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SENSORS I SESSION

Wind feedforward: blowing away the myths

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ABSTRACT

The paper examines the use and requirements for wind feedforward.

The aim of wind feedforward is to counteract the wind forces on the vessel before they affect the position. This is achieved by measuring the wind speed and direction and calculating estimated forces from a model of the vessel wind resistance.

The paper looks at a number of influences on the efficacy of wind feedforward, including accuracy and repeatability of wind sensors, accuracy of wind force models, the variability of the wind, both spatially and temporally, and the effect of nearby structures.

It is shown that some types of vessels and operations can gain great benefit from the inclusion of wind feedforward. However, there are certain situations in which wind feedforward has the potential to degrade DP performance. The paper attempts to summarize where, and under what circumstances, wind feedforward should be used, and also where it should not.

INTRODUCTION

The wind is a significant disturbance on vessels using dynamic positioning (DP) systems. The aim of wind feedforward is to counteract these wind forces before they cause the position to drift (Wise and English, 1975). This is achieved by measuring the wind speed and direction and calculating estimated forces from a model of the vessel wind resistance. In the ideal case, if the wind loads were calculated accurately, the thrusters could develop reactions of the same amplitude as the wind forces and the vessel would remain practically stationary (Faÿ, 1990).

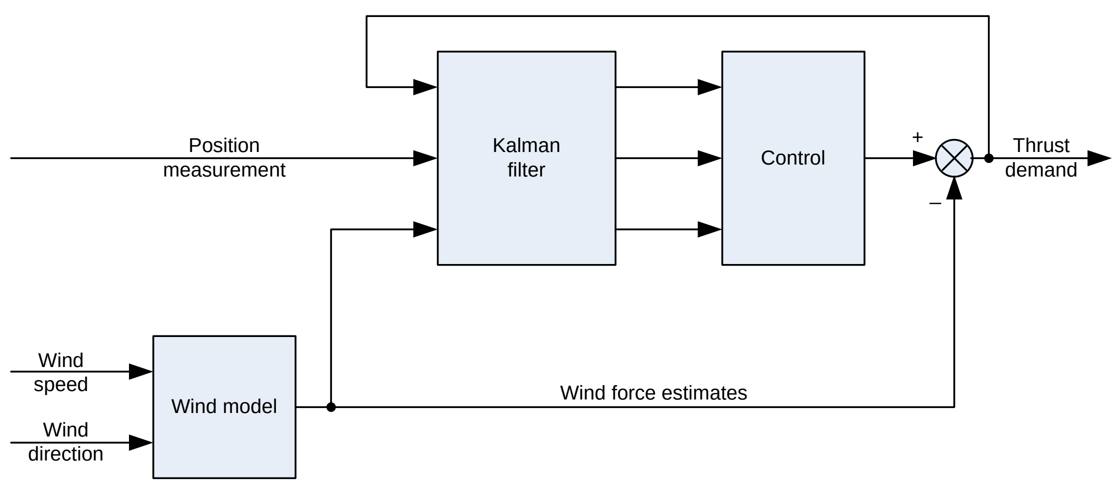

Figure 1: use of wind feedforward in DP controller

Figure 1 shows a typical use of the wind measurements in reducing the effect of wind forces on a vessel. The measurements of wind speed and wind direction from the anemometers are fed into a wind force model from which are obtained estimates of the forces on the vessel in each axis, surge, sway and yaw. These forces are fed into the Kalman filter (KF) which is used to estimate vessel motions, and are also fed directly into the thrust demands in order to counteract the estimated forces. The wind model also includes vetting and filtering of the measurements (Grimble et al, 1980).

From the diagram it can be seen that the wind feedforward force estimates are used by the KF. This ensures that the estimates of environmental force (sometimes displayed as ‘sea current’) in the KF exclude the effects of the wind. If no anemometers are selected or available, and wind feedforward is unavailable, the mean effect of the wind on the vessel will be identified as part of the environmental force. Note that wind feedforward is not strictly necessary for good position-keeping. However, if the force estimates from the wind feedforward are good, the position-keeping may be improved, particularly where the wind is changing (either as a result of the weather or as a result of the vessel altering its heading).

