A New Approach to the Derivation of V-Line Criteria for a Range of Naval Vessels

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Abstract: Previous work has gone some way to understanding the applicability of the current naval V-lines standards to modern day naval designs by carrying out damaged vessel simulations using the CRN developed time-domain ship motion program FREDYN. The work presented in this paper seeks to further this understanding of V-lines by analysing the damaged motions of six vessel types, varying from a small Mine Counter Measure Vessel (MCMV) to a large auxiliary, and implementing a new methodology for the calculation of probabilistically derived dynamic motion allowances for heave and roll. Furthermore, analysis has been conducted in sea states up to a sea state 6 in order to understand the applicability of V-line criteria at greater wave heights and periods. This paper compares heave and roll allowances derived from the probability of exceeding water heights on the bulkheads bounding the damage in varying sea states for each vessel type, each with two damage cases at eight wave headings and at two speeds. Conclusions are drawn regarding the suitability of current criteria for vessels of varying size and design and their sensitivity to sea state.

Key words: V-lines, Naval Standards, FREDYN, Numerical Simulation, Time Domain Simulation, Red-Risk Lines, Damaged Stability

1. Introduction

Significant subdivision is common practice in naval ship design. These internal arrangements introduce both symmetric and asymmetric flooding when damaged. Traditional damage stability analysis using quasi-static approximations cannot predict in a seaway the head of water on a bulkhead bounding a damaged region. For many navies around the world including the UK's Royal Navy, a dynamic allowance over and above the static damage waterline is included in order to account for heave and roll in a seaway (Red Risk and V Lines).

The Red Risk and V-line criteria found in most current naval standards are based on criteria originally presented by Sarchin and Goldberg in 1962. It is recognised that more refined understanding of the criteria could be developed using the latest tools and knowledge; it is also recognised that vessel design has changed significantly since the initial development of V-line criteria.

An assessment of V-line and red risk criteria has been conducted on six distinct vessel types, from a small MCMV to a large auxiliary. Each model has been simulated in two damage cases. Static stability analysis of the two damage scenarios can be performed using standard static stability software; however, this does not take account of the vessel motions or consequential progressive flooding which can occur as the vessel moves in waves.

The use of the time domain simulation tool FREDYN (De Kat et al 2002, MARIN 2011, MARIN 2010) enables the dynamic performance of the damaged vessel to be analysed in a seaway, allowing the water heights on the bulkheads bounding the damage to be monitored in the time domain. This water height data can then be compared with the Sarchin and Goldberg static criteria in varying sea conditions to identify the applicability and limitations of these criteria to a range of modern vessel designs.

The current Sarchin and Goldberg based criteria are the foundation of the standard used by the UK MoD, defined in Defence Standard 02-900 (DefStan) and MAP 01-024. V-line requirements take the general form of the following dynamic allowances over the worst case static damaged waterline:

- A roll allowance above the static damaged list angle to account for dynamic roll motion. (Angle from upright to out)
- A heave allowance above the damaged water level to account for the ship's heave motion and the relative wave height.

Table 1 compares the current UK Naval standards with the original Sarchin and Goldberg suggested criteria:

Table 1 Sarchin and Goldberg dynamic allowance as compared to DefStan 02-900

Allowance	Sarchin and Goldberg (1962)	UK MOD and other navies (DefStan 02-900)
Angle of list	15 degrees static list assumed following asymmetric damage.	Worst case damage angle of heel (limited by 20 degree list/loll criteria).
Angle of Roll	Related to displacement as per graph in published paper.	15 degrees above static damaged angle of heel.
Heave	4 foot heave allowance.	1.5m heave allowance.

This work focused its investigation on the probability of exceedence of water heights on the bounding bulkheads of the damage region and compares the results with the current V-line criteria requirements. Using the probability of exceedance data and an acceptable probability of exceedence associated with naval standards, it is possible to evaluate both heave and roll values for comparison with current criteria.

