USN's Recently Defined Standard Practice for the Construction of a Composite Allowable KG Curve for Single Load Point Evaluation using the Load Shift Method

Vytenis A. Senuta, *Naval Surface Warfare Center Carderock Division*
Lauren E. Moraski, *Naval Surface Warfare Center Carderock Division*

ABSTRACT

USN ships are required to satisfy stability criteria in accordance with T9070-AF-DPC-010/079-1 "Design Practices and Criteria for U.S. Navy Surface Ships Stability and Reserve Buoyancy" dated 19 January 2016. These criteria address the hazards at sea and expected loading conditions throughout the service life of a ship. Allowable KG (KG_A) is the highest vertical center of gravity that satisfies a stability criterion. Typically, ships are required to satisfy multiple intact and damage criteria, so multiple KG_A's are calculated. This paper and the recent update of USN T9070-AF-DPC-010/079-1 is intended to inform the commercial community of the USN practice of the load shift method for damage KG_A calculations.

Keywords: *Allowable KG, Load shift method …*

1. INTRODUCTION

USN ships are required to satisfy stability criteria in accordance with T9070-AF-DPC-010/079-1 "Design Practices and Criteria for U.S. Navy Surface Ships Stability and Reserve Buoyancy" dated 19 January 2016. These criteria address the hazards at sea and expected loading conditions throughout the service life of a ship. Allowable KG values are calculated for intact and damage stability.

In the USN, the vertical center of gravity (G) is measured from the bottom of the keel (K), and the distance is referred to as KG. Allowable KG (KG_A) is the highest vertical center of gravity that satisfies a stability criterion. Typically, ships are required to satisfy multiple intact and damage criteria, so multiple KG_A's are calculated. The lowest of these KG_A is the governing KG_A. Often the governing KG_A represents a combination of criteria at various displacements. This is often referred to as Composite KG_A, or, just simply, KG_A. When assessing ship stability, a ship's KG (typically from a weight report or inclining experiment) is compared to (plotted against) its KG_A. If KG is below the KG_A, the ship satisfies all stability criteria. If KG is above, then it fails at least one stability criterion and corrective measures must be taken – either lower KG or raise KG_A.

For the USN, all KG_A values reference the Full Load Departure Condition. The lowest of the calculated KG_A values at a particular displacement becomes governing for that displacement; these lowest values are then connected to create a KG_A curve over a specified displacement range.

Typically, intact KG_A is calculated for the following hazards as applicable to the design: beam wind, high speed turn, icing, towline pull, crowding of personnel, and lifting of heavy weights. Damage KG_A is calculated for side damage and raking. Intact KG_A calculation is sufficiently applicable for the operating displacement range of a ship since all hazards are applied to the hull externally. However, since damage impacts the hull internally, it is highly dependent on loading (e.g. tank volumetric emptiness) and therefore KG_A necessitates the use of the Load Shift Method. This method projects damage KG_A values calculated for other load conditions to its Full Load Departure condition equivalent.

USN ship design was traditionally performed by the USN technical community up through contract design. The load shift method was commonly known and formal documentation was not deemed necessary. However, with changing times, commercial design agents and shipyards are increasingly involved in USN ship design. Without proper documentation, guidance and design requirements, commercial entities could not be expected to properly implement the load shift concept. This paper and the recent update of USN T9070-AF-DPC-010/079-1 is intended to inform the commercial community of the USN practice of the load shift method for damage KG_A calculations.

2. ALLOWABLE KG

USN Allowable *KG* (KG_A) references the Full Load Condition. It is a singular curve, that represents the most conservative or limiting intact and damage stability capability that satisfies all design applicable USN stability criteria. It is calculated during the ship design phase. It is meant to satisfy all foreseeable loading conditions throughout the operating range (Min Op to Full Load) and throughout the expected or projected service life (typically 30 years). Once calculated during the design phase, there is no need to recalculate, unless the hull form, watertight bulkhead configuration, or ship mission changes which affects liquid amount or location, or space load densities. A singular KG_A curve also simplifies stability limits to the Sailor. A singular Allowable KG curve contributes to commonality as crews change throughout the service life. Also, once a singular KG_A curve is calculated, it does not need to be recalculated for unique loading conditions. It is a relatively conservative limit, but it is an efficient, all-inclusive limit that is relatively simple to understand for the non-naval architect, ship design management, and ship's force who must assure ship safety.

