Voyage Optimization Versus Weather Routing

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Introduction

Many ship weather routing service providers in the market claim the ability to save fuel and increase safety and schedule reliability. Yet ships using these services still flounder, and hundreds of lives and over 5000 containers are lost overboard every year. P&I Club reported container total losses have increased one third over 2006 and 2007, and serious partial losses have gone up 270% in the last decade. A major survey conducted by Maritime Economics and Logistics in 2007 revealed that over 40% of the vessels deployed on worldwide liner services arrived one or more days behind schedule.

With exaggerated capabilities and unsubstantiated benefits advertised by weather routing companies, ship charterers and owners often face the difficult task of selecting the right service provider and level of technology suitable for their operations. Anticipating high fuel prices in years to come and the recent emphasis on reducing greenhouse gas (GHG) emission have resulted in renewed interests for further optimizing ship performance. A recent IMO study (MEPC58/INF.21) indicated that while weather routing can achieve 2-4% reduction in fuel consumption and associated GHG emission, as much as 50% improvement can be achieved through technical and operational measures such as speed management and fleet planning.

Any such improvements have to take into account the ship performance characteristics in the ocean environment caused by changing weather in order to optimize a voyage. Now is the time to review the state-of-art of weather routing and to discuss the current technologies for voyage optimization as the logical progression toward increasing safety and efficiency of marine transportation as well as protecting the environment.

All Weather Routing Services Are Not Equal

Traditional shore-based weather routing services and some of the onboard weather routing programs operate on the principle of “storm avoidance”. A typical system allows the user to plan a route using a set of generic speed reduction curves (% speed reduction as a function of wave height in head, beam and following seas) to dead reckon ship positions to avoid storms as depicted by the lows on surface pressure charts. After trying out several candidate routes, the recommended route is sent in a brief email/telex to the ship requesting the service, with updates when workload permits or are requested by the ship. The fuel consumption is estimated based on tons per day and number of days to arrive.

Furthermore, such cursory route advisories often do not take into account navigation hazards and shipping lanes. The user has to manually modify the route on ECDIS or nautical charts to ensure safe navigation.

More than 50% of weather routing services are ordered by charterers to monitor their chartered vessel for speed claims. As a result, there are a few “good enough” weather routing companies with minimal technology to perform post voyage analysis. Vessel response to wind and waves is of little concern. The criteria for routing and charter party speed claims are still based on Beaufort Wind Force Scale invented in the 1800s, regardless of the size of the ship and loading condition reacting to varying forecast wave height period and direction. Consequently, fuel saving is “hit and miss” when weather routing can lead to unnecessary diversions (i.e. longer distance route) to avoid bad weather.

Jeppesen Marine, a Boeing company, has launched the Vessel and Voyage Optimization Service (VVOS) to overcome many shortcomings of traditional weather routing methods. This article will discuss the effect of key issues in voyage optimization. Figure 1 shows a route generated by VVOS plotted on a nautical chart using the C-Map CM93 database.