The following sections examine the conditions under which the assumption that wind feedforward improves control is true. The factors include the quality of measurements from the anemometers, the variability of the wind and the ability to model the wind's effect on the vessel.

ANEMOMETERS

The efficacy of wind feedforward relies on the estimates of wind force matching the actual force acting on the vessel. In order to achieve good force estimates, the measurements of wind speed and wind direction from the anemometers must be reliable, accurate and consistent.

Anemometer readings have been monitored on a number of vessels and it has been found that anemometers of all types can be very sensitive to gusts and turbulence. For example, the measured wind direction can rotate through 360^o in two or three seconds. The devices seem susceptible to this when the wind speed drops briefly. When this occurs, the direction measurement is completely wrong for several seconds. Anemometers can also swing or oscillate wildly, giving direction measurements that vary by 90^o or more.

These behaviors mean that the measurements must be carefully vetted before being used in the wind feedforward model. The direction measurement must, therefore, be treated with particular caution. Straightforward filtering of the direction is not usually adequate and can result in erroneous data being used in the wind force model.

There can also be differences between anemometers. A study has been made of 20 active vessels, on each one, the measurements from two or more anemometers were compared and the mean differences in measured direction and speed were calculated. The results are summarized in Table 1. This table shows that significant differences in the measured wind occur using different anemometers on the same vessel. However, this is not just due to poor calibration of the anemometers. Time series data show that the difference between measurements sometimes depends on the relative heading of the wind. For example, Figure 2 shows the change in direction measurement when the vessel heading is altered by about 30^o. In particular, the difference in the direction measurements before the turn is approximately 0^o, while the difference after the turn is about 14^o. This highlights the need for careful siting of anemometers to avoid interference from other structures on the vessel.

	Mean error across vessels	**Max error**
Direction	9.2^o	28.0^o
Speed	0.63 m/s	2.1 m/s

Table 1: measured anemometer errors

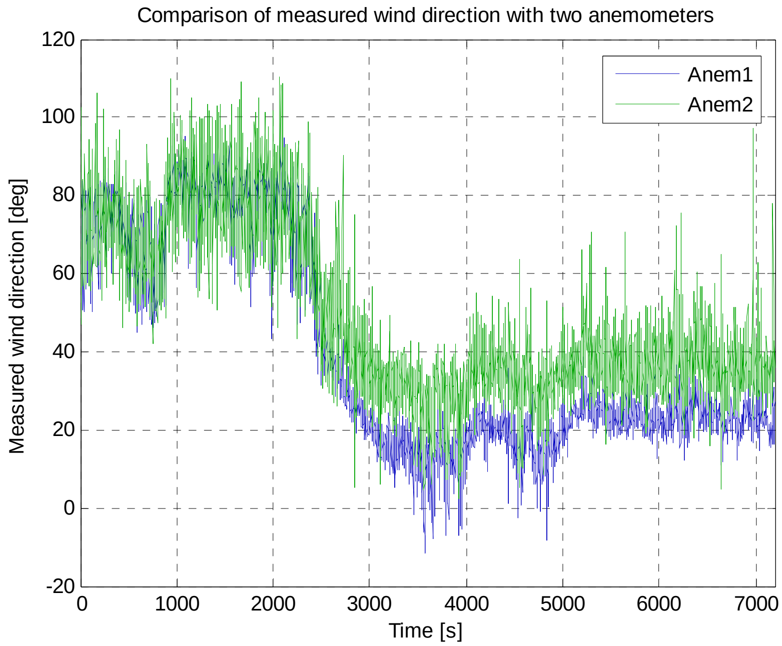

Figure 2: comparison of measured wind direction with two anemometers

WIND BEHAVIOUR

This section looks at the behaviour of the wind itself and how this affects the achievable performance of a wind feedforward control scheme.

The way in which the wind varies in time and in space will have an effect on the ability of the wind feedforward system to, firstly, measure values representative of the wind acting on the whole vessel, and secondly, to calculate good estimates of the loads that affect the vessel.

