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Comparison of CFD determined squat on sailing ship MIRCEA with empirical methods

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Abstract. The paper presents a study of hydrodynamic parameters related to ship squat acting on sailing ship MIRCEA hull in shallow waters, using CFD methods. The vertical hydrodynamic forces obtained in ANSYS CFX were analysed in respect with various domain depths and ship's speeds, but also used for squat calculations. In order to evaluate the reliability of previously determined squat, a comparison study was made with nine of the most common empirical formulae for calculating squat in open shallow waters, ranging from *Barrass* to *Huuska* or *Eryuzlu and Hausser*. Some of these methods offer good results and were often experimentally validated with scale models.

1. Introduction
The evaluation of hydrodynamic parameters of ships began to gain momentum with the appearance of mechanically propelled ships in the 19th century. The most recent approach is the Computational Fluid Dynamics or CFD numerical method, which is the computational technology for analyzing systems that include fluid flow, heat transfer and associated phenomena through computer-based simulation methods [1].

The study presented in this paper follows the variation of hydrodynamic parameters related to ship squat acting on sailing ship MIRCEA hull in shallow waters, using CFD methods. Having the body plan of sailing ship MIRCEA, the hull was geometrically shaped up to the 7 m waterline, after which the fluid domain was defined to study depth effects on the body. A largely enough domain has been created to avoid that its boundaries affect the flow along the hull. The dimensions of the domain (length, width, depth) around the ship are one hull length in front of the ship, two lengths in the aft and two lengths abeam. These dimensions were adopted according to the guidelines of the International Towing Tank Conference (ITTC) [2]. The ratio between depth of water h and draft T allows simulation of the shallow water influence on the hydrodynamic parameters of the vessel, such as drag or drift. The simulations were performed for depths of h/T = 1.1, 1.2, 1.5, 2.0, 2.5, 3.0 and at speeds of 2, 4, 6 and 8 knots.

2. Empirical formulae of ship squat
Over time, studies have been carried out on naval models and ships to find a mathematical formula that can define ship squat. In the specialized literature there are different forms of squat calculation. Among them the most commonly used are those of *Barrass*'s, *Millward*'s, *Norrbin*'s or *Tuck*'s.

In 1997, the PIANC Working Group 30 report included 11 empirical formulas and a graphical method from 9 different authors for predicting ship squat. These were based on experiments carried out on physical models and on-site measurements for different vessels, channels and loading conditions. The formulas included the pioneering work of *Tuck*, *Tuck and Taylor* or *Beck et al.* and more recent research of *Hooft*, *Dand*, *Eryuzlu and Hausser*, *Romisch* or *Millward* [3].

In this comparison study the squat for MIRCEA hull was calculated using nine of the most common empirical formulae of ship squat in open shallow waters, as follows:

- ***Barrass***: A first empirical formula is based on *Barrass*'s (1979, 1981, 2004) research for calculating the maximum squat S_{max}, being obtained after the regressive analysis of over 600 laboratory and prototype measurements. *Barrass*'s formula is one of the simplest and easy to use and can be applied to all channel configurations.
- ***Eryuzlu* and *Hausser***: *Eryuzlu* and *Hausser* (1978) performed trials on large tankers in unrestricted channels [4].
- ***Eryuzlu et al.***: One of the most recent series of tests on physical models and field measurements was led by *Eryuzlu et al.* for cargo ships and bulk carriers with bulbous bows, in restricted and unrestricted channels. The tests were carried out on the self-propelled models with bulbous bows [3].
- ***Hooft***: *Hooft* (1974) combined *Tuck*'s (1966) relations for squat calculation, produced by draft increase and changing of trim, into an easier-to-use form [5].
- ***Huuska***: Finnish professor *Huuska* expanded *Hooft*'s research for unrestricted channels to include restricted channels and canals by adding a correction factor for channel width K_s, developed by *Guliev* [4].
- ***ICORELS***: The ICORELS (*International Commission for the Reception of Large Ships*) formula for bow squat is one of the formulas outlined in the PIANC Working Group 30 report and it was developed only for open or unrestricted channels, so it should be used carefully if it is used for restricted channels or canals. It is similar to the relationships of *Hooft* and *Huuska* [5].
- ***Yoshimura***: *Ohtsu et al*. (2002) proposed a formula for squat calculation, which derives from *Yoshimura*'s relation for open and unrestricted channels. In 2007, *Ohtsu* proposed a small change to the vessel speed in order to include the blocking factor *S*. Thus, the relation can also be used to predict squat in restricted channels and canals [4].
- ***Millward***: *Millward* (1990) developed an expression for calculating the bow squat in shallow but unrestricted waters, valid for block coefficients of fineness between 0.44 and 0.83 and for *L/h* ratios between 6 and 12. He noted that the formula is conservative and by virtue of navigation safety tends to provide higher squat values [6].
- ***Soukhomel* și *Zass***: Under conditions of limited depth, squat phenomenon of the ship is accentuated, especially when the ratio h/T = 1.2 ... 1.5 is met. *Soukhomel and Zass* proposed to determine the medium squat S_m [6].

