Decision Support for Avoiding Roll Resonance and Wave Impact for Ship Operation in Heavy Seas

Knud Benedict

Prof. Dr.-Ing.
Wismar University of Technology, Business and Design, Dept. of Maritime Studies, Germany
Richard-Wagner-Str. 31, 18119 Rostock-Warnemuende, Germany
Email: k.benedict@sf.hs-wismar.de
Tel: +493814985891

Matthias Kirchhoff

Dipl.-Ing.
Wismar University of Technology, Business and Design, Dept. of Maritime Studies, Germany
Richard-Wagner-Str. 31, 18119 Rostock-Warnemuende, Germany
matthias.kirchhoff@sf.hs-wismar.de
+493814985827

Michael Baldauf

Dr.-Ing.
Wismar University of Technology, Business and Design, Dept. of Maritime Studies, Germany
Richard-Wagner-Str. 31, 18119 Rostock-Warnemuende, Germany
m.baldauf@sf.hs-wismar.de
+493814985844

Abstract There have been several instances of ships being badly damaged due to heavy rolling motion in sea state, which clearly shows the need for a method to estimate the potential danger in order to support the work of the ships' officers. In the paper a simplified but robust method is shown for the on-board calculation, based on the comparison of the ships natural rolling period and the period of wave encounter to prepare a polar diagram for synchronous and parametric resonance and other wave effects from basic data of the ship and the sea state, even by manual calculation. It is also possible to include the potential danger of high wave group encounter or Surf-riding and broaching respectively.

A computer program ARROW–Avoidance of Roll Resonance and Wave impact was developed to display the potential dangerous conditions of rolling resonances or other high wave impacts on ships due to specific wave encounter situations. The tool allows

for quick variation of the relevant parameters and was implemented as a module into a ship weather routing program.

0 Introduction

Over the last few years several vessels have experienced the dangerous effects of rolling resonance. Investigations have shown that these effects are based on phenomena known as synchronous and parametric roll resonance[1, 2]. Moreover, there can be additional dangers by reduction of intact stability caused by riding on the wave crest on successive high wave attacks or dangers of surf-riding and broaching in following seas. The phenomena described in Table 1 can occur when a ship is affected by high sea state, either separately or combined.

Table 1 Overview on dangerous phenomena in high sea state, occurrence and effects

Phenomena	Occurrence		Effect
	Direction	Periods/Encounter	
1. Synchronous rolling motion	All directions possible	Natural rolling period of a ship coincides with the encounter wave period.	Heavy oscillations with high amplitude
2. Parametric rolling motion	Specifically for head and stern wave conditions	Wave encounter period is approximately equal to half of the natural roll period of the ship	Heavy oscillations with high amplitude
3. Reduction of stability riding on the wave crests of high wave groups	Following and quartering seas	Wave length larger than 0.8 x ship length and significant wave height is larger than 0.04 x ship length	Large roll angle and capsizing
4. Surf-riding and broaching-to	Following and quartering seas	The critical wave speed is considered to be about 1.8√L~3.0√L with respect to ships' length	Course deviation and capsizing

Over the last decade there have been many investigations and recommendations into this phenomena and publications can be found on how to calculate some of these effects but either they do not cover all the effects which are mentioned above or they were not designed to support the ship's crew in order to give effective guidance for the operation of ships. The IMO 1995 has published guidelines to the master for avoiding dangerous situations in following and quartering seas to be aware of several effects due to sea state [3, 4]. In 2003 a draft of a new German guideline for stability on board ships was published[7] and some of its aspects were given to the IMO where a review of the IMO guideline is currently taking place [5, 8]. Summarizing all these methods, the current methods are lacking a simplified, user friendly approach for the calculation of the effects,

necessary for education and training, for use on board and an overall approach for presentation of all effects in one diagram related to the actual ship and wave conditions.

This paper describes briefly how to effectively find out the potentially dangerous situations. Simplified calculation methods are given which were developed to manually calculate a polar diagram presentation e.g. on RADAR Plotting Sheets. The software program ARROW will be described as a tool to estimate and display the potential dangerous conditions of rolling resonances or high wave impacts on ships due to complex wave encounter situations e.g. for long range voyage planning in co-operation with a weather routing program.

