5 to km 654 where the maximum drift angle is reached. But at the same time the vessel speed decreases by about 0.7 m/s and the underkeel clearance increases by about 1.0 m. If this section consisted of a straight channel the squat would decrease gradually as a function of ship speed and underkeel clearance. Compared to a linear fit between the last not curve-disturbed value before the curve and the first not curve-disturbed value after the curve at the condition drift angle = 0, the measured squat is larger by
about 0.1 m. Attributable to the lower ship speed the second curve at km 657 (see Fig. 20) shows not such a significant effect on the vessel squat as the preceding curve.

4. Summary

A new method has been used to measure the squat of sea-going vessels on restricted waterways within the project “Squat field measurements of sea-going vessels”. This new procedure permits to determine and to analyse the squat with continuously high accuracy for a whole transit of a sea-going vessel.

Some examples for the influences of waterway factors on the vessel squat are presented in this paper. These are factors such as water depth, channel/canal width and curves measured on waterways like Lower and Outer Weser, Lower Elbe and Kiel Canal.

A fitted squat curve ascertained by all data of a measurement allows a better description of other influences other than speed affecting the squat of the vessel.

The influence of the underkeel clearance on the squat was determined on the data basis of a 103,000 t container ship on the Outer Weser. The data illustrate that the vessel underkeel clearance has a square reciprocal influence on the vessel squat.

The maximum Froude depth number was determined for a 100,000 t container ship at a shallow section of the Elbe, a section where an increase of propeller revs does not lead to an increase of the vessel speed, but to a considerable increase of the vessel squat.

An example from a section of the Lower Weser shows the direct impact on the squat of a 55,000 t bulk carrier by small underkeel clearances. Similar to the example of the 103,000 t container ship a relation between underkeel clearance and squat was worked out on the basis of $1/\text{UKC}^2$.

The influence of a changed canal cross section on the vessel squat is discussed in an example from the Kiel Canal. It is shown that a decreasing canal cross section has an influence on the vessel squat.

The influence of waterway curves on the vessel squat is described by the transit of a 100,000 t container ship on the Lower Elbe. The increase of the immersed ship cross section by the transverse motion of the container ship compensates a simultaneous decrease of vessel speed and increase of vessel underkeel clearance and results in an increase of the vessel squat of about 1% of the static draft.

5. Literature


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[7] WSV
   www.elwis.de/Schifffahrtsrecht/SeeSchStrO/Vierter_Abschnitt_Sechster_Abschnitt/30/30.html


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