All these formulas provide for all types of channels predictions of the squat produced at the bow. *Barrass*'s formula calculates the squat at the stern for unrestricted channels, and for restricted channels and canals, squat depends on the value of the block coefficient of fineness, C_B. Each formula has certain constraints that must be satisfied before being applied. If these formulas are used under conditions other than those for which they were developed, special attention must be paid [3].

3. Ship squat calculation by CFD method and comparison with empirical formulae

The vertical hydrodynamic forces, calculated with ANSYS CFX, were used for squat calculation; these being interpreted as total forces acting on the hull. They represent the sum of the static buoyancy force and the dynamic force, the latter being modified depending on the hydrodynamic pressure generated by the hull movement above the bottom of the domain. The total buoyancy force (F_Z) values and its variation depending on the ship's speed are shown in figure 1 for each of the six depths tested.

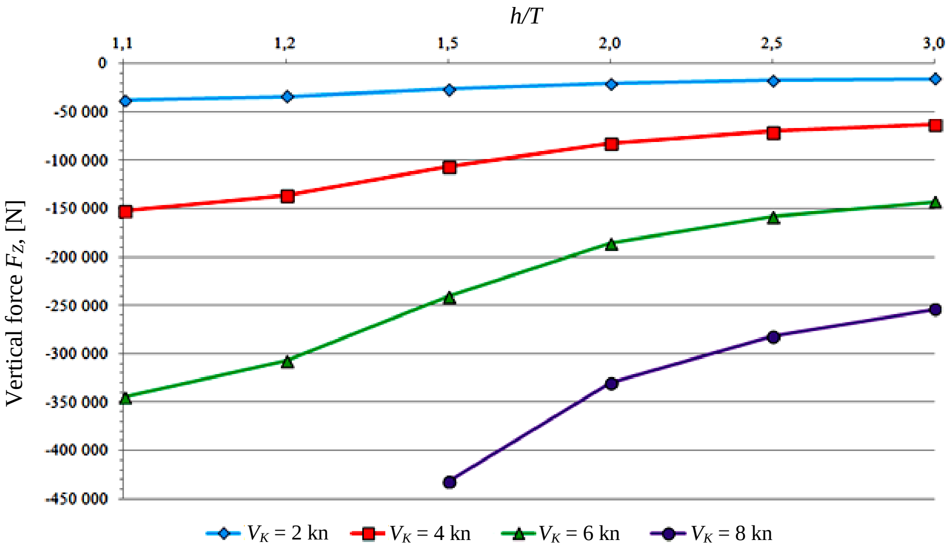


Figure 1. Hydrodynamic force variation depending on speed and depth.

In the case of *h/T* = 1.1, the speeds for which the simulations were performed were 2, 4 and 6 knots, because the speed of 8 knots exceeded the critical speed determined for the considered depth. The maximum value of the vertical hydrodynamic force is – 37 932 N and is found at the speed of 2 knots, and the minimum value of – 344 670 N, at the speed of 6 knots. It is observed that the force increases with increasing the speed, the variation being normal under these conditions.

At the depth *h/T* = 1.2, the speeds considered were the same as in the previous case, the maximum value of the force F_Z being – 34 072 N, and the minimum value – 307 190 N. The same variation is observed with the increase of the speed. At the same time, comparing the two cases, a decrease with 10.18% of both the minimum value and the maximum value with respect to the first situation is observed, where the increase of the depth is 9.09%.

In the case of *h/T* = 1.5, the speeds for which the simulations were performed were 2, 4, 6, and 8 knots, respectively. The maximum value of the vertical hydrodynamic force is – 26 664 N at the speed of 2 knots, and the minimum value of – 431 700 N, at the speed of 8 knots. The variation of the force is a normal one, proportional to the increase of the speed, and keeps the downward evolution from the previous situations. The values of the vertical hydrodynamic force decrease, compared to the case *h/T* = 1,2 with approximately 21.7% at the speeds of 2, 4 and 6 knots, where the increase of depth is 25%.