1   Description of effects and methods

1.1   Ships' motion and ship natural rolling periods

The ships' motion can be generally subdivided into 6 degrees of freedom. For the problems handled within this paper we will mainly focus on rolling motion and the surge/sway and yawing motion for the surf riding and broaching. To calculate the rolling period Tr of a ship one can apply the so called WEISS–Formula. For small roll angles up to $\Phi \approx 5$ or even to $\Phi \approx 10°$ it reveals:

$$Tr(10°) = \frac{Cr \cdot B}{\sqrt{GM}}$$

where:

GM–Initial stability, metacentric height (m), B–ship's beam (m); Lpp–length (m)

Cr–the inertia coefficient for rolling motion, e.g. according to IMO–Guidelines as to $Cr = 2*c$ with

$c = 0.373 + 0.023(B/d)–0.043(Lpp/100)$ with d–draft(m).

For large roll angle amplitudes up to $\Phi \approx 40°$ or more the roll period can change, compared to the period $Tr(10°)$ for small angles. The magnitude of the difference is according to the type of the stability curve. There are three types of curves:

Strong over-proportional increase of the up-righting lever, compared to the tangent according to GM indicated by the dotted line in Fig. 4, i.e. $Tr(10°) > Tr(40°)$, as it can be seen from the values for Tr(10°) and $Tr(40°)$ in that Fig. (left part),

Nearly linear gradient up to the maximum, proportional to the tangent according to GM (i.e. $Tr(10°) = Tr(40°)$),

Strong under-proportional decreased curve, i.e. $Tr(10°) < Tr(40°)$.

To calculate the rolling period $Tr(40°)$ for rolling angles Φ up to 40° a formula can be used (according [6, 9]).

1.2   Sea state and encounter period to waves

The sea state is approximated by a regular wave system with one characteristic direction, average

wave height, described by average wave period *Tw*, wave length Lw and wave speed *Cw*. The wave period *Tw* is the period a fixed observer would time between the passing of two consecutive wave crests or two consecutive wave troughs. The wave period directly corresponds to the wavelength *Lw*. The following relation holds between the wave length and wave speed for harmonic waves:

$$Lw = k \cdot Tw? \quad and \quad Cw = k \cdot Tw$$

where:

k denotes the coefficient for the wave system (wave number), which is according to the types of wave systems (*k* = 1.56 for full developed swell, long crested; *k* = 1.3 for heavy seas not fully developed in intermediate conditions; *k* = 1.04 for wind sea, short crested with new developing sea waves).

Lw: wavelength (m); *Tw*: wave period (s); *Cw*: Wave speed / celerity (m/s)

The encounter situation between ship and waves is very important for the wave impact: The ship will be forced into oscillation exited by the encounter period *TE* between ship and sea. For general encounter situation the encounter period *TE* can be calculated as to:

$$TE = \frac{k \cdot Tw?}{k \cdot Tw + 0{,}514 \cdot V \cdot \cos\gamma}$$

With:

V–ship's speed vector[kn] and component *V* * cos (*γ*)–For conditions where the ship is overtaking the waves the wave speed has to be considered as negative

γ– encounter angle (*γ*=0° for head sea; *γ*=180° for following sea)

Generally for a given encounter period TE and wave period the speed can be calculated to:

$$V_{TE} = \frac{k \cdot T_w}{0{,}514 \cdot \cos\gamma} \cdot \left(\frac{T_w}{T_E} - 1 \right)$$

1.3   Conditions for synchronous and parametric rolling resonance

Resonance develops when the ship's natural rolling period coincides with the excitation period of the waves (the encounter period). The rolling amplitudes of the ship may be stimulated depending on the ratio between the ships' natural rolling period *Tr* and encounter period *TE*. There are two significant types of resonance:

Synchronous resonance occurs when the ships' natural period Tr and the encounter period TE have nearly the same value. There is Direct Resonance at *Tr = TE* or *Tr / TE* = 1.0 where the maximum amplitudes are to be expected and in the range 0.8 ≤ *Tr / TE* ≤ 1.1 where still up to about 50% higher amplitudes occur. In the resulting polar diagram (Fig. 1) synchronous resonance conditions are to be seen as red stripes whereas specifically the Direct Resonance condition is

represented as a line (also seen in Fig. 3) nearly in the middle of the stripes and the conditions for 50% lower amplitudes are at the outer border lines.