2. Modelling Approach

The six vessels were categorised into combatant and non-combatants with three generic designs produced for each category. The six vessel types modelled were:

- Combatant 1 – Destroyer
- Combatant 2 – Mine Counter Measure Vessel (MCMV)
- Combatant 3 – Offshore Patrol Vessel (OPV)
- Non-combatant 1 – Small auxiliary
- Non-combatant 2 – Large auxiliary
- Non-combatant 3 – Tanker

The models were created in the software package Paramarine with indicative hull form coefficients and internal subdivision in order to create a set of modern representative hullform models. Light and deep loading conditions were generated and all models were checked for compliance with both intact and damaged Def Stan 02-900 stability criteria. The small auxiliary, large auxiliary, and tanker were modelled with typical double bottom arrangements. Damage cases were generated using DefStan 02-900 extents for combatant and non-combatant vessels as appropriate. Accidental damage templates were used in Paramarine to generate a full range of damage scenarios in order that suitable severe damage cases could be selected. Two damage cases were modelled for each vessel, one representing an asymmetric damage case with damage to the centreline and the other a fully symmetric damage case. The asymmetric damage case was simulated in a light seagoing loading condition and the symmetric damage case was modelled in a deep sea going load condition. This was done to attempt to capture the worst case roll and heave motions in these damage cases. Powering characteristics, roll damping and natural roll periods were all selected based on data from similar real vessels to ensure realistic vessel motions were obtained.

Initially each vessel was statically assessed with all tanks and compartments modelled. The results of the static assessment allowed the identification of the worst case asymmetric and symmetric damage case and load condition combination, as well as identification of any load condition tanks with significant free surface moment that had to be modelled. The impact of this modelling was checked through the comparison of intact GZ curves; this approach ensured that the condition modelled in the time domain simulation captured the essential characteristics of the vessel whilst minimising computational time.

Tanks with large free surface moments and damaged compartments were modelled in FREDYN using the standard QinetiQ approach (Dawson 2013) with damage openings defined to the centerline and with full vertical damage extent. Static validation of the damage case was conducted against the results of the Paramarine analysis using a new Matlab based GZ generator tool, which uses FREDYN to produce GZ moment and trim plots for comparison to the static tool.

Fig. 1 shows an example of a damaged GZ validation and the level of correlation between the FREDYN flooding module and Paramarine. As can be seen, there is excellent agreement across the entire heel range.

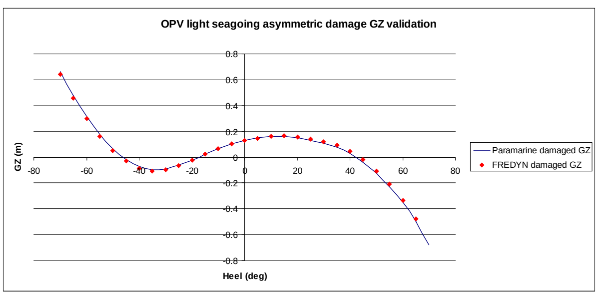

Figure 1: OPV light seagoing asymmetric damage GZ validation

3. Simulation Details

The analysis simulated conditions from a sea state 4 to sea state 6. Previous work (Peters 2004) has focused on the assumptions of the initial Sarchin and Goldberg work which aligned with a sea state 4. Waves were modelled in the simulation using a JONSWAP spectrum (Hasselmann et al., 1973) with a peak enhancement factor of 3.3. Ten one-hour simulations were run for each wave height and period modelled, each with a different wave realisation. Long crested seas were used in all the simulations. A summary of the wave definitions used in the simulations, derived using the World Meteorological Organisation sea state code (Ewing 1974) as guidance, is seen in Table 2:

Table 2 Simulation wave definitions

Sea State	Modal wave period (s)	Significant wave height (m)
SS4 mean	7.35	1.88
SS4 max	7.35	2.50
SS5 mean	8.10	3.25
SS5 max	8.10	4.00
SS6 mean	10.35	5.00
SS6 max	10.35	6.00

Each vessel and damage case combination was simulated at zero (free to drift) and five knots. Eight headings were simulated, from head to stern seas with the damage opening facing into and away from the waves. The models were free to drift in the waves however constant heading was achieved by freezing yaw in order to fully understand the impact of wave heading on internal bulkhead water heights.

In total 960 hours of simulations were performed for each vessel, equating to 40 days of damaged sea time.