At the depths *h/T* = 2.0 and *h/T* = 2.5 the maximum valuesof the F_Z force are – 20 597 N, respectively – 17 569 N, at the speed of 2 knots, and the minimum values of – 330 260 N, respectively - 281 970 N, for the speed of 8 knots. The same variation proportional to the speed increase is observed in these cases, but the decrease of values has other proportions. Thus, when the depth increases by 25%, from *h/T* = 2.0 to *h/T* = 2.5, the vertical hydrodynamic force decreases by about 14.7% for all speeds.

For the depth *h/T* = 3.0 the maximum value of the vertical hydrodynamic force is – 15 829 N at the speed of 2 knots, and the minimum value of – 254 050 N, at the speed of 8 knots. The variation of the force keeps its downward evolution from the previous situations, and the percentage of decrease compared to the previous case is about 9.9%, at a depth increase of 20%.

As a conclusion, it can be stated that as the ship's speed increases, under conditions of shallow waters, even extreme in some cases (*h/T* = 1.1 and *h/T* = 1.2), the vertical hydrodynamic force decreases, having higher negative values, which indicates a strong interaction between the hull and the bottom of the domain.

Regarding the variation of the total buoyancy force with respect to the depth, at the same speed, its increase is observed as the depth increases. For all speeds, the minimum value of the force is found at *h/T* = 1.1, and the maximum at *h/T* = 3.0, except for the speed of 8 knots, where the minimum value is obtained at *h/T* = 1.5.

Thus, at the speed of 2 knots, comparing the values for each tested depth, the value of the force increases from – 37 932 N, for *h/T* = 1.1, to – 15 829 N, for *h/T* = 3.0. This increase has a steeper slope between *h/T* = 1.2 and *h/T* = 2.0, because the percentage increase in depth is also higher. At the speed of 4 knots, the minimum is – 151 990 N, and the maximum – 63 395 N, the variation keeping its evolution observed at the previous speed. In the case of the speed of 6 knots, the minimum value is – 344 670 N, and the maximum one – 142 740 N, the variation having the same evolution here. For these three speeds, the percentage increase from minimum to maximum is about – 58.38%, where the depth varied from 5.885 m to 16.05 m, increasing by 180.37%.

At the speed of 8 knots, the variation between the minimum of – 431 700 N and the maximum of – 254 050 N is – 41.15%, since the comparison was made starting with the depth *h/T* = 1.5. The evolution of the variation is similar to the previous cases, considering the last four depths, but the increase from *h/T* = 1.5 to *h/T* = 2.0 is steeper.

It can be concluded that by increasing the depth and implicitly under keel clearance, this negative force increases, the interaction between the ship and the bottom of the domain being smaller, and the squat effect decreasing in intensity. An overview of the variation of this hydrodynamic force as a function of speed and depth is presented in figure 1.

Using the values of the total buoyancy force (F_Z) obtained in the simulations, the squat for each of the 22 cases was calculated. Thus, for the body of sailing ship MIRCEA the values of the squat presented in table 1 were obtained.

Table 1. Calculated squat [m] for tested conditions.

h/T / V_K	*h/T* = 1.1	*h/T* = 1.2	*h/T* = 1.5	*h/T* = 2.0	*h/T* = 2.5	*h/T* = 3.0
2 kn	– 0.006858	– 0.006160	– 0.004821	– 0.003724	– 0.003176	– 0.002862
4 kn	– 0.027480	– 0.024670	– 0.019329	– 0.014917	– 0.012720	– 0.011462
6 kn	– 0.062316	– 0.055540	– 0.043475	– 0.033578	– 0.028635	– 0.025807
8 kn	-	-	– 0.078051	– 0.059711	– 0.050980	– 0.045932

Graphically, the squat variation as a function of speed is shown in figure 2, for each of the six simulated depths.

In the first situation (*h/T* = 1.1), the squat is calculated only for speeds of 2, 4 and 6 knots. Considering the very restrictive conditions of the depth, with an under keel clearance of only 0.535 m, the squat values are the highest compared to the other cases. However, the speeds are not so high that one can say that the squat is "*visible*", its values being within 0.006858 m for the speed of 2 knots and 0.062316 m for the speed of 6 knots. Squat increases by 300.7% from 2 to 4 knots and 126.77% from 4 to 6 knots.