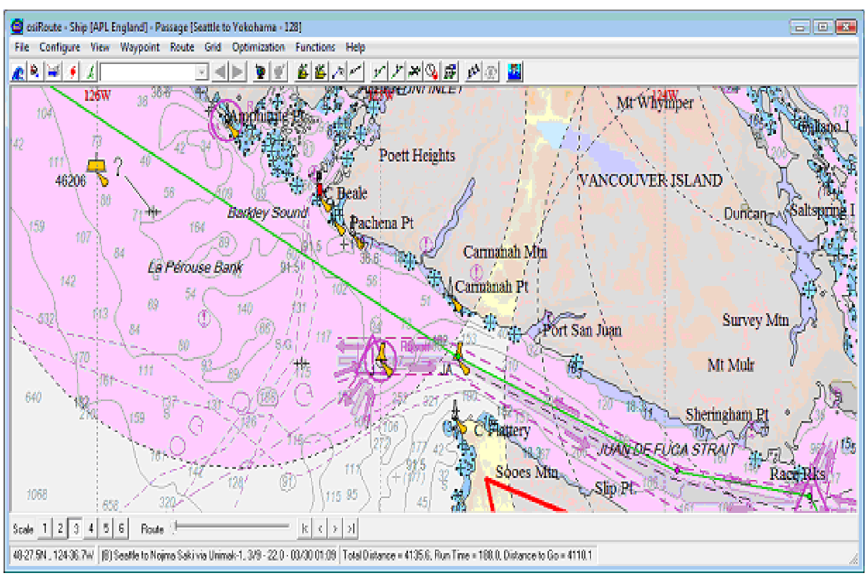

Figure 1. Route plotted on a navigation chart using C-Map CM93

Weather Routing Does Not Take Into Account Ship Responses

A ship slows down due to one of two reasons: involuntary speed reduction due to increased resistance from the onset of wind and waves, and voluntary speed reduction due to navigation hazards or fear of heavy weather damage resulting from excessive ship motion, propeller racing, slamming or boarding seas. The weather routing advisory service must take both of these into account when estimating dead-reckoned ship positions in relation to the movement of weather systems. Otherwise, the best route perceived by the unknowing planner could lead to a dangerous situation. One example is the famous M.V. Derbyshire incident. Would the master still have taken the action to outrun Typhoon Orchid if he had known that his vessel would be slowed down due to severe motions caused by advancing waves ahead of the eye of the storm? In the case of M.V. APL China, how can one responsibly recommend a route if the weather routing software can not predict the risk of excessive accelerations due to Parametric Roll along that route? More importantly, if the ship speed cannot be accurately predicted using the simplistic speed reduction curves, can the weather routing advisory be trusted since the dead-reckoned future positions in relation to the forecast storm tract may be wrong?

It is reassuring that some of the weather routing companies have started to realize the limitations of their methods and are trying to develop ship response prediction capabilities. Ship motion theory has been around for decades. To predict ship motions, slamming and boarding waves, the first step is to digitize the ship’s body plan, bilge keels and other appendages as well as calculate its weight distributions. A sophisticated hydrodynamic program then computes added mass and damping coefficients and solves the equation for motion. The results are the so-called Response Amplitude Operators (RAO), which are then combined with forecast wave spectra to predict ship responses. Only during the last few years, such sophisticated tools can be part of the onboard software to provide seakeeping guidance and safe operating limits for ship routing. Figure 2 is an example of a polar diagram that shows the speed and heading combinations that will exceed the safe operating limits (red areas) in forecast wave conditions, providing the officer on watch immediate guidance in setting the speed and heading to stay within safe operating limits. Figure 3 shows the plot of wave-induced bending moments and shear forces at critical frames for ± 90 degree heading changes from the current ship course.

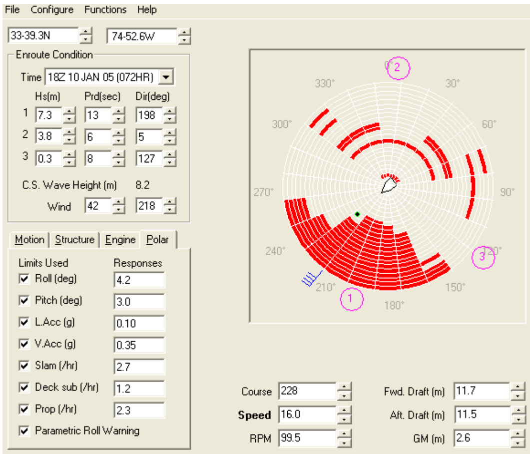

Figure 2. Polar Diagram shows Safe Operating Speed and heading. (VVOS)

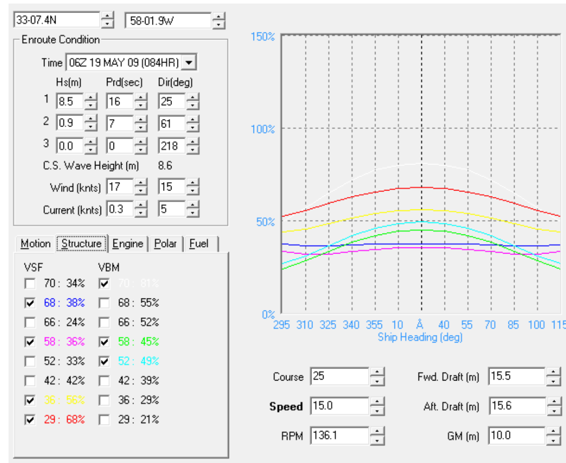

Figure3. Effect of changing ship heading on wave induced BM and SF from VVOS

Since response characteristics can be vastly different for different loading conditions, the computation must be carried out for the ship's current draft and metacentric height (GM). Shortcuts such as pre-computed RAOs or Warning of Resonance using empirical approaches may lead to dangerous situations and/or unnecessary route diversion. More importantly, such approaches cannot predict Parametric Roll, which occurs when roll and pitch periods have certain ratios, and the ship's flare immerses in waves.