Variation of wind with time

DP controllers, of whatever form, include the ability to cancel out the effects of mean forces from wind, waves or any other disturbance. This is achieved using integral action, whether implemented in a KF or other controller architecture. Therefore, the mean wind force is not a problem and wind feedforward is not essential to maintain the steady-state position. From the point of view of position-keeping, *variation* of wind forces is the main reason for including wind feedforward. Such variations can be due to changes in the wind speed or direction, or changes in the vessel position or heading. The integral action will track slowly varying changes, with periods greater than about 1000 s, but cannot track faster changes.

A DP vessel is a large mass floating on a dense (relative to air) fluid. This means that any DP vessel has a large inertia compared to the wind gusts. A large inertia leads to a slow response to disturbances and it is therefore true that high frequency variations of the wind will not greatly affect the vessel position. The cut-off frequency for significant gust effects will depend on the vessel. For a shuttle tanker or similar large vessel, variations in wind with a period less that about 100 s do not significantly affect the position. For a small support vessel, the minimum period of interest might drop to 40 s.

In summary, the DP position is not affected by variations with very long periods (greater than 1000 s) or very short periods (less than 40 s). The wind variations of interest, therefore, lie between these extremes.

Spatial variation of wind

The wind incident on an offshore vessel is not a uniform flow. There is always turbulence within the wind field, even in open water. This means that for large vessels, the wind incident on one part of the vessel may be different from that on another part. The total forces on the vessel therefore depend on variation of wind in space.

Variation of wind speed with vertical height is one aspect which must be addressed in the estimation of wind loads on vessels. Friction between the air and water surface means that wind speed increases with increasing height above the sea. The shape of the wind speed profile with height varies from location to location, from one day to the next and with time of day. Since the measurement of the wind is typically performed at one height, it is necessary to include in the wind force model some factor to correct for the vertical wind profile. It is usual to assume a logarithmic wind profile, but this approximation will not hold at all times (DNV, 2010).

Variation of wind speed with horizontal displacement is more difficult to model than vertical displacement. The usual method of incorporating this into wind force estimates is to include factors in the wind force coefficients. For example, for the wind forces on the side of a ship, a non-uniform wind speed tends to give lower overall forces than a uniform wind speed. In contrast, a non-uniform wind speed tends to give larger yaw turning moments on the vessel than would be predicted with uniform wind (Feikema and Wichers, 1991).

All of the above effects are present even in open water areas. They are complex and difficult to model with accuracy (HSE, 2002), but they can be at least partly accounted for in the wind coefficients used in the wind force models. There are, however, further effects which have an even more significant effect on the usefulness of the wind measurements.

The effect of a fixed platform on the wind is illustrated in Figure 3 using two-dimensional computational fluid dynamics (CFD) (Engwirda, 2006). This figure shows a contour plot of the wind speed in the region of a static platform with an incident wind of 10 m/s. Blue contours represent low wind speeds, while red contours represent high wind speeds. It can be seen that behind the platform for a distance in excess of 1 km, the wind is highly disturbed. Places with contours close together represent positions in which an anemometer on the vessel would give a reading unrepresentative of the wind acting on the full vessel. It should be noted, too, that the situation is extremely dynamic and that the areas of high and low wind move past the platform and away towards the right of the figure.