3. OPERATING RANGE AND LOADING

The design operating range of a USN surface combatant is from the Minimum Operating Condition (Min Op) to the Full Load Departure Condition (Full Load), unless otherwise specified. Min Op is basically 1/3 of Full Load loads, with exceptions. The Load Shift Method is used to calculate the damage KG_A curve based on the expected limiting case loading condition of the operating range yielding the highest *KG*. It assumes that, if the ship design can satisfy USN stability criteria for the worst loading condition with the highest *KG*, then the ship is safe in the entire range of operating conditions.

Stability is calculated for the worst loading condition to meet USN criteria. The result is an allowable KG, but for that worst loading condition only. The worst case loading condition can be any loading combination between Min Op and Full Load, per DDS 079-1. Traditionally, the worst operating loading condition has been a modified Min Op. This is a loading scenario, where loads located below *KG* are depleted, but loads above *KG* are preserved. This is a very likely scenario, e.g. a ship returns from deployment with fuel and other liquids depleted, but with ammunition and other stores still onboard. In this case, the modified Min Op yields a higher *KG* than traditional Min Op. Therefore, it will be used in the example below.

4. LOAD SHIFT

USN KG_A curves reference the Full Load Condition. The delta between the worst loading condition loads and the Full Load Condition loads must be calculated. This delta will serve as the load shift. The load shift consists of a weight (Full Load Condition loads weight minus the "worst" loading condition loads weight) and vertical moment (Full Load Condition loads vertical moment minus the "worst" loading condition loads vertical moment). The load shift will be added to the calculated damage allowable KG values of the worst loading condition to produce Full Load Equivalent Damage KG_A values. The load shift can be applied to the worst loading condition damage KG_A's at a range of displacements to produce Full Load Equivalent Condition damage KG_A's at a range of displacements. This is the Full Load Equivalent Damage KG_A curve. The Full Load Equivalent Damage KG_A values are then compared against the calculated Full Load Damage KG_A values and the lesser of the two values at each calculated displacement is used in the Composite Damage KG_A curve.

5. METHODOLOGY

The weight (LS_{WT}) and vertical moment (LS_{MOM})components of a load shift from Full Load of any other condition are defined as:

$$LS_{WT} = WT_{WL} - WT_{MO} \quad (1)$$

$$LS_{MOM} = WT_{FL} \cdot KG_{FL} - WT_{MO}KG_{MO} \quad (2)$$

where:
WT_{FL} full load displacement
WT_{MO} minimum operating displacement
KG_{FL} full load vertical center of gravity KG
KG_{MO} minimum operating vertical center of gravity KG

Accordingly the Minimum Operating Allowable KG, KGA_{MO}, can be load shifted back to the Full Load range of displacements as follows:

$$KGA_{LS} = \frac{KGA_{MO}WT_{MO} + LS_{MOM}}{WT_{MO} + LS_{WT}} \quad (3)$$

KGA_{MO} - minimum operating allowable KG
KGA_{LS} - Load shifted minimum operating Allowable KG

Example

The chart in Figure 1 shows the positions of Full Load and Min Op displacement and KG. These are typically attained from a design weight estimate. The Full Load displacement and *KG* are 7400 tonnes and 20.278 meters, respectively. The Min Op condition is 6400 tonnes and 22.000 meters, respectively. A load shift is calculated below:

$$LS_{WT} = WT_{FL} - WT_{MO} \quad (4)$$
$$= 7400 - 6400 = 800\,tonnes$$

$$LS_{MOM} = WT_{FL}KG_{FL} - WT_{MO}KG_{MO} \quad (5)$$
$$= 7200 \cdot 20.278 - 6400 \cdot 22.000$$
$$= 5198.3\,tonne-meters$$

A damage allowable KG (KG_A) is then determined via typical stability analysis methods for the appropriate stability criteria for a Min Op Loading Condition:

Condition	Displacement (tonnes)	Allowable KG (meters)	Moment (tonne-meters)
Min Op	5500.0	23.500	129250.0

The load shift is applied to the above modified Min Op Condition KG_A to produce a Full Load Equivalent Damage Allowable KG (the MinOp KG_A is "load shifted" to the Full Load Condition displacement range):

Condition	Displacement (tonnes)	Allowable KG (meters)	Moment (tonne-meters)
Min Op	5500.0	23.500	129250.0
+ Load shift	800.0		5198.3
Full Load	6300.0	21.341	134448.3

The load shift application is repeated for a range of Min Op Condition displacements and corresponding damage allowable KG's to produce a range of Full Load Equivalent Condition displacements and damage allowable KG's, see data in Table 1. With the damage Full Load Equivalent Allowable KG's now calculated, a curve can be plotted, see Figure 2 . When compared to a sample family of calculated intact and damage Allowable KG curves, the chart may appear as shown in Figure 3. The lowest of all allowable KG points will be used to produce the final, composite, and singular Full Load Allowable KG, shown in Figure 4.

In the example above, the ship's Full Load displacement and KG is plotted and compared with the Allowable KG and Displacement Limit. Fortunately for this ship, it is currently below the Allowable KG and less than the Displacement Limit. Therefore, it is safe in not only the Full Load condition, but in all operating conditions that contributed to the composite KG_A curve. However, the ship's weight/KG growth may change over time and will require monitoring.

This curve will serve all foreseeable loading scenarios within the design operating range during the service life of the ship. It will not need to be recalculated, unless there is a change in hull form and appendages, watertight boundaries, significant load change or change in ship mission which affects liquid amount or location, or space load densities.

Incorporating LCG/Trim Shift

When discussing standard USN load shift practice, shifting the weight and KG were discussed previously; however, shifting the LCG between the two loading conditions is not typically considered. Historically, LCG shifts and trim ranges are not considered for combatant type ships since typical combatants operate with close to zero trim. For amphibious type ships with an expected operating trim range, a range of potential trims are examined for each displacement of interest. Based on the curves for the analyzed trim range at each displacement, the expected design operating trim range can then be located on those curves and the lower KG from one end of the range is then used as the limiting KG for that displacement in order to cover the entire operating trim range. The Figure 5 shows Allowable KG (KG_A) values at a particular displacement for which an example ship has been analyzed in a trim range between -2.0m and 2.0m, though the ship is only expected to operate between a -1.5m and 1.5m trim. The KG_A value at the -1.5m trim condition is less than the KG_A value at the 1.5m trim condition and thus the -1.5m trim KG_A value becomes the governing KG_A limit for this particular displacement.