<u>Parametric Resonance</u> occurs specifically in head or stern seas when the ships natural period T and the encounter period TE have nearly double or half values. There is Direct Parametric Rolling Resonance: for $Tr = 2 * TE$ or $Tr / TE = 2.0$; and range $1.8 \leq Tr / TE \leq 2.1$ with still up to 50% higher amplitudes. In the resulting polar diagram (Fig. 1) they are to be seen as red sector segments in head or stern seas where the Direct Resonance conditions are represented as a line (seen also in Fig. 3) nearly in the middle of the segment and the conditions for 50% lower amplitudes are at the outer border lines. These conditions are represented in the polar diagram as sector segments +/– 30° off the wave direction. This type of rolling can occur in head and bow seas where the wave encounter period is exiting the ship preferably by the effects due to the stability change when on wave crest or in wave trough. Therefore the excitation is high specifically for those types of vessels with large stability differences at the respective wave positions as for instance modern container vessels with a "pontoon" stern shape and tremendous bow flare.

Fig. 1 Resulting Polar diagram with dangerous course and speed vectors based on the example ship and calculated with the respective formulas from Table 2 indicated by coloured circles. (Example-Ship: L_{pp}=113m, B = 17.6m; rolling coefficient $Cr = 0.74$; i.e. $Tr=Tr(10°)= 10$ s; Sea from 23° with $Tw= 8$ s in Wind sea (k=1.04)
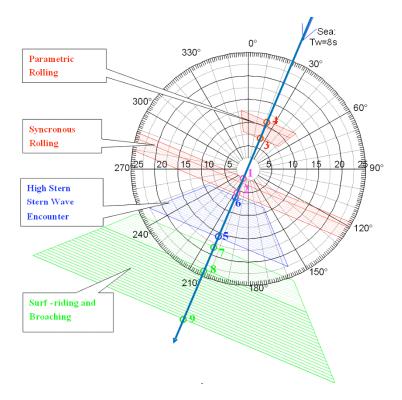

Fig. 2   Resulting Polar diagram

1.4   Dangerous stern wave encouter

During high wave groups' encounter and when a ship is riding on the wave crest, the intact stability will be decreased substantially according to the ship shape. The amount of stability

reduction is nearly proportional to the wave height and the ship may lose the stability when the wave length is one to two times of ship length and wave height is large. This situation is especially dangerous in following and quartering seas, because the duration of riding on wave crest, i.e. the time of inferior stability, becomes longer. Besides the danger of reduction of stability when the ship is riding on the wave crest for a long time there is also an exciting effect of waves in Head /Stern Sea when the waves are travelling along the ships hull periodically–this will yield potential for parametric rolling. This leads to extreme dangerous situation when several high waves will trigger the ship coming as a group.

The IMO 1995 has given in the guidelines a diagram highlighting the potential occurrence of high wave group encounters; however, the information is given in a dimensionless format only by a ratio of ships speed V and wave period Tw. Here the new polar presentation can have its benefit by relating the data to the current values of ships speed and wave period / direction with the potential of High wave group encounter as for example is given in Fig. 1: The segment for direct following and quartering seas+/-45° is shown as blue dot and dash area.

1.5　Surf-riding and broaching-to

Surf-riding and broaching occurs if the ship speed is so high that its component in the wave direction approaches to the phase velocity of waves. Then the ship will be accelerated to reach surf-riding and broaching condition. That means the ships will be lifted by a following wave at the stern and accelerated; if then the ship is affected by small course change a yawing/ swaying motion can occur followed by large heel angels up to capsizing. The critical speed for the occurrence of surf-riding considered to be $1.8\sqrt{L}$ (kn), where L is ship length. It should be noted that there is a marginal zone ($1.4\sqrt{L} \sim 1.8\sqrt{L}$) below the critical speed. Here a new polar diagram can have its benefit by relating the data to the current values of ships speed and length as well as wave direction. For the example in Fig. 1 the potential of surf riding / broaching-to for direct following and quartering seas is given for the green segment in the lower part of the Fig..