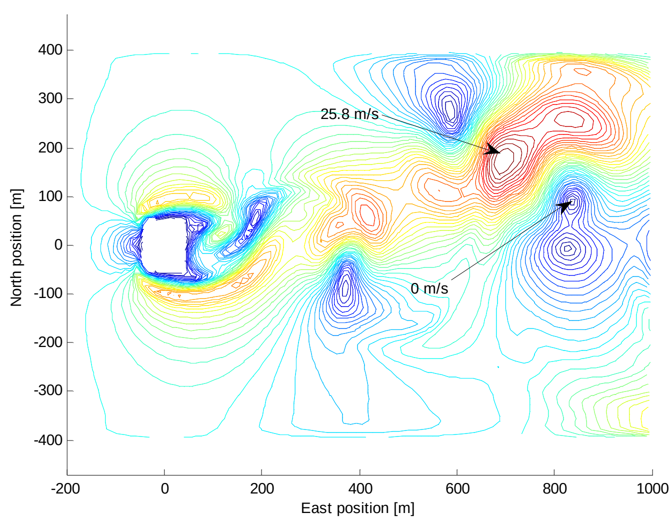

Figure 3: wind speed variation in the region of a static platform

Figure 4 shows the variation of the wind speed and direction at bow and stern of a supply vessel in the lee of the platform. It was generated by plotting the variation of wind from the CFD analysis at two points about 100 m apart. The variation of wind speed and direction at the bow is far in excess of that at the stern. Clearly, if the anemometers are near the bow, they will read large variations in the wind conditions that other parts of the vessel do not experience. The dramatic changes in wind velocity caused by the proximity of the platform render wind feedforward a liability in this region, i.e. the forces applied to the vessel due to wind feedforward predictions are liable to be entirely inappropriate and could exacerbate position loss. It is recommended that consideration be given to disabling wind feedforward (by deselecting anemometers) when a vessel is within 1 km of another large structure.

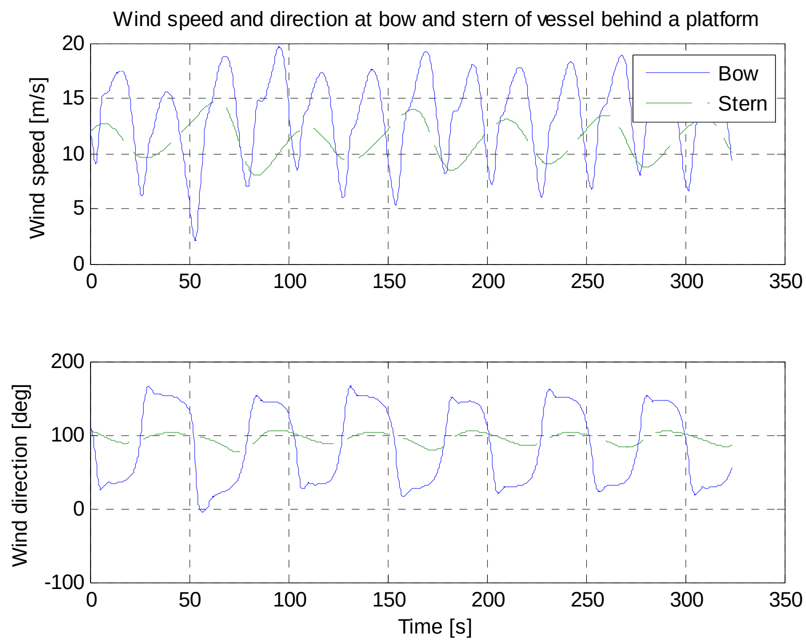

Figure 4: time variation of wind speed and direction for vessel in lee of platform

WIND FORCE MODELLING

Wind feedforward requires that the forces on the vessel can be estimated from the measured wind speed and direction. This requires a mathematical model of the wind forces, usually specified in terms of wind force coefficients. A model of this type can be obtained from wind tunnel tests on a scale model of the vessel, or from analytical calculations. Wind tunnel tests are usually only performed for large vessels, like tankers, drill ships or semi-submersibles. Smaller vessels tend not to have wind tunnel tests available.

Analytic modelling can take a number of forms. One method of producing wind coefficients for merchants vessels is due to Isherwood (1972), it is based on measurements from a selection of wind tunnel tests and makes use of the wind areas and centroids of areas. A number of other methods exist, for example Lewis (1988), Van Berlekom et al (1974) and Hughes (1930).

It is difficult to estimate the errors which might be present in any set of wind coefficients, since the true wind model cannot be determined. In this paper, wind coefficient errors have been estimated by comparing two different methods of calculation.

Where the windage area or wind profile of a vessel changes during operation the wind forces may change significantly. This can occur where a vessel (e.g. a shuttle tanker) experiences large draught changes. It is common, in this case, to incorporate different wind coefficients for different draughts and in this way to take account of the change in wind profile. Another example of changing wind profile is a crane barge, where the cranes can present a large, moving surface area to the wind. It is rare that the position of the cranes is known to the DP system, and in this case the errors in the wind coefficients could be significant. This scenario is investigated in the sections below.