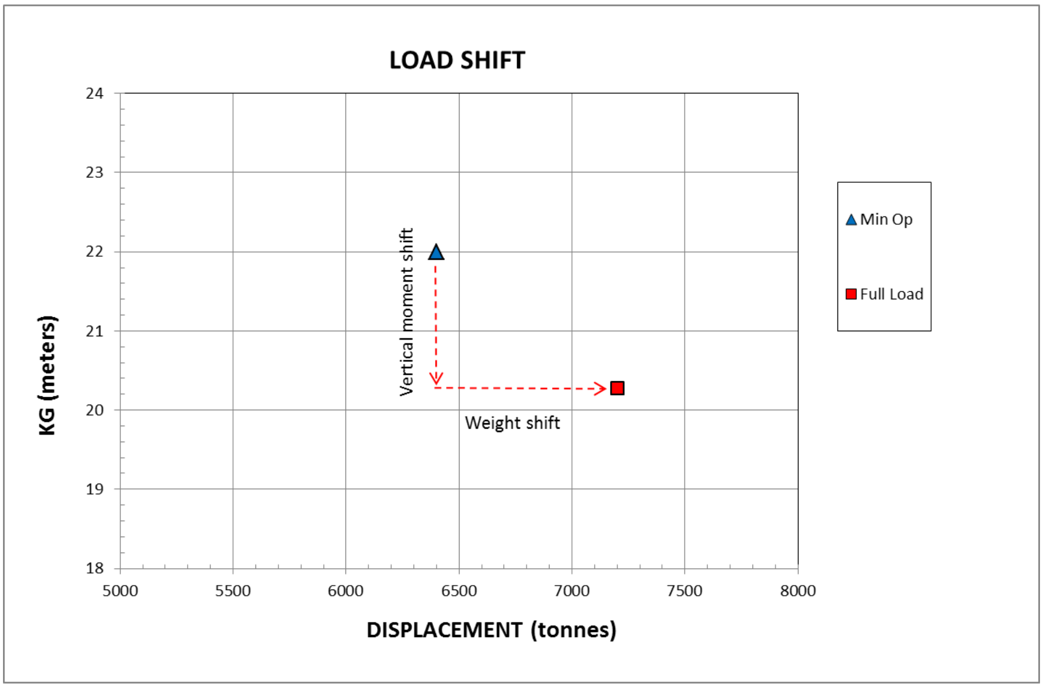

Figure 1 Example of load shift

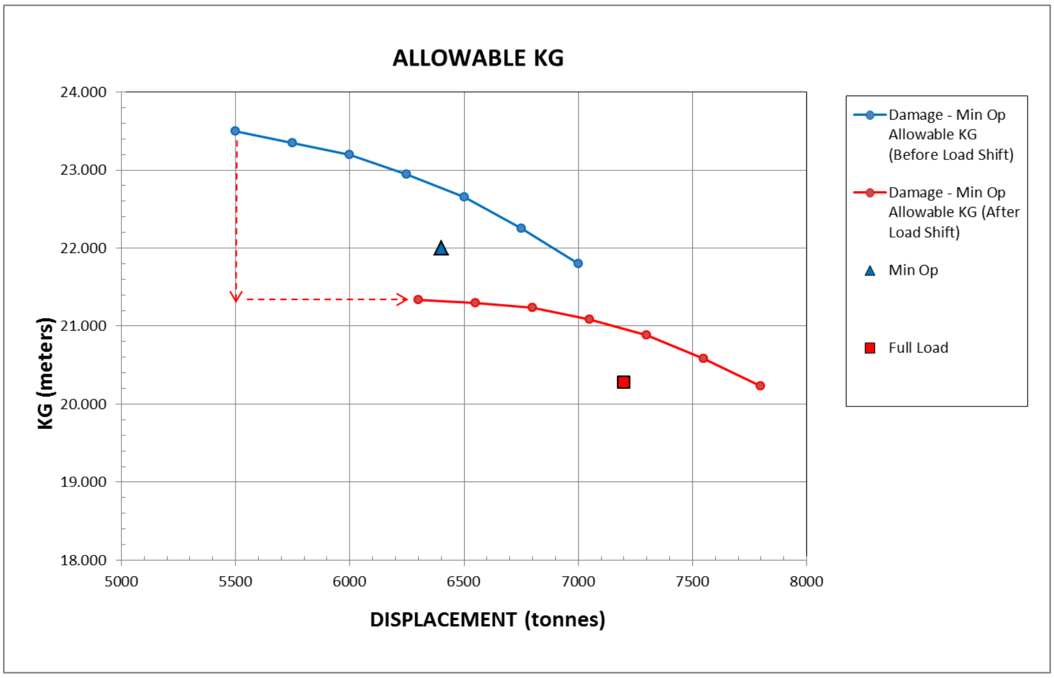

Figure 2: Load shifted allowable KG curves

Table 1 Example of load shift

BEFORE LOAD SHIFT			LOAD SHIFT		AFTER LOAD SHIFT		
Minimum Operating Condition					Full Load Condition		
Disp	Allowable KG	Moment	Weight	Moment	Disp	Allowable KG	Moment
(tonnes)	(meters)	(tonne-meters)	(tonnes)	(tonne-meters)	(tonnes)	(meters)	(tonne-meters)
5500	23.500	129250.0	800	5198.3	6300	21.341	134448.3
5750	23.350	134262.5	800	5198.3	6550	21.292	139460.8
6000	23.200	139200.0	800	5198.3	6800	21.235	144398.3
6250	22.950	143437.5	800	5198.3	7050	21.083	148635.8
6500	22.650	147225.0	800	5198.3	7300	20.880	152423.3
6750	22.250	150187.5	800	5198.3	7550	20.581	155385.8
7000	21.800	152600.0	800	5198.3	7800	20.231	157798.3