In the second situation, the values of the squat fall quite a bit as the variation of the depth (~ 9%) is also small. Thus, at the speed of 2 knots, the squat decreases by 10.18%, at the speed of 4 knots by 10.23%, and at the speed of 6 knots by 10.87%. Depending on the speed, in this case, the value of the squat increases by 300.49% from 2 to 4 knots and by 125.13% from 4 to 6 knots, values comparable to the variation of the previous case.

At *h/T* = 1.5, the difference in depth being greater (25%) a "*jump*" of squat values is observed. Thus, at the speed of 2 knots, the decrease is of 21.74%, at the speed of 4 knots of 21.65%, and at the speed of 6 knots of 21.72%. Comparing the increase from one speed to another there is seen a variation of 300.93% from 2 to 4 knots, 124.92% from 4 to 6 knots and 79.53% from 6 to 8 knots. Of all the simulated conditions, the highest value is obtained in this case at the speed of 8 knots, 0.078051 m, which is otherwise normal to obtain the highest value of the squat for a restrictive depth and the highest speed tested. The variation of the squat is similar to the previous cases, being proportional to the increase of the speed, but keeping the descending evolution.

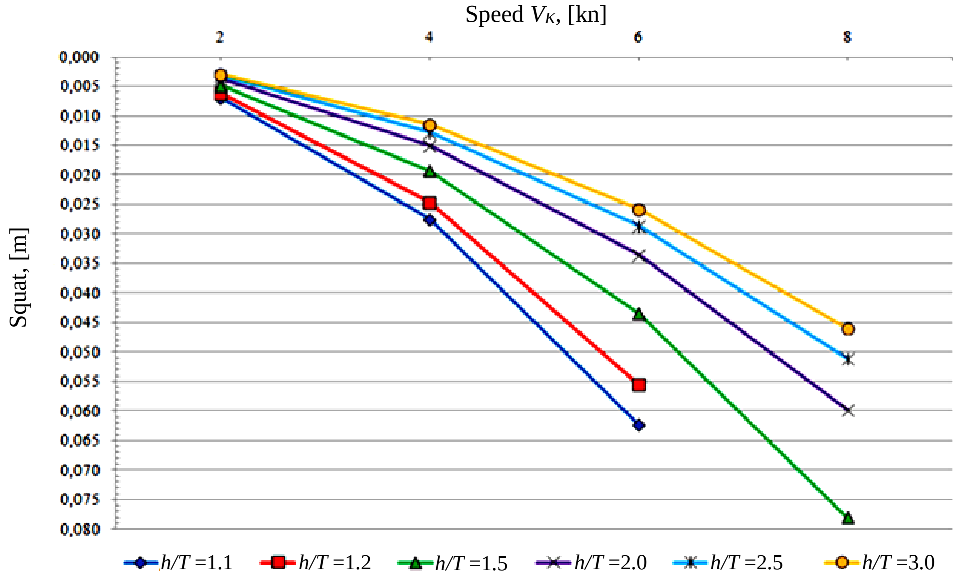


Figure 2. Squat variation depending on speed and depth.

In the fourth case (h/T = 2.0) a second "*leap*" is observed, in the conditions of increasing the depth by 33.3%. Thus, at the speed of 2 knots, the decrease is 22.75%, at the speed of 4 knots of 22.83%, at the speed of 6 knots of 22.76%, and at the speed of 8 knots of 23.5%. The increases in speeds, in this case, are similar to the previous case for all 4 speeds, these being 300.56%, 125.1% and 77.83% respectively.

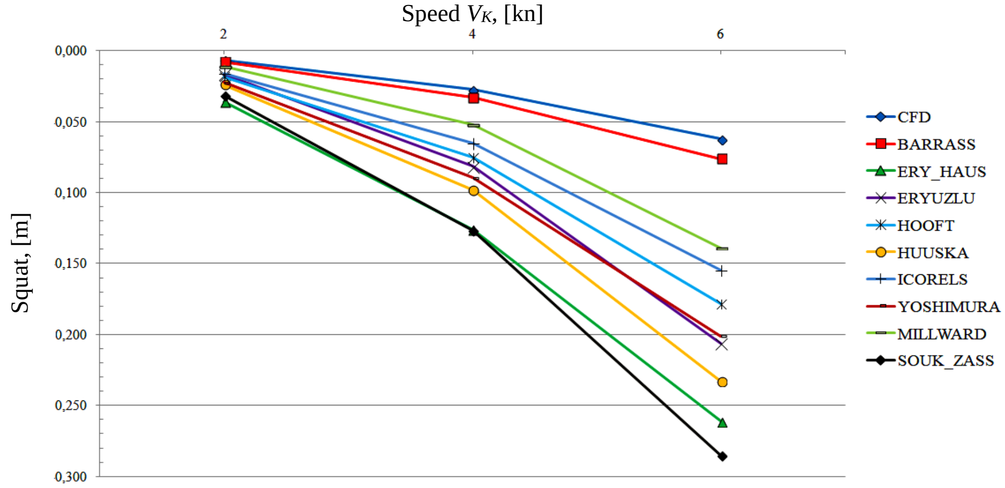
When the depth increases by 25% (h/T = 2.5), the squat variation from the previous situation is smaller, which is about 14.7% for all speeds. Also, the same increases from one speed to another, as in the situations analyzed above, of 300.5%, 125.12% and 78.03% respectively.