4. Calculation Methodology

Previous V-line investigations have compared water height cumulative distribution functions (CDF) at the centerline and outboard points to water heights generated from the existing V-lines, in order to understand the probability of exceedence water heights defined by the current V-line criteria. The work conducted for this study deviates slightly from this approach in so far as the required output is a set of V-line roll and heave allowances varying with the probability of the water level exceeding the line. This approach allows the simple selection of V-line and red risk criteria based on an acceptable probability of exceedence.

Throughout this paper the measure 'percentile water height' is used in place of a probability of exceedence in order to align with convention. For example the 95th percentile water line refers to a line with a 5% probability of exceedence; i.e. a line that provides coverage of 95% of recorded water heights.

In order to calculate the V-line allowances, water height sensors were placed on the bounding bulkheads of the damage regions arising from each of the damage scenarios. Sensors were placed at the centreline and at outboard points within the damaged compartments. Where subdivision was present in the deck plane, multiple sensors were required in order to provide coverage of the full range of water heights. An example of water height sensor placement is seen in Fig. 2.

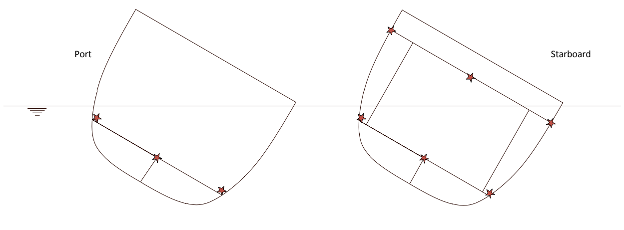

Figure 2 - Placement of water height sensors

The data was then combined into a single time history at the centreline and at outboard points. From these histories both centreline and outboard CDF were calculated. In order to generate V-lines allowances with varying probabilities of water exceedence, corresponding outboard and centreline percentile water heights were joined to form a percentile V-line, the angle of which could then be calculated from the transverse position of the outboard water height sensor. This approach is seen illustrated in Fig. 3.

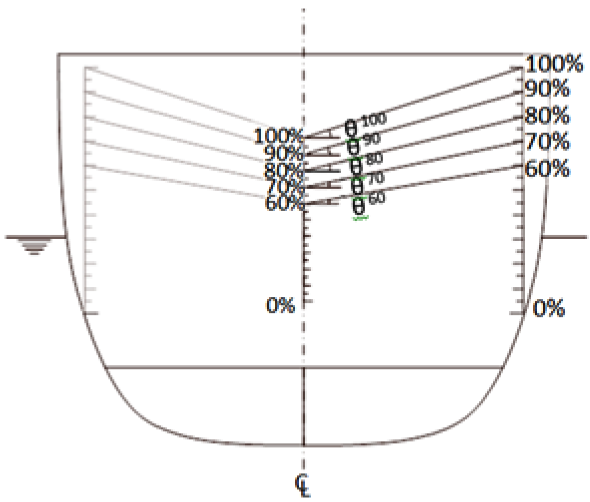

Figure 3 –Lines of probability of exceedence of water heights for the calculation of V-line criteria

The resulting percentile relative water height allowances are referred to as heave and roll allowances in line with the terminology of the V-line standard, however in reality these terms are not conceptually accurate. By combining the centreline and outboard water height probabilities, the vessel heave allowance directly impacts the roll allowance calculated; for example maximum roll motions may predominantly occur as the vessel is at the peak of its heave oscillations, meaning the outboard 95th percentile water height may only be fractionally higher than the centreline point, despite the vessel rolling significantly. This results in a 'roll' allowance of only a few degrees despite the vessel rolling significantly more than this. Fundamentally, the approach adopted succeeds in combining both roll and heave motions to give a probabilistic V-line which reflects the actual waterline as opposed to modelling it through independent criteria where the worst case roll and worst case heave are assumed to occur simultaneously.

In order to further understand the relationship between vessel motion and local water height, global vessel motions, taken from vessel earth axis motions, were calculated, highlighting where the vessel was contouring the waves in heave and roll or where waves were affecting the local water height at each bulkhead.

5. Results

Tables are presented giving a summary of the worst case 95th percentile heave and roll allowances for the combatants and non-combatant vessels. The results for the maximum sea state 4 and a maximum sea state 6 are presented. In conjunction with these results statistical measures of the vessel roll and heave motions are also presented.