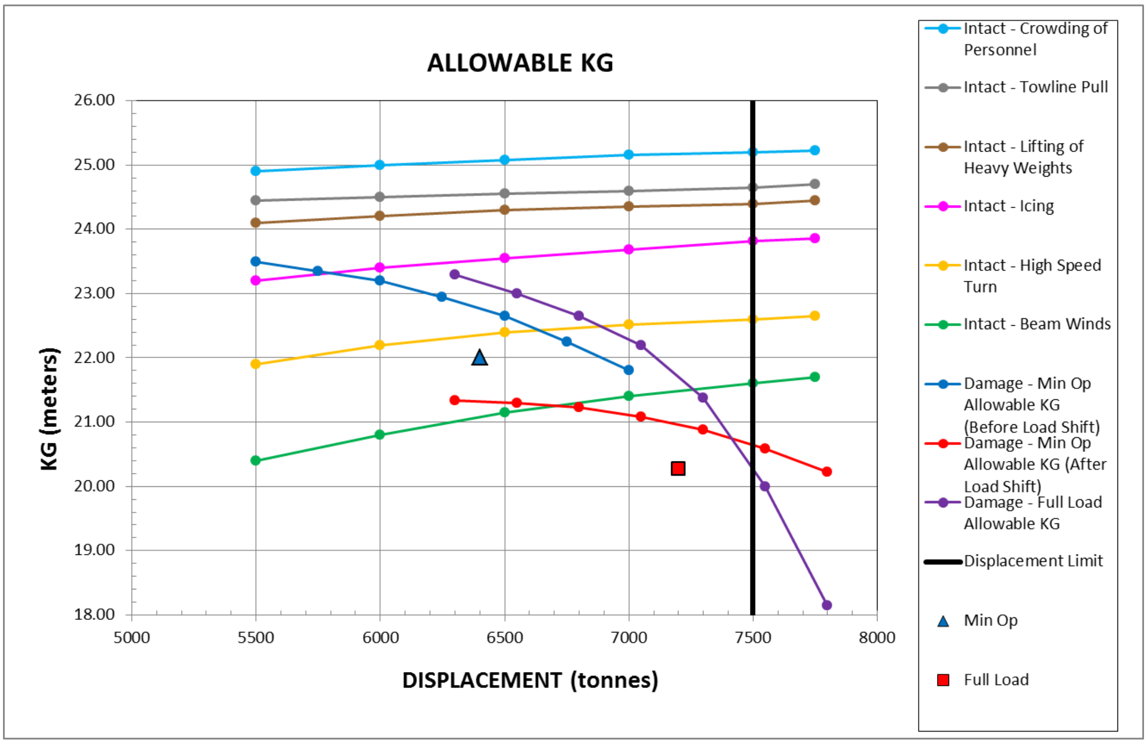

Figure 3: Family of Allowable KG curves

As mentioned earlier though, an inverse approach to addressing an operating trim range is to have a family of trim-based KG_A curves. A differentiation was made above between ship types with regard to design operating trim ranges. When considering a ship's anticipated operating trim range, another differentiation that should be considered is the variability in loading conditions. The family of trim-based KG_A curves approach would not be recommended for amphibious ships requiring a ballast polygon, for example. The family of trim-based KG_A curves approach should only be considered when a single composite KG_A curve can be used to evaluate the current status of a ship's stability and the ship's hullform type also exhibits trim sensitivity (such as SWATHs, Off Shore Supply Vessels, etc).