For the depth h/T = 3.0 the squat values are the smallest because the under keel clearance of 10.7 m is the largest of all the analyzed cases. Thus, the minimum is only 0.002862 m, and the maximum 0.045932 m. The decrease from the previous depth is much smaller, which is 9.89% for all four speeds, at a depth increase of 20%. For this situation, the proportions of the squat increase according to the speed are also kept.

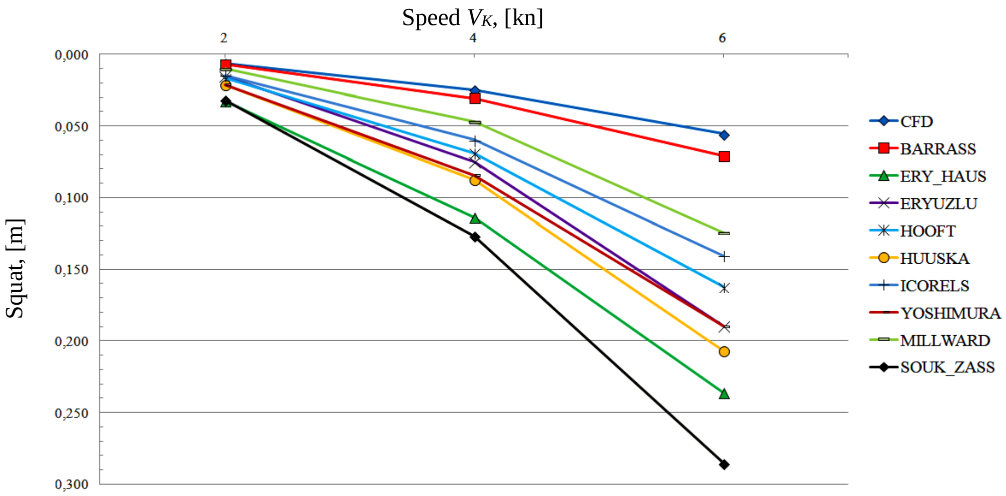
In conclusion, it is observed that the variation of the squat is dependent on depth and speed. Thus, the lower the under keel clearance, and the higher the speed, the larger the squat and produces the ship's draft increase. However, it should be emphasized that the values obtained from the CFD simulations are of the order of centimeters, values that are in accordance with the dimensions of the ship and the speeds considered, but which could be difficult to detect in reality, which was found in the experimental research carried out on board of sailing ship MIRCEA.

In order to evaluate the reliability of the ship's squat prediction using the vertical hydrodynamic forces determined with ANSYS CFX, a comparison was made with nine of the most common empirical methods for calculating squat in unrestricted shallow waters. The 9 methods are: *Barrass*, *Eryuzlu and Hausser*, *Eryuzlu et al.*, *Hooft*, *Huuska*, *ICORELS*, *Yoshimura*, *Millward*, *Soukhomel and Zass*, which were fully presented in a previous article. Some of them provide good results, being often experimentally validated with scale models, others are based on more recent research.