In the tables of results the vessel designators are followed by either a H, corresponding to the vessel heave allowance, or by an R, corresponding to the vessel roll allowance.

Table 3 outlines the static damaged list angles of all vessels following damage allowing an understanding of the final Red Risk and V-line levels.

Table 3 Damaged list angles

Sea State	Symmetric damage list angle (deg)	Asymmetric damage list angle (deg)
OPV	0	17.4
MCMV	0	17.3
Destroyer	0	7.2
Small Auxiliary	0	18.1
Large Auxiliary	0	17.9
Tanker	0	6.3

5.1. Combatant Results

Table 4 summarises the worst case heave and roll allowance results of the OPV, MCMV and the Destroyer (DEST) in sea state 4 conditions following symmetric and asymmetric damage.

Table 4 Summary of combatant heave and roll allowances (angle from upright) in a maximum sea state 4

Ship/ allowance	Damage	Heading (deg)	95% V-line criteria		95% Vessel motions	
			Heave (m)	Roll (deg)	Heave (m)	Roll (deg)
OPV H	Sym	178	0.70	0.18	0.50	0.32
OPV R	Sym	090	0.40	10.20	1.10	12.28
OPV H	Asym	315	0.98	0.70	0.66	19.72
OPV R	Asym	090	0.55	5.70	1.13	25.10
MCMV H	Sym	002	0.74	0.15	0.64	0.29
MCMV R	Sym	090	0.40	7.02	1.12	8.55
MCMV H	Asym	002	0.84	2.62	0.73	20.58
MCMV R	Asym	090	0.44	5.77	1.10	23.10
DEST H	Sym	002	1.00	0.08	0.50	0.20
DEST R	Sym	090	0.28	3.54	1.09	4.07
DEST H	Asym	002	0.77	0.00	0.39	7.52
DEST R	Asym	090	0.30	2.69	1.06	10.53

In sea state 4 conditions the heave allowances can be seen to be below both the original Sarchin and Goldberg dynamic heave allowance of 1.22m and the larger DefStan 02-900 allowance of 1.5m. The worst case 95th percentile heave allowances are seen to occur predominantly in following sea and head sea conditions, as expected, where pitching motions are at their greatest, contributing to waterline height on the bulkhead centre point.

In all cases the worst case roll allowance is also substantially below the 15° defined in DefStan 02-900. Even where large vessel roll motions are seen, the corresponding roll allowance is seen to be small, suggesting that the smaller vessels are contouring the beam sea waves. It is important to note that where high roll allowances are seen following symmetric damage, these are unlikely to drive final V-line angle as following symmetrical damage the mean list angle is negligible. This is illustrated in Fig 4:

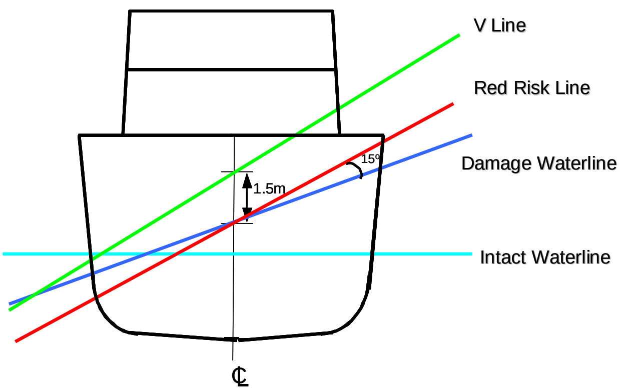

Figure 4 – V-line and Red Risk line composition

Table 5 presents the results of the three combatants following damage in a maximum sea state 6. Due to the significant damage cases (worst cases under DefStan 02-900) the OPV was found to capsize in a number of heading in these large sea state 6 waves and as a consequence results are not available for these runs.