To develop a family of trim-based KG_A curves, a range of displacements are examined at specified trims of interest. This is again because certain hullforms can display significantly different characteristics with regard to hydrostatics and stability when considering trim. This may be a result of drastically changing waterplane area, LCF, LCB, or location of available reserve buoyancy over a range of trims, for instance. In contrast to the approach previously described, in cases where a family of curves is provided for guidance and those curves see significant variation depending on trim, unique consideration must be given to account for the change in LCG between loading conditions as well. Since the reason a ship would need multiple KG_A curves at multiple trim conditions is the result of significant changes to the ship's hydrostatic properties due to hullform, while a shift in LCG between loading conditions can be calculated in a manner similar to the shift in KG, it cannot be applied using the same approach. However, the same assumption applies that by using a fixed LCG shift when applying the load shift between loading conditions during design, the majority of displacement changes over the ship's service life are assumed to be lightship changes and not a result of changes to the loads. The previous load shift example has been updated to account for a trim shift and is shown below.

Full Load Condition (table to be populated with calculated LCG values at corresponding displacement/trim combinations using hydrostatic properties, see Table 2). Calculation the LCG Load Shift is done in Table 3.

MinOp Condition (calculated MinOp LCGs for each MinOp displacement based on applying LCG shift to Full Load LCGs, see Table 4.

The above calculated MinOp LCGs can then be used to calculate corresponding trim values. These are the trim values that should then be used to perform a damage stability analysis in the MinOp Loading Condition and are then considered equivalent to the Full Load trim values when load shifting the MinOp results back to Full Load for comparison.

By shifting the LCG in addition to the displacement and KG, an equitable comparison can be made between liquid loading conditions, such as MinOp and Full Load, at a given displacement and trim to determine the limiting KG in a family of allowable curves, see Figure 6. By not shifting the trim along with the displacement and KG, the damage stability analysis would not be performed at an approximately equivalent LCG in the alternate loading condition and would contradict the intent of performing the load shift in the first place, which is to create an equitable comparison of conditions. This also means that by not shifting the trim between liquid loading conditions for ships that are trim sensitive, the final KG_A curves for multiple, different trims provide an inaccurate representation of the safe operating range for the ship's KG