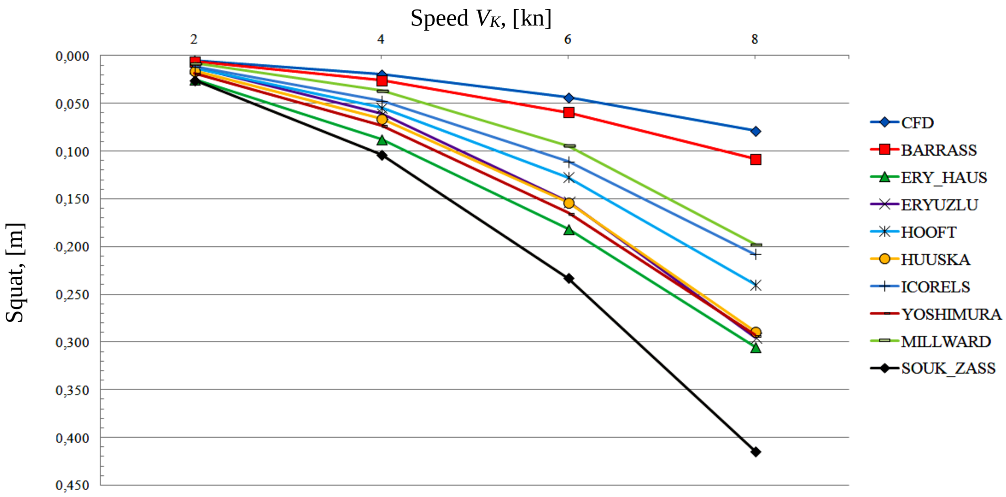
Figure 3 illustrates, for each considered depth, the squat variation for all 10 methods used. In general, there is a tendency of squat increase proportional to the speed, in all situations and for each method. Regarding the differences between the methods, it is appreciated that *Barrass*'s method gives the closest values to the CFD method, in all the analyzed situations, and the rest of the methods overestimate the squat in different proportions from one depth to another; the method of *Soukhomel and Zass* being the one with the highest values of the squat. Also, it is observed that at the speed of 2 knots, the values are close to each other, but as the speed increases, the differences are increasing.