1.6　Summary of effects and formulas

The method presented here briefly (a complete description is published in[9]) allows for calculating and plotting a polar diagram for ship operation in a very simplified way as indicated in Fig. 1 and with formulas given in Table 2. Using a Radar Plotting sheet (with speed values at the axis instead of distances) the only task is to draw a line in the direction of the wave propagation and to calculate the encounter speed values *V* (indicated by small circles and numbered according to the numbers of the formulas in Table 2) on courses with direct head sea (*V* positive) or following sea (*V* negative). The Table 2 summarizes the effects and formulas for calculating the circles with the respective numbers of the formula in the table.

Table 2　Summary of effects and formulas for calculation of basic polar diagram values

Phenomena	Direction / Sector/Area	Equations to Calculate the speed values as basis for the Diagram Elements (numbers acc. to circles in Fig. 1)	
1.　Synchronous rolling motion	Stripe segments over diagram; All directions	1. for TE=Tr/0.8:	2. for TE=Tr/1.1:

	possible	$V_{0.8} = \dfrac{k \cdot Tw}{0.514} \cdot \left(\dfrac{Tw}{Tr/0.8} - 1 \right)$	$V_{1.1} = \dfrac{k \cdot Tw}{0.514} \cdot \left(\dfrac{Tw}{Tr/1.1} - 1 \right)$
2. Parametric rolling motion	Segment for direct head and stern wave conditions +/-30°	3. for TE=Tr/1.8: $V_{1.8} = \dfrac{k \cdot Tw}{0.514} \cdot \left(\dfrac{Tw}{Tr/1.8} - 1 \right)$	4. for TE=Tr/2.1: $V_{2.1} = \dfrac{k \cdot Tw}{0.514} \cdot \left(\dfrac{Tw}{Tr/2.1} - 1 \right)$
3. Reduction of stability riding on the crest in wave groups	Segment for direct Following and quartering seas +/-45°	5. $V\_DWaveGr_{0.8} = -0.8 * T_w$ 6. $V\_DWaveGr_{2.0} = -2.0 * T_w$	
4. Surf-riding and broaching-to	Segment for direct Following and quartering seas +/-45°	7. $Vsurf\,1.4 = -1.4 * \sqrt{L_{pp}}$ (marginale Zone) 8. $Vsurf\,1.8 = -1.8 * \sqrt{L_{pp}}$ 9. $Vsurf\,3.0 = -3.0 * \sqrt{L_{pp}}$	

The results will be used to draw specific shapes of areas with potential danger in a Polar Diagram taking the speed values (in the circles) as a basis for the diagram elements:

A synchronous resonance area will be drawn as a red stripe over the whole angle area of the polar diagram, orthogonal to the sea direction. The parametric excitation will be drawn in the same way but only for a red sector segment of ±30° around the direction of stern sea or against the sea respectively. Additionally the areas for surf-riding (green) and encounter of wave groups (blue) in zones of ±45° around stern sea directions will be drawn.

By means of the polar diagram an assessment of situation or estimation of countermeasures can easily be done to find out suitable values of the ships' speed and course or measures to change stability and likewise the ships roll time period T avoid resonance–either by means of that diagram manually created as in Fig. 1 or more convenient by using the computer software ARROW described in the following chapter.

2 Arrow–Software Program

2.1 Overview

The ARROW program is a software tool to estimate and display the potential conditions and countermeasures to Avoid Rolling Resonances Or Wave impacts on ships due to specific wave encounter situations. By means of the Main user interfaces (Fig. 3) the a small amount of data is needed to be entered into the areas of the Ship Parameter Input (top left side) and Wave Parameter Input (lower left side) to provide the qualitative results in the Result Display Area (right hand side):
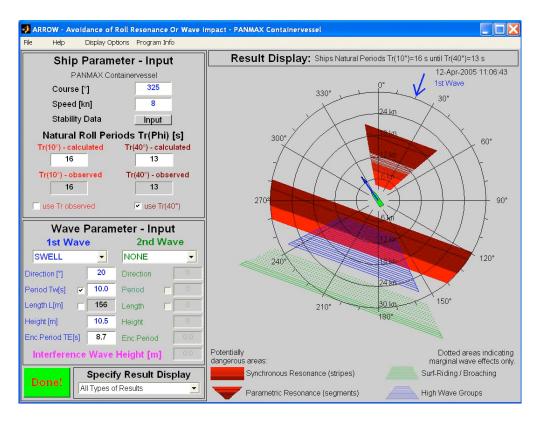
Fig. 3   ARROW program window–overview on main user interface elements

2.2   Parameter input

Ships course and speed can be entered in the respective data fields. The heading direction of the ships contour and speed vector in the Result Display will immediately change according to changes in the data fields. Alternatively these values can be set by mouse click (right button) into the ARROW－Result Display Area.