SIMULATION TESTING

A number of simulation tests have been conducted in order to assess the effect of some of the problems highlighted in the previous sections. The tests were performed for three different vessels: a platform supply vessel, a shuttle tanker and a heavy lift crane semi-submersible. The simulation scenarios were chosen to reflect some typical operations of these vessels.

From the previous sections, it is clear that wind feedforward is likely to be most effective in open water, where the wind speed is fairly uniform across the whole of the length and breadth of the vessel. In other words, when the measured wind speed and direction at the anemometers is most likely to give a representative reading for the whole vessel. Therefore, the initial simulation tests were performed for open water.

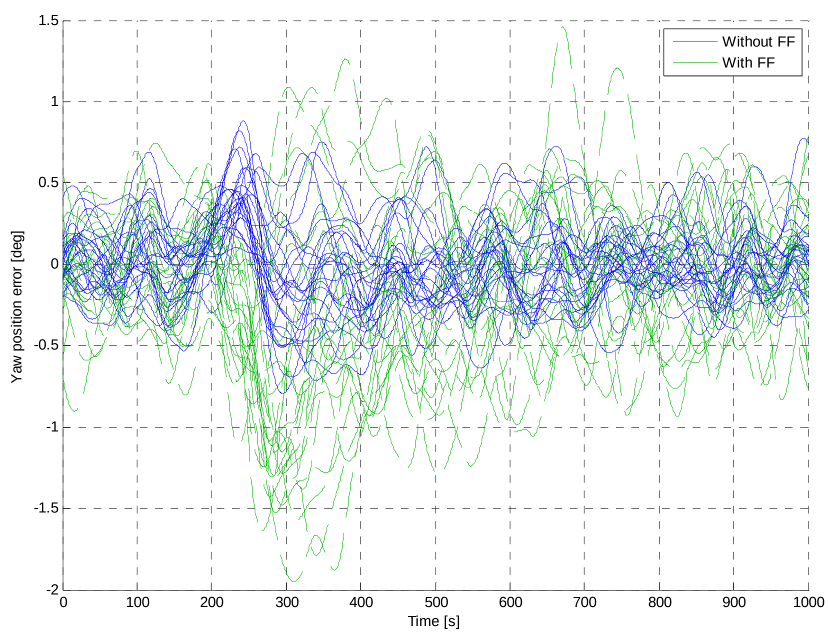

Figure 5: example yaw position error results for crane barge

An example of the results obtained are shown in Figure 5 for the crane vessel. The figure shows the error in heading during 25 simulation runs in which the wind direction changed by a random value between 20^{o} and 45^{o}, and the anemometer exhibited an angle error of between 0^{o} and 9^{o}. The solid blue lines show the performance without wind feedforward, the dashed green lines the position with wind feedforward. It is clear, in this particular case, that wind feedforward makes the heading control worse. But how often is this the case?

Results like Figure 5 are useful in visualizing how the wind feedforward might perform. But in order to get a full picture, thousands of simulation must be performed, and the results are not easy to interpret. Rather than present pages of plots like Figure 5, the next section attempts to summarize the maximum usefulness of wind feedforward.

ANALYSIS OF WIND COEFFICIENTS

This section presents a new method of analysing the theoretical ability of wind feedforward to improve position-keeping given a number of scenarios. The method makes the assumption that wind feedforward has the greatest benefit to position-keeping when the incident angle of the wind on the vessel heading is changing. Very slow changes will be attenuated by the normal integral control action, but a change in the vessel heading, or a shift in the mean wind direction should be counteracted by the feedforward.

The second assumption is that the force acting on the vessel will be different from the force generated by the wind feedforward due to the errors in modeling and measurement outlined in previous sections. By estimating the form that these errors might take, it is possible to calculate the maximum deviation of a vessel from its aim position given a sudden change in the wind direction, with and without feedforward, due purely to the action of the wind and the feedforward thrust. This is done by calculating the change in total forces predicted by the 'true' wind model at two angles of incidence representing a shift, or step change, in the wind angle. This is compared to the change in *error* between the true wind forces and the predicted wind forces at the start angle and after the step. Where the change in the force error is less than the actual change in force, wind feedforward will improve position-keeping. Where the change in error is greater than the change in true force, wind feedforward will be detrimental.