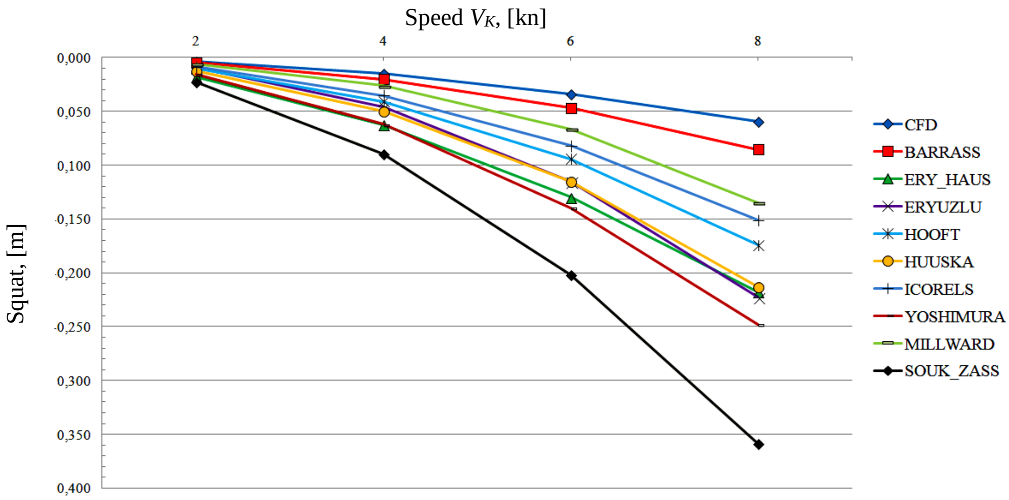
(a) *h/T* = 1.1



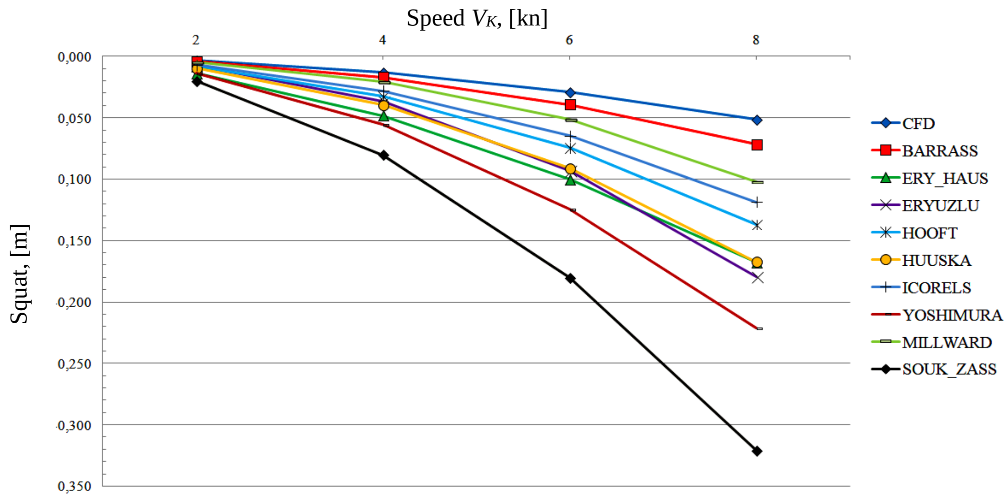
(b) *h/T* = 1.2



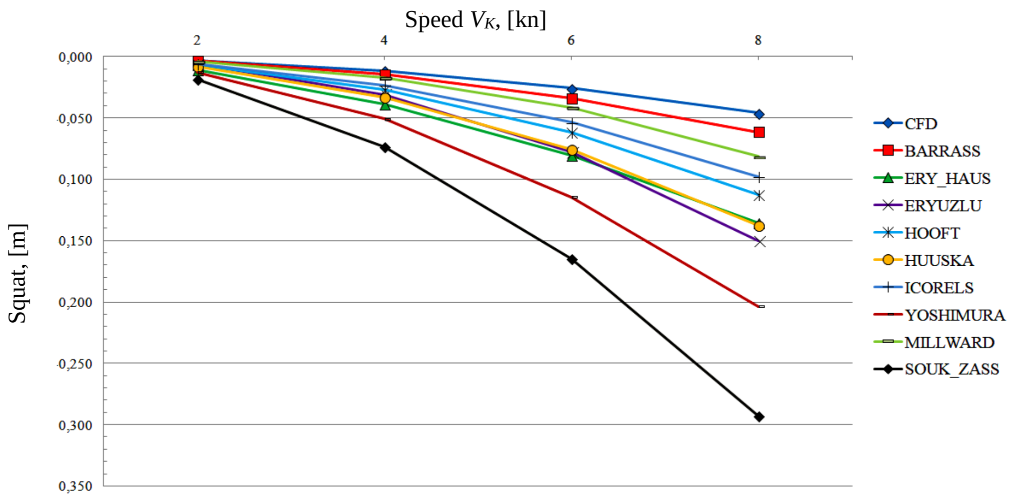
(c) *h/T* = 1.5



(d) h/T = 2.0



(e) h/T = 2.5



(f) h/T = 3.0

Figure 3. Comparison between calculated squat using empirical methods and CFD method for each h/T value.

It should be emphasized that these empirical methods have restrictions on their application, such as the block coefficient of fineness, the ratio between the width and draft of the ship or the ratio of depth, but all can be used to calculate the squat in unrestricted channels and only some of them can be used for restricted channels or canals.

Thus, for reliable results, *Barrass*'s method can be applied only for h/T = 1.1 - 1.5 and C_B = 0.5 - 0.9, but these conditions were not taken into account because it was used a formula that is valid for any situation. The *Millward* method has a single constraint, with respect to the block coefficient of fineness, which must have values between 0.44 and 0.83; this condition being fulfilled. The only method that does not have any conditions is the one formulated by *ICORELS*, but it applies only to unrestricted channels.

In the first case (figure 3.a), h/T = 1.1, the *Barrass* method gives squat values higher than the CFD method with 12.96% at 2 knots, 19.19% at 4 knots and 22.16% at 6 knots. By the overestimation order, the following methods are *Millward* with increases of 62.64%, 88.53%, respectively 123.02%, *ICORELS* with increases of 131.25%, 137.6%, respectively 148.36%, *Hooft* with increases of 166.61%, 173.94%, respectively 186.35%, *Eryuzlu et al.* with increases of 143.34%, 196.78%, respectively 231.07%, *Yoshimura* with increases of 225.72%, 225.15%, respectively 222.62%, *Huuska* with increases of 248.12%, 257, 69%, respectively 273.89%, *Eryuzlu and Hausser* with increases of 427.37%, 358.3%, respectively 319.31% and *Soukhomel and Zass* with increases of 362.29%, 361.48%, respectively 357, 88%. All increases relate to the values obtained by the CFD method, for the three speeds. It is noted that although the conditions of application for *Soukhomel and Zass* method are respected, it overestimates the squat, as opposed to other methods, such as *Yoshimura* or *Huuska*, where the conditions have not been fully met, but which provide values closer to the CFDs.

At the depth h/T = 1.2 (figure 3.b), the tendency is repeated, but with slightly different proportions due to depth increase. After the degree of squat overestimation, the order of the methods is the same as in the previous case.