Natural Roll periods of the ship can be either calculated (a) by using stability data or alternatively (b) by entering observed roll periods directly:

(a) Using Stability Data Input the data can be entered into the respective input fields of ARROW －Stability Data Window. The input of these Stability Data can be checked in the plot of the *GM* and *GZ_* values versus roll angle (Fig. 4 left). To compare the *GZ_*-values with the initial stability *GM* a tangent is drawn (dotted line) from 0 to the *GM* value at roll angle *Phi* = 57.3°. The ships' natural roll periods *Tr* will be immediately calculated and shown in the left side of the ship parameter input area (s.Fig. 3) parallel to the stability data input. The *Tr* values are displayed both for small (up to 10°) and large (up to 40°) roll angles. Corresponding to the draft input the inertia coefficient *Cr* for rolling motion is shown (s. Fig. 4 right) in the field below the draft input field from the ships hydrostatic tables.

(b) Using Alternatively the Direct Input of Natural roll period from Observations it is possible to use ob-served ships roll periods instead-for this purpose a checkbox is available to change between "calculated" and "observed" roll periods. In this case the respective *Cr* value is highlighted according to the *GM* value.

Fig. 4 Stability Data Window–Graph of up righting lever versus roll angle *Phi* and *GM* tangent (left) and Graph of Inertia coefficient *Cr* and respective *Cr* value due to draft input (right).

For Wave Parameter Input the ARROW program accepts the input of two different wave systems. The 1st Wave area (left side) is designated for the input of the dominant wave system interacting with the ship. Only a few wave input parameters, taken either from observations on the ship or from weather reports and forecasts, have to be entered in the respective fields. The input for the 2nd Wave system is identical to the 1st Wave. The direction of the first wave system is drawn as a blue arrow outside of the polar diagram in the ARROW－Display Area (s. Fig. 3), the second system as green arrow. Another arrow shows the direction of the interference wave.
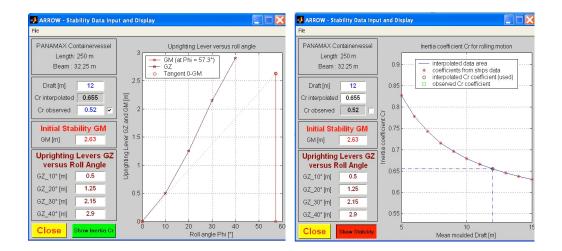

Fig. 4　Stability Data Window

2.3　Result display area and measures to avoid problems due to wave effects

The polar diagram provides the critical course and speed ranges resulting in resonance areas by stripes and sectors of high wave impact according to IMO guidelines. All types of resonance and wave impacts are drawn with different colours and shapes to distinguish between them. Even for large amplitude rolling periods the potential resonance conditions can be shown in brown colour next to the red areas for small rolling amplitudes displayed in parallel. Beneath the polar diagram a legend is drawn to clarify the relation of the different colours and shapes with respect to the different types of resonance and wave impacts. If the point of the ships' arrow (ships speed vector) is within one (or even more) of the dangerous areas the ships conditions are potentially unsafe. In this case the ships speed and course have to be changed to bring the arrow top out of those areas. Alternatively the ships rolling period could be varied by changing the stability parameters (*GM* or *GZ*_values) in order to avoid resonances as shown in Fig. 5. All of these countermeasures can be checked by trial variations using the ARROW program modules.