To display the results, a map is used which shows the number of axes for which wind feedforward improves the performance, plotted against the initial incident angle of the wind and the size of the change in relative heading. These are displayed for various scenarios in Figure 6 to Figure 9. On each map, white indicates that wind feedforward gives an improvement on all three axes. Darker colors indicate that wind feedforward is only beneficial on two, one or no axes.

Anemometer error

The first vessel considered is the supply vessel with an error on the anemometer. The wind coefficients are assumed to be known but there is an error on the measured angle of the wind from the anemometer of 28°. The value of this error is the largest found in the logged data of Table 1. The results are shown in Figure 6. There are very few white squares in Figure 6 indicating that wind feedforward is rarely beneficial on all three axes at the same time. There are a number of cases, where the wind starts on the port bow and moves round onto the starboard bow, where wind feedforward makes position keeping worse on two or three out of three axes (i.e. the orange and red blocks).

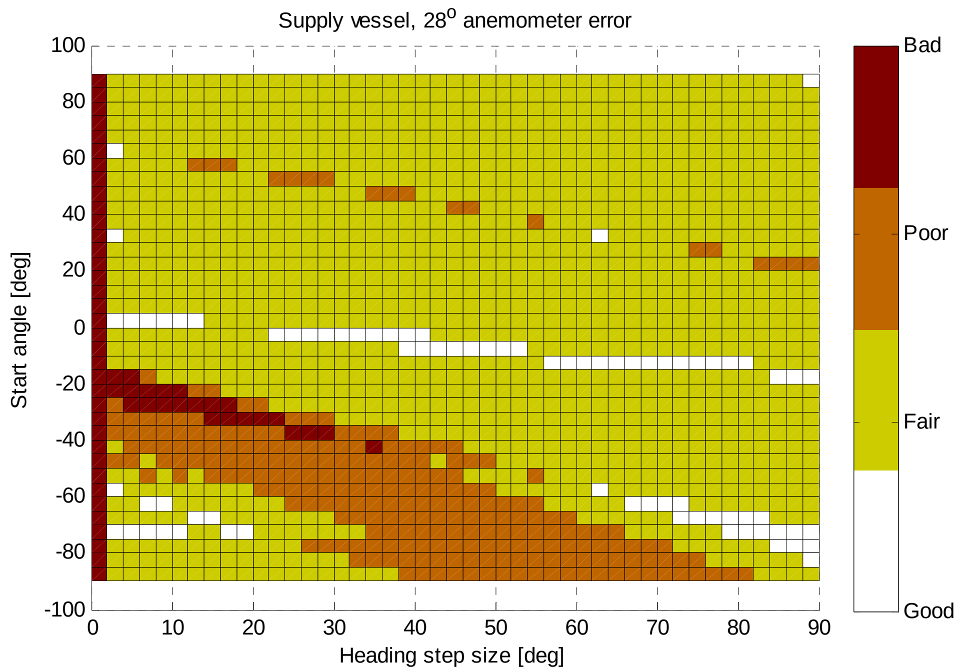

Figure 6: effectiveness map, supply vessel with 28° anemometer error

Error in wind coefficients

The supply vessel is again considered in Figure 7. This time, errors in the wind coefficients have been introduced by using wind coefficients from different sources. The first uses the Isherwood (1972) model, while the second uses a scaled set of wind tunnel tests for a similar vessel. An error of 10^{o} has also been added to the anemometer direction representative of the average anemometer error found in the logged data (Table 1). There is a greater area of white, showing that wind feedforward is likely to be beneficial on all three axes for many cases. However, the majority of the poor performance (dark colors) are for small heading changes, which are perhaps more likely in practice.