In the third case (figure 3.c), the order of the methods is kept, except for *Huuska* with increases at speeds of 2, 4 and 6 knots of 234.49%, 240.77%, respectively 253.69% and *Yoshimura* with increases of 279.36%, 278.48%, respectively 278.61%, whose order is reversed. At the speed of 8 knots, the differences related to the CFD method are: *Barrass* - 38%, *Millward* - 152.8%, *ICORELS* - 166.65%, *Hooft* - 207.43%, *Huuska* - 270.66%, *Eryuzlu et al.* - 277.75%, *Yoshimura* - 274.91%, *Eryuzlu and Hausser* - 290.89% and *Soukhomel and Zass* - 430.65%.

At the depth h/T = 2.0 (figure 3.d) it is observed the change of the order of the methods from the point of view of overestimation, but also a smaller variation, compared to h/T = 1.5, of the methods *Huuska*, *Eryuzlu et al.*, *Eryuzlu and Hausser*, *Yoshimura*. For this trial the maximum difference is also observed in the *Soukhomel and Zass* method, the values being five times higher, at the speed of 8 knots.

In the case of h/T = 2.5 (figure 3.e), the greater depth influences the squat increase less and it can be observed that some of the methods give approximately equal values for the four speeds, such as the *Huuska*, *Eryuzlu et al.* and *Eryuzlu and Hausser*. The *Barrass* method is still closest to the CFD values, with variations of 25.44%, 32.43%, 36.72%, 39.7%, respectively, and the *Yoshimura* and *Soukhomel and Zass* methods have the highest overestimation.

In the last case (figure 3.f), the trends identified above are preserved. The increase of the values by the *Barrass* method is 20.1%, 26.78%, 30.88%, respectively 33.77% compared to the CFD. *Huuska*, *Eryuzlu et al.* and *Eryuzlu and Hausser* methods also have approximately equal values.

The *Huuska* method gives higher values because the calculation does not meet the conditions of the block coefficient of fineness, C_B = 0.6 - 0.8, and the L/T ratio, but satisfies the other depth restrictions and the b/T and L/b ratios. The methods of *Eryuzlu and Hausser*, *Eryuzlu et al.* give higher values, but it should be noted that a condition for applying the formulas is $C_B \geq 0.8$, restriction not fulfilled in the calculations performed. The reason why *Soukhomel and Zass* method offers the highest proportion in all six cases cannot be specified, even if it has all the conditions fulfilled.

In general, it is appreciated that the methods that are close to the values obtained by CFD simulations are *Barrass*, *Millward*, *ICORELS* and *Hooft*. In the calculations made, the application restrictions were respected for all these methods.

The comparisons presented above show the influence of water depth and ship's speed on squat. It is observed that the squat calculated by the CFD method is in accordance with most of the empirical methods presented, the *Barrass* method being the closest in values, overestimating with percentages between 12% and 43%, in the conditions in which, all methods overestimate the squat, but with values that exceed 100% to 500%. The calculated values of the squat are between 0.0028 m and 0.078 m for the actual speeds of the ship of 2, 4, 6 and 8 knots.

The results of the presented study demonstrate that ANSYS CFX can be used efficiently for the prediction of naval squat in shallow waters, but further investigation of the hydrodynamic effects produced in shallow waters, restricted channels and canals is required.

4. Conclusions

This paper presents a comparison study between squat values obtained by CFD numerical simulations on sailing ship MIRCEA hull and different empirical formulae for ship squat. Having the body plan of sailing ship MIRCEA, the hull was geometrically modeled up to 7 m waterline, after which 6 fluid domains with depths of $1.1 \cdot T$ and $3.0 \cdot T$ were defined.

Following the analysis of the results it was observed that the speed variation obtained in the fluid domain along the hull has a normal distribution, with a potential increase of the flow velocity under the hull, due to the interaction between the body of the ship and the bottom. As the velocity increases, the vertical hydrodynamic force decreases, having higher negative values, which indicates a strong interaction between the hull and the bottom of the domain.

It has been observed that the squat variation is dependent on depth and speed. Thus, the smaller the under keel clearance and the higher the speed, the more pronounced the squat is, producing an increase of the ship's draft. However, it should be emphasized that the values obtained from the CFD simulations are of the order of centimeters, values that are in accordance with the dimensions of the ship and the considered speeds, but which could be difficult to detect in reality, which was found in the experimental research carried out on board sailing ship MIRCEA.

In order to evaluate the reliability of the ship's squat prediction, using the vertical hydrodynamic forces determined with ANSYS CFX, a comparison was made with nine of the most common empirical methods for calculating squat in unrestricted shallow waters. It was appreciated that the methods that best approximate the values obtained through CFD simulations are of *Barrass*, *Millward*, *ICORELS* and *Hooft*.

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