Weather Routing Does Not Take *into* Account Engine Overload

The competitive nature of the shipbuilding industry and marine classification societies has resulted in reduced design safety margins in ship structures. Shipyards use sophisticated finite element models and high tensile steels to reduce steel weight and production costs in order to be competitive. Similarly, the propulsion systems are often optimized for calm weather trial conditions. One such design consequence for slow speed diesel engines with direct-drive fixed-pitch propellers is high pitch coupled with minimum acceptable sea margin. With calm weather and a clean hull lightly loaded, the vessel easily makes the contracted speed. Unfortunately, such practice leads to frequent engine overload when the ship is in service encountering high wind/seas and/or as its hull/propeller starts to get rough.

Again, if such events cannot be predicted by the weather routing tools, it can lead to over-predicted ship speed and wrong diversion decisions when facing heavy weather, not to mention inaccurate estimates of fuel consumption and time of arrival.

All Optimization Algorithms Are Not Equal

There has been substantial research over the years in the area of ship routing algorithms. Most of the weather routing software uses variations of the Dijkstra Algorithm, in which the program simulates a vessel departing with full power toward the arrival port with different headings. After each time interval (e.g. 6 hours), the ship's dead-reckoned position forms a so-called "isochrones" until it arrives at the destination. (see Figure 4) A route is then traced back from the earliest arrival time, and fuel consumption is estimated using a tons-per-day rate. The claim is that minimum time results in minimum fuel consumption. The solution is fast, especially when only using speed reduction curves and not taking into account ship responses or engine overload.

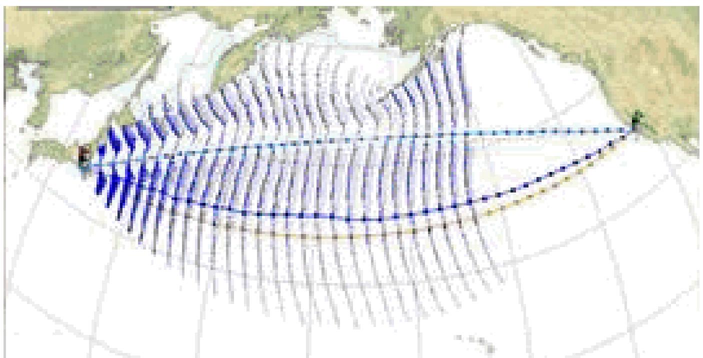

Figure 4. Example of Isochrones generated by SPOS

Unfortunately, the problem with such an approach is the algorithm ignores one important option: speed management. As storms move across the ocean, it is possible for the ship to slow down and let them pass and then catch up, instead of sailing a longer distance to go around or "hove-to" in bad weather. Such strategy not only significantly reduces fuel consumption for a given arrival time, it also reduces the risk of heavy weather damage when fully implemented with ship response and engine overload.

Since speed and heading are both introduced into the route optimization, the problem becomes multi-dimensional. An algorithm called Dynamic Programming can be utilized to minimize fuel consumption for a range of arrival times subjected to the constraints of safe operating limits imposed by the captain. The optimization is performed on a user-defined grid for safe navigation. Figure 5 shows an example of estimated arrival times versus predicted fuel consumption over a grid of possible routes. (The green pointer indicates the scheduled arrival time)