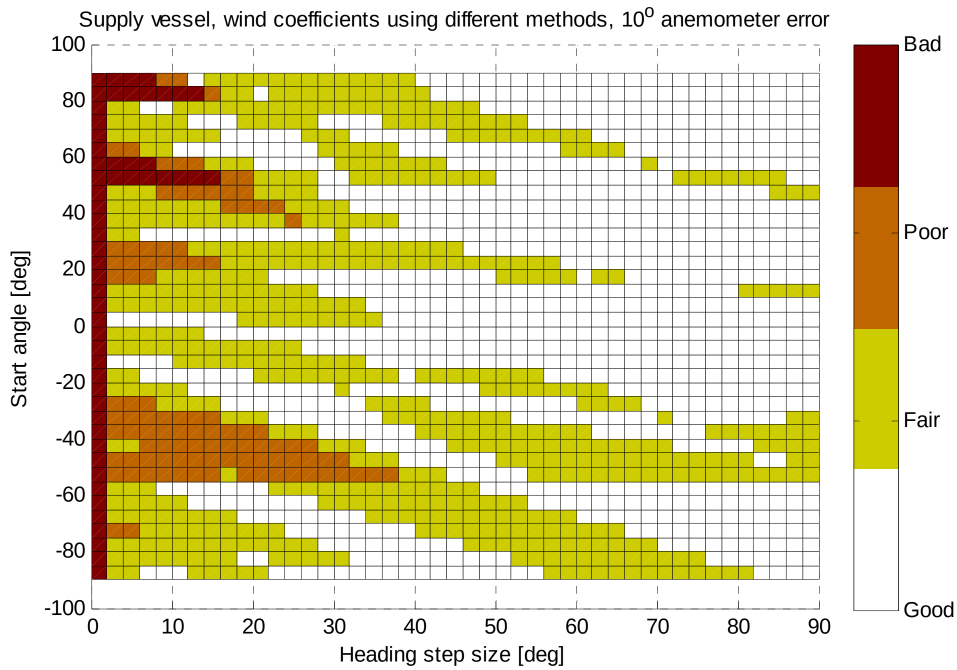

Figure 7: supply vessel using different wind modelling methods, 10^{o} error on anemometer

Cranes affecting wind forces

Figure 8 shows the results for a crane barge with two cranes that have been moved from a stowed position to a fully extended position. The effect is to alter the way that wind heading changes affect the forces on the vessel. The total area of white is small compared to that of the other colours, indicating that wind feedforward is of questionable benefit.

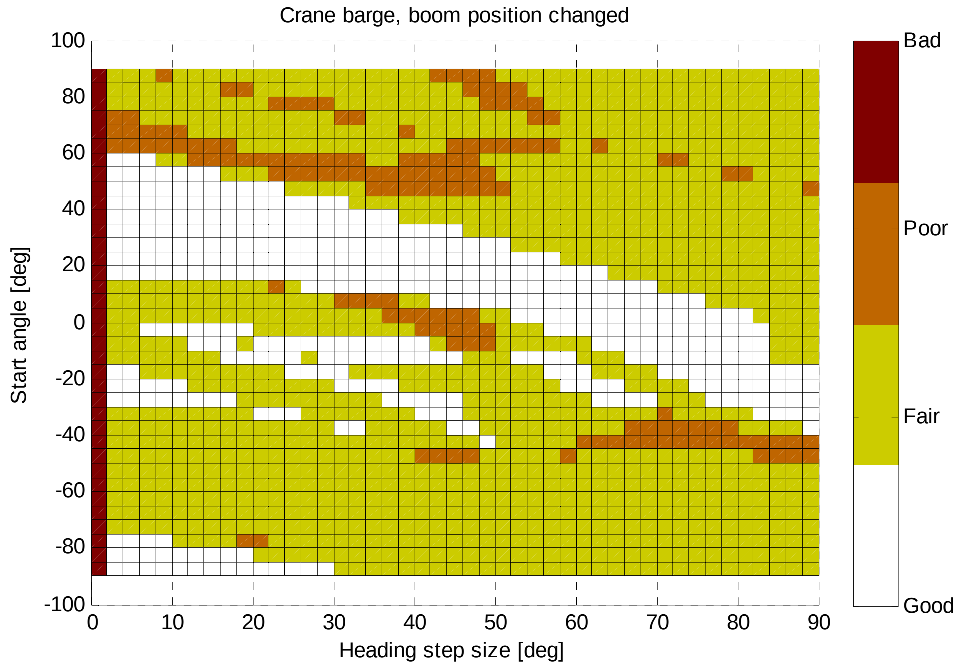

Figure 8: crane barge, crane boom moved, no anemometer error

Shuttle tanker at different draughts

The final case study is a shuttle tanker whose draught compensation has been removed for the wind feedforward. The wind coefficients in the feedforward model are therefore in error. Figure 9 shows the results, including a 10^o error on the measured anemometer direction. The large areas of white blocks indicate that wind feedforward is advantageous much of the time on all three axes.