Table 5 Summary of Combatant heave and roll allowances in a maximum sea state 6

Ship/ allowance	Damage	Heading (deg)	95% V-line criteria		95% Vessel motions	
			Heave (m)	Roll (deg)	Heave (m)	Roll (deg)
OPV H	Sym	Vessel capsized – no results available				
OPV R	Sym	Vessel capsized – no results available				
OPV H	Asym	Vessel capsized – no results available				
OPV R	Asym	Vessel capsized – no results available				
MCMV H	Sym	045	1.16	8.89	2.40	16.49
MCMV R	Sym	270	0.40	**17.58**	2.39	19.03
MCMV H	Asym	135	1.45	7.44	2.39	25.43
MCMV R	Asym	270	0.56	11.73	2.42	30.92
DEST H	Sym	002	1.32	0.24	1.70	0.92
DEST R	Sym	225	0.57	13.38	1.76	12.15
DEST H	Asym	178	1.27	0.00	1.65	8.88
DEST R	Asym	090	0.58	8.48	2.63	16.98

The MCMV and Destroyer are both seen to experience large vessel roll angles, indicated by the 95th percentile vessel motion statistics. Despite this, roll allowances are again seen to be predominantly low.

Following symmetric damage to the MCMV a roll allowance of 17.6° was seen. Whilst this is outside the roll allowance found in DefStan 02-900, the DefStan allowance is applied to the worst case damaged waterline, i.e asymmetric heel up to 20 degrees. Therefore, a DefStan V-line angle would be 35° under current rules compared to 17.6° using the results of the analysis, despite a larger roll allowance being used.

In all cases heave allowances were seen to fall below current naval V-line standards despite large heave motions being seen. Once again worst case heave allowances were calculated in head and following seas.

5.2. Non-combatant Results

The non-combatants examined were all large vessels with greater freeboard and reserves of buoyancy than their combatant counterparts. In addition the relative wave size of a sea state 6 when compared to vessel size is less onerous than those seen in the smaller combatant vessels.

Table 6 outlines the worst case roll and heave allowance for the three non-combatants in sea state 4 conditions.

Table 6 Summary of non-combatant heave and roll allowances in a maximum sea state 4

Ship/ allowance	Damage	Heading (deg)	95% V-line criteria		95% Vessel motions	
			Heave (m)	Roll (deg)	Heave (m)	Roll (deg)
Small Aux H	Sym	002	1.06	0.05	0.43	0.53
Small Aux R	Sym	090	0.34	2.66	1.00	3.59
Small Aux H	Asym	270	**1.83**	0.00	0.57	22.52
Small Aux R	Asym	090	1.06	2.63	1.15	24.63
Large Aux H	Sym	002	1.05	0.04	0.32	0.47
Large Aux R	Sym	090	0.30	1.03	0.87	1.71
Large Aux H	Asym	178	**1.66**	0.00	0.31	15.76
Large Aux R	Asym	090	0.95	0.86	0.93	15.45
Tanker H	Sym	045	1.30	0.08	0.69	1.18
Tanker R	Sym	090	0.61	2.31	0.79	3.24
Tanker H	Asym	090	**1.51**	0.00	0.92	7.15
Tanker R	Asym	270	0.67	3.65	0.62	13.89

In all cases the DefStan 02-900 roll allowance was not exceeded by the simulation results; this is despite relatively large roll motions being seen in the case of the small auxiliary (24.63°). Worst case roll allowances were seen to occur in beam sea conditions and were seen following symmetric damage, with the exception of the tanker whose worst case roll allowance was seen following asymmetric damage (13.89 degrees).

The DefStan heave allowance was seen to be exceeded by all three vessels, the worst being the small auxiliary with 0.33 metre exceedence following asymmetric damage. In these cases vessel global heave motions were low, suggesting that the vessel did not react in heave to the incident wave, resulting in the centreline water height being water inflow through the damage. These results suggest that for a larger vessel, reacting more slowly to incoming waves, the current naval standards do not provide coverage of likely centreline water levels.

Table 7 outlines the worst case roll and heave allowance for the three non-combatants in sea state 6 conditions. The results presented in table 7 (* correspond to a mean sea state 6).