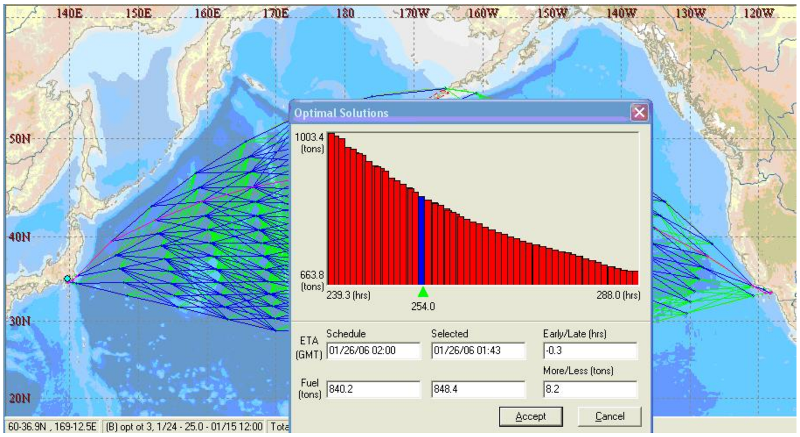

Figure 5. Optimization using Dynamic Programming in VVOS

The computation effort is obviously greater since the algorithm must evaluate thousands of speed and heading options compared with hundreds in the case of heading-only weather routing. With computer processor speeds doubling every year, the time to solve the problem is reduced from several hours to a few minutes, including the full implementation of ship responses and engine overload. Such systems can be implemented at routing centers shore-side, or onboard ships with daily updates of forecast environmental conditions via satellite communication.

A more recent approach advertised by some weather routing companies is to use the so-called “genetic-evolutionary algorithms”. In essence, such algorithms start a feasible solution and then improve it through mutating waypoints and speed combinations. The “survival of the fittest” of the routes will continue to evolve to build the so-called Pareto Fronts across the ocean until the arrival port is reached. The algorithm can go on for a long time and one is never assured that it reaches the optimum. It can be stopped when the rate of improvement becomes marginal after each iteration.

The advantage of such algorithms is that they can handle multiple-objectives such as minimum fuel consumption, arrival time, and heavy weather damage in a probabilistic sense. However, since the ship captain is the ultimate decision maker in selecting the route, presenting such information in a practical way to show relative risks between routes is a major challenge when faced with uncertainties in long range weather forecasts

All Weather Forecasts Are Not Equal

The advent of Super Computers and numerical models has significantly improved the accuracy of weather forecasts over the past decade. National centers such as NCEP/NOAA, US Navy, UKMET, JMA and ECWFM are routinely producing long range wind and wave forecasts out 10 days and beyond. However, the accuracy of each model varies due to model resolutions, how the physics are implemented, initial conditions from observations as input at the cut-off time, as well as many other factors. Forecasters tend to calibrate their models to perform better when storms threaten their own countries, but pay less attention to mid-ocean storms passing shipping lanes.

None of the models can produce accurate forecasts for tropical cyclones due to their complex physics and rapid development. Human forecasters are employed during the typhoon/hurricane seasons to issue track and intensity forecasts based on consensus of model outputs as well as past experience. In any case, accuracy starts to deteriorate after 3-5 days, leading to even larger uncertainties between 5-10 days.

Most of the weather routing service providers use products from only one forecast center. In the U.S., surface pressure, wind and sea state forecasts are available for free download over the Internet. While the quality of such forecasts may be good enough for weather routing, their level of detail is not sufficient for ship motion response prediction and voyage optimization. This is particularly true in predicting the sea and swells generated by tropical cyclones since meteorologists at typhoon/hurricane centers often issue vastly different forecasts from the model predictions.

Currently, the best approach to ocean weather forecasts is to adopt a “man-machine” mix, in which experienced forecasters quality-controls the sea surface pressure forecasts including the wind fields derived from the track and intensity forecasts from various forecast centers. This forms the input to a marine boundary layer wind model and the output drives a numerical wave directional spectra model. This “Super Ensemble” forecast approach takes the best of each national center forecast and quantifies the uncertainties in wind and waves. At each grid point in every forecast horizon extending to 10 days, the values for minimum, most likely and maximum can be used to judge the accuracy levels of the forecast. The spread between min and max typically is smaller in shorter range forecasts as various models are more in agreement. The spread will increase as the forecast horizon increases and the accuracy of the forecast models differ. This type of consensus knowledge will provide greater insight in selecting the optimum route taking into account the risk of heavy weather damage.