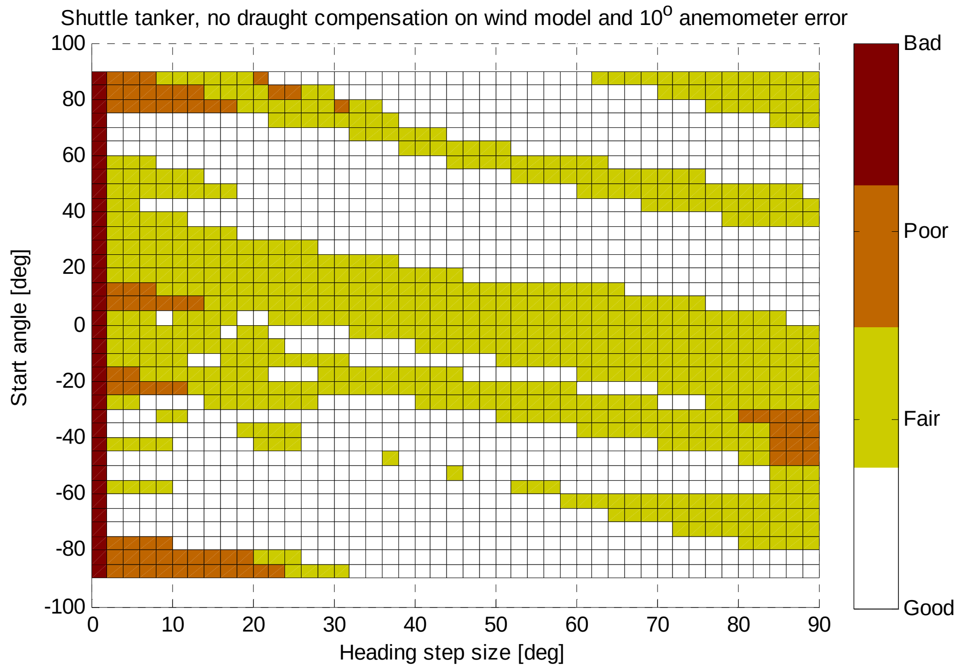

Figure 9: shuttle tanker, no draught compensation on wind coefficients, 10^o anemometer error

CONCLUSIONS AND RECOMMENDATIONS

The hope for the research reported in this paper was to be able to answer the question "Is wind feedforward beneficial". Unfortunately, the investigation of both theoretical research and logged data from real vessels has brought the resounding answer "Sometimes!". These conclusions attempt to summarise where and when wind feedforward can be considered beneficial and when detrimental. However, the first conclusion is that further work is required in order to improve our understanding of the limitations of wind feedforward.

Errors in anemometers, particularly in direction measurements, have been found to be fairly common on real vessels. Analysis of the effect of these suggests that they could have a large impact on the effectiveness of wind feedforward. Further work needs to be performed to see if these errors can be further quantified and whether they can be reduced.

Errors in wind coefficients for calculating wind forces will always be present. It is difficult to quantify these errors. Where wind tunnel tests are available their results should be used to inform the wind feedforward model. Further work is recommended in assessing how good other types of wind force modelling are.

Some vessels have radically changing wind profiles. The effect on wind feedforward depends upon the nature of the changes. Changes in draught, for example, tend to maintain the overall shape of the wind coefficient curves and do not cause major problems. Other factors, e.g. large cranes, can alter the shape of the curves and limit the usefulness of wind feedforward. Careful consideration should be given to disabling wind feedforward in such circumstances.

The final conclusion is that wind feedforward is not essential. The results have shown that it can be detrimental to position-keeping. It is therefore recommended that operators be introduced to the concept of turning off wind feedforward under certain circumstances, and that further work be carried out to clarify better what those circumstances are.

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