Table 7 Summary of non-combatant heave and roll allowances in a maximum sea state 6

Ship/ allowance	Damage	Heading (deg)	95% V-line criteria		95% Vessel motions	
			Heave (m)	Roll (deg)	Heave (m)	Roll (deg)
Small Aux H	Sym	002	**1.93**	0.14	1.54	1.01
Small Aux R	Sym	090	0.64	8.79	2.78	10.08
Small Aux H	Asym	270	**2.66**	0.00	2.08	24.37
Small Aux R	Asym	045	**1.53**	2.33	1.93	22.48
Large Aux H	Sym	135	**1.75**	3.79	1.44	2.75
Large Aux R	Sym	225	1.09	6.38	1.32	2.29
Large Aux H	Asym*	178	**2.59**	0.00	0.77	17.90
Large Aux R	Asym*	090	1.17	3.29	2.09	18.13
Tanker H	Sym	002	**3.48**	0.03	0.26	1.59
Tanker R	Sym	225	**2.15**	8.45	1.61	21.37
Tanker H	Asym	002	**2.48**	0.00	1.37	6.10
Tanker R	Asym	270	1.05	6.45	1.93	19.40

In sea state 6 conditions roll allowances are still seen to fall substantially below the current DefStan requirement, suggesting that for these larger vessels the criteria could potentially be relaxed from the 15 degree roll allowance.

The worst case heave V-line allowances are seen to be very high when compared to the current 1.5m standard. In most cases these high allowances correspond to relatively low global vessel heave motions, aligning with the results seen in the sea state 4 analysis. The 95th percentile heave allowance for the large auxiliary was found to exceed current standards in all conditions greater than a sea state 4 with a 25% probability of the 1.5m allowance being exceeded seen in a sea state 4. In the sea state 6 the internal water level heave allowance was between 1 and 2m above the current V-line standard.

6. Conclusions

It has been shown that following this methodology and using a suitable time-domain code that the Red Risk and V-lines criteria can be evaluated for different sized vessels.

Current Def Stan 02-900 V-line criteria are based upon the original Sarchin and Goldberg work of 1962 which was based around the seakeeping characteristics of frigate sized vessels of that time. By examining water heights at the bounding bulkheads of damage cases across a range of modern indicative vessel designs, the suitability of these historic criteria has been assessed.

The new approach of forming a probabilistic water height line, which covers probability percentiles of bulkhead submergence, leads to heave and roll being considered together to form allowances that represent the actual percentage of time that points on the bounding bulkhead spend submerged. This is in contrast to current criteria which are based on the individual consideration of maximum roll angles and maximum heave motions, and do not account for the fact that these two occurrences are unlikely to manifest themselves at the same time.

It is clear that the vessels considered in this report must be assessed as two groups to truly understand the applicability of the existing standards; namely smaller combatants and larger non-combatants. Unsurprisingly, vessel size is seen to significantly affect the probabilistic heave and roll allowances of a vessel as a direct result of the different seakeeping behavior the vessels exhibit in larger sea states.

The current naval standards, based around World War 2 frigates, appear conservative when applied to a modern day destroyer design. Maximum roll allowance angles are predominantly seen following symmetric damage cases and the application of these allowances to an asymmetric list angle results in an additional level of conservatism. All the vessel-damage scenario combinations examined have a 95th percentile probabilistic roll allowance in a sea state 4 of less than 11°, showing the current criteria is suitable for sea state 4 for modern vessels.

The heave allowance is seen to be significantly more sensitive to vessel size than roll allowance. The current heave allowance is not exceeded by any of the smaller combatant vessels in a sea state 4, with the maximum 95th percentile heave allowance of 1.0m in the case of the destroyer.

In a maximum sea state 6 the highest combatant 95th percentile heave allowance was seen to be 1.45m. However in the case of the larger non-combatant ships examined, these heave allowances do not appear to be as suitable. The larger ships are seen to experience greater bulkhead water heights, not as a result of the vessel global vertical motions, but instead as a result of local water height as the vessel experiences small vertical motions and large flows in and out of the damage region. A heave allowance of 1.9m is required in order to ensure a 95% probability of compliance in a sea state 4 for the vessels and damage cases examined. This allowance increases to 3.5m in a sea state 6.

It appears evident that applying the current V-line standard roll allowance of 15° and heave to modern combatant designs is conservative up to a sea state 6. Similarly the current heave allowance of 1.5m also appears conservative when applied to modern combatants up to the sea state 6 conditions examined. The roll allowance standard for large non-combatants is seen to be very conservative and could be reduced significantly whilst still maintaining a 95% probability of compliance in a sea state 6, however, the non-combatant heave allowance may require a significant increase over current standards.

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