Fig. 5 Shifted resonance areas after changes of rolling period due to change of *GM*: Results for *Tr*(10°)=11.3 s *GM*= 1.32 m (left) and for *Tr*(10°)=8.24 s *GM*= 2.50 m (right)
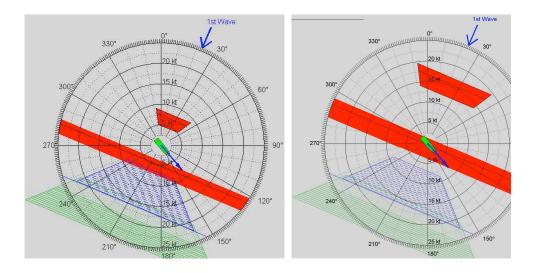
Fig. 5   Shifted resonance areas after changes of rolling period due to change of GM

3   ARROW: Versions and USE

3.1   Training institute version

There are two version of the ARROW software in existence. One is for Education and lecturing of Wave Effects at Seafaring Training Institutions. For this reason several different vessels and encounter situations can be prepared and loaded for demonstrations according to the specific training needs. An encounter situation consist of ship information on speed, course and own rolling period and of wave information (direction, period, height) of two wave systems. Fig. 6 show the procedure of loading an encounter situation from a list of several different situations.

After selecting a situation the data will be loaded and a previously stored comment will be shown explaining the encounter situation.
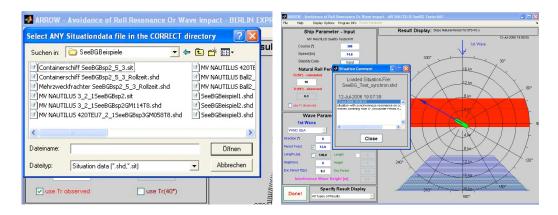

Fig. 6   Procedure to selection of different stored encounter situations for education

3.2   Use of arrow software together with ships routing program "bon voyage"

The second version of the ARROW software is the onboard version. The basic version is specifically designed and database adjusted to quickly calculate and display all wave effects for

one specific vessel. A permanent storage of a special wave encounter situation is possible. The enhanced version of the ARROW software establishes a link to an onboard weather routing system (see Fig. 7).

When using the onboard routing system Bon Voyage from Applied Weather Technology AWT the most recently edited route can be imported (top menu: "Route Database/Load Route Database") and viewed in the ARROW route list table. ARROW will instantly analyse the route points of this route in terms of the formerly described risks.

The status of a route point can be viewed (see Fig. 7) in both, the ARROW route list table and the Result Display / Wave Parameter-Input section:

If any line in the ARROW route list table has been highlighted red then there is a potential risk, if orange then a marginal risk may have been left.

By clicking on the corresponding line in the ARROW route list table (e.g. middle row of table left below) the ARROW main interfaces pops up to display the respective situation highlighting potential dangerous conditions and allows the check whether the ships' speed vector is within or out of these conditions (top left of Fig. 7).

Fig. 7 Use of ARROW program together with onboard routing system "Bon Voyage" (AWT): Sea chart with weather information along the planned route on rhumb line (right) and ship with rolling period Tr=18.2 s at a specific position (Triangle), ARROW main interface (top left) with information for that respective position/situation, ARROW route list table (left below) with information overview for all waypoints.

In order to avoid potential resonance conditions, either the ships natural rolling period could

be adjusted by GM corrections in the ARROW interface (see Fig.8). Or the route can be changed

in the Bon Voyage system (course or speed respectively, see Fig.8 GM corrections in the

ARROW interface

Fig.).

Both options can be used to find suitable conditions by simple trail and error methods.

Fig. 8 Use of ARROW program together with onboard routing system "Bon Voyage" (AWT): Avoiding Resonance by Changing Stability from rolling period Tr=18.2 s to Tr=22.2 s.
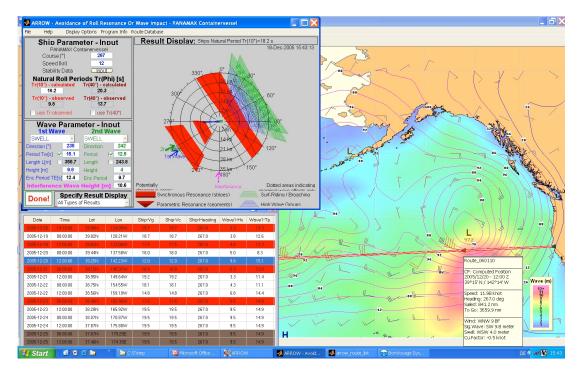
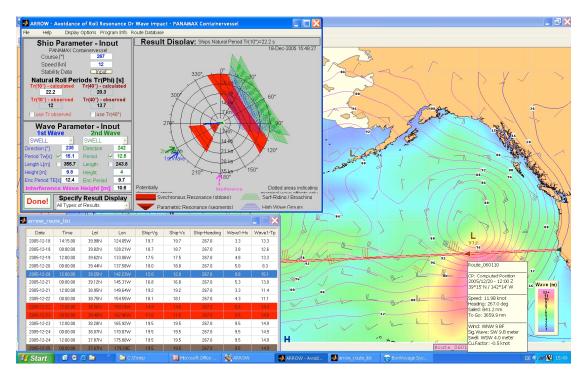Fig. 7   ARROW software establishes a link to an onboard weather routing system