Besides the more accurate wind and wave forecasts, voyage optimization should also take into account sea surface currents since they can significantly impact ship speed and fuel consumption. High resolution global circulation models enhanced by satellite measurements can now produce accurate depictions of major currents and eddies daily. Figure 6 shows examples of current maps. The 1/32-degree resolution allows the locations of Kuroshio and Loop currents to be clearly identified. The speed and direction at every grid point are used in Jeppesen's VVOS voyage optimization algorithm.

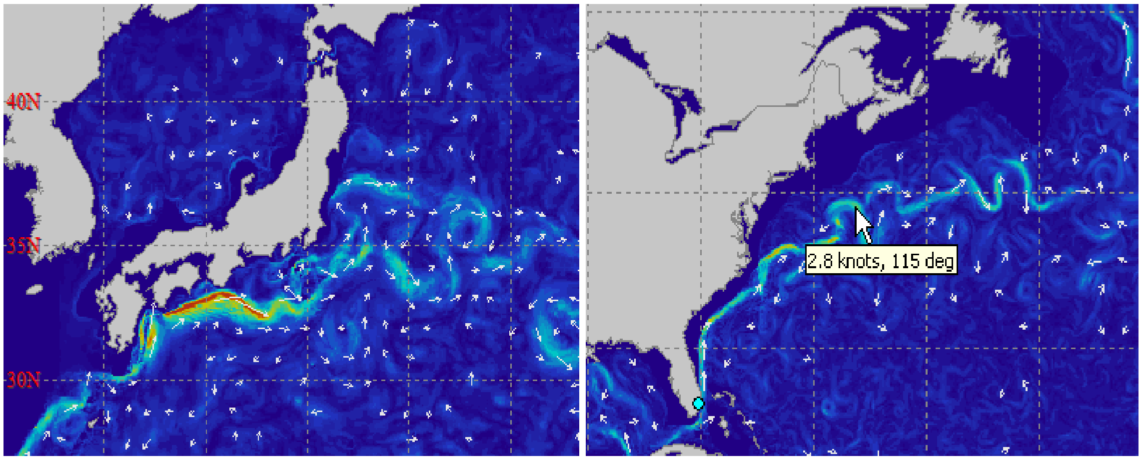

Figure 6 Plot of Kuroshio and Loop currents from Jeppesen's VVOS

Benefit of Voyage optimization

It is clear that past decades of "hit and miss" weather routing approaches can be much improved with today's technology. Accurate ship seakeeping performance models can help ship masters in making better route decisions that save fuel and avoid heavy weather damage. Benefits of voyage optimization can be further extended to the ship design, deployment and operation logistics. Here are some examples:

- Determine ship design criteria such as speed, sea margin, maximum ship motion and bending moment by repeatly simulating the voyages using historic wind and wave hindcast databases.
- Optimize the deployment and schedule of vessels for the trade route taking into consideration schedule reliability, fuel cost and seakeeping quality.
- Estimate the probability of on-time arrival so shore-side operations such as loading/unloading truck and trains can be efficiently scheduled
- Extend the fatigue life of ship structures by predicting stress cycles and providing ship officers with seakeeping guidance to reduce ship stresses.

Without a doubt, significant benefits in saving energy as well as GHG can be achieved through technical and operational measures as expressed by the IMO study. The Art of Weather Routing needs to evolve into the Science of Voyage Optimization in order to bring added benefits in ship design and operational logistics. To achieve such benefits, the key ingredients are:

- Quality-controlled ocean wind and wave predictions with additional Super Ensemble forecasts

- High-resolution tidal currents and global circulation currents
- State-of-the-art full ship motion modeling for actual drafts, GM and loading conditions during the voyage
- A powerful optimization algorithm to find the optimum route with minimum fuel consumption for a desired arrival time while not exceeding the safe operating limits.
- Global wind and wave hindcast database for voyage simulations to establish benchmarks for voyage efficiency and CO_2 index
- A method for estimating the probability of on-time arrival taking into account weather forecast uncertainties and ship capabilities.
- Computer-based training to transfer the scientific knowledge to aid operations decision
- Shore-based support centers to assist ships at sea at any time.

Ship operators and owners should be made aware that voyage optimization will result not only in very high Return On Investment (ROI) through increased operating safety and efficiency, but also in the benefit of being proactive in reducing GHG to protect the environment.