Fig.8   *GM* corrections in the ARROW interface

Fig. 9 Use of ARROW program together with onboard routing system "Bon Voyage" (AWT): Avoiding Resonance due to change of the ships route by shifting of one waypoint on Rhumb line.
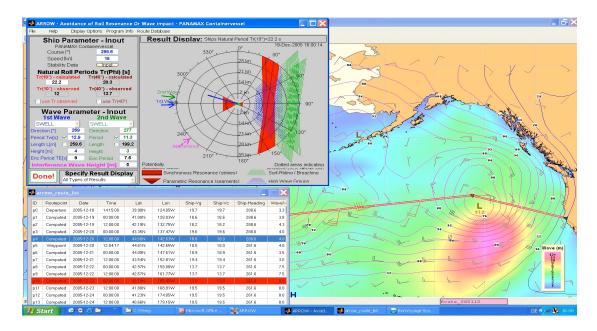
Fig.9   The route can be changed in the Bon Voyage system

4 Conclusion

In the paper a simplified but robust method is shown to estimate the potential danger of wave impact in order to support the work of the ships' officers. It is based on the comparison of the ships natural rolling period and the period of wave encounter and allows preparing a polar diagram for synchronous and parametric resonance and other wave effects from basic data of the ship and the sea state, even by manual calculation. It is also possible to include the potential danger of high wave group encounter or Surf-riding and broaching respectively.

A computer program ARROW–Avoidance of Roll Resonance and Wave impact was developed to display the potential dangerous conditions of rolling resonances or other high wave impacts on ships due to specific wave encounter situations. The tool allows for quick variation of the relevant parameters to find out safe conditions by trail and error methods and to see the tendency of changes in the parameters. The ARROW Program was implemented as a module into a ship weather routing program in order to analyse all the route points and segments in terms of the described risks and to give and overview in the ARROW route list table.

Reference

[1]   France & William a o. 2001. An Investigation of Head-Sea Parametric Rolling and its Influence on Container Lashing Systems. SNAME, Annual Meeting 2001.

[2]   Scharnow U. 1987. Ship and Manoeuvre–Seamanship Vol. 3 (in German: Schiff und Manöver-Seemannschaft Bd. 3), Berlin: Transpress.

[3]   IMO 1993. Code on Intact stability for all types of ships, Resolution. A.749 (18) Nov 1993.

[4]   IMO 1995. Guidance to the master for Avoiding Dangerous Situations in Following and Quartering Seas, MSC Circular 707, Adopted on 19. October 1995.

[5]   IMO 2005. Paper: Revision of The Code on Intact Stability, Proposed Revision of MSC/Circ.707: SLF 48/4/8, 10 June 2005 (Submitted by Germany).

[6]   Ammersdorffer R. 1998. Parametric Exited Rolling Motion in Bow and Head Seas (in German: Parametrisch Erregte Rollbewegungen in Längslaufendem Seegang). Schiff & Hafen Heft 10-12, 1998.

[7]   BMVBS/See-BG 2004−German Ministry of Transport: Guidance for Monitoring Ship's Stability. Verkehrsblatt- Document Nr. B 8011; Release 2004.

[8]   Cramer H, Krueger S. 2001. Numerical Capsizing Simulations and Consequences for ship Design, JSTG 2001, Springer.

[9]   Benedict K, Baldauf M, Kirchhoff M. 2004. Estimating Potential Danger of Roll Resonance for Ship Operation. Schifffahrtskolleg 2004, Proceedings (5): 67-93, Rostock 2004.