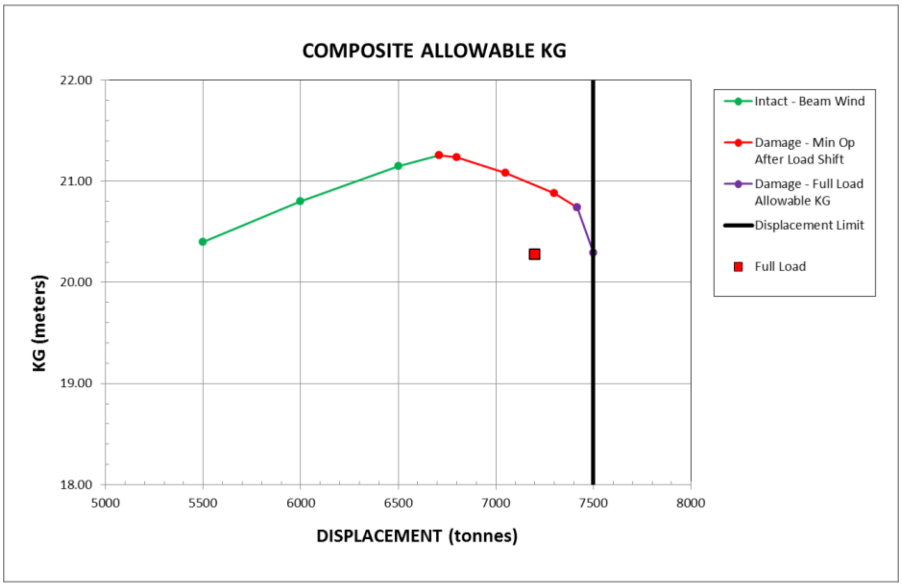

Figure 4: Full Load condition composite Allowable KG curve

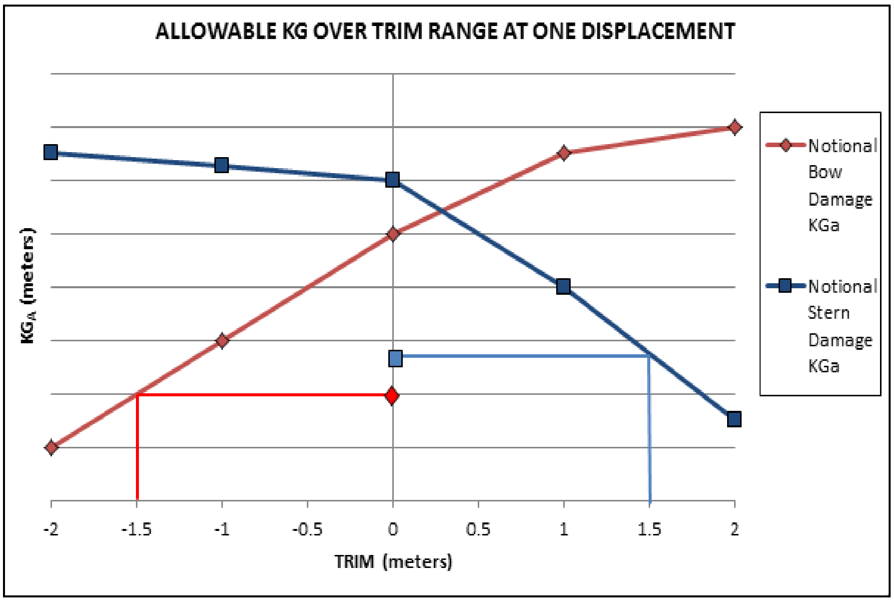

Figure 5: Allowable KG over trim range at one displacement

Table 2 LCG Trim Shift

Displacement [mt]	+0.5m trim	0.0m trim	-0.5m trim
6300	$LCG_{(6300,+0.5)}$	$LCG_{(6300,0.0)}$	$LCG_{(6300,-0.5)}$
6550	$LCG_{(6550,+0.5)}$	$LCG_{(6550,0.0)}$	$LCG_{(6550,-0.5)}$
6800	$LCG_{(6800,+0.5)}$	$LCG_{(6800,0.0)}$	$LCG_{(6800,-0.5)}$
7050	$LCG_{(7050,+0.5)}$	$LCG_{(7050,0.0)}$	$LCG_{(7050,-0.5)}$
7300	$LCG_{(7300,+0.5)}$	$LCG_{(7300,0.0)}$	$LCG_{(7300,-0.5)}$
7550	$LCG_{(7550,+0.5)}$	$LCG_{(7550,0.0)}$	$LCG_{(7550,-0.5)}$
7800	$LCG_{(7800,+0.5)}$	$LCG_{(7800,0.0)}$	$LCG_{(7800,-0.5)}$

Table 3 Calculation the LCG Load Shift:

Condition	Weight [MT]	LCG [m AFP]	L-Mom [m-MT]
Total Full Load Condition	7400	55.00	407000
Total Min Op Condition	6400	56.50	361600
Load shift	800		45400

Table 4 Calculated Min Op LCGs

Displacement [mt]			
5500	[6300*LCG(6300,+0.5)]-45400 5500	[6300*LCG(6300,0.0)]- 45400 5500	[6300*LCG(6300,-0.5)]- 45400 5500
5750	[6550*LCG(6550,+0.5)]- 45400 5750	[6550*LCG(6550,0.0)]- 45400 5750	[6550*LCG(6550,-0.5)]- 45400 5750
6000	[6800*LCG(6800,+0.5)]- 45400 6000	[6800*LCG(6800,0.0)]- 45400 6000	[6800*LCG(6800,-0.5)]- 45400 6000
6250	[7050*LCG(7050,+0.5)]- 45400 6250	[7050*LCG(7050,0.0)]- 45400 6250	[7050*LCG(7050,-0.5)]- 45400 6250
6500	[7300*LCG(7300,+0.5)]- 45400 6500	[7300*LCG(7300,0.0)]- 45400 6500	[7300*LCG(7300,-0.5)]- 45400 6500
6750	[7550*LCG(7550,+0.5)]- 45400 6750	[7550*LCG(7550,0.0)]- 45400 6750	[7550*LCG(7550,-0.5)]- 45400 6750
7000	[7800*LCG(7800,+0.5)]- 45400 7000	[7800*LCG(7800,0.0)]- 45400 7000	[7800*LCG(7800,-0.5)]- 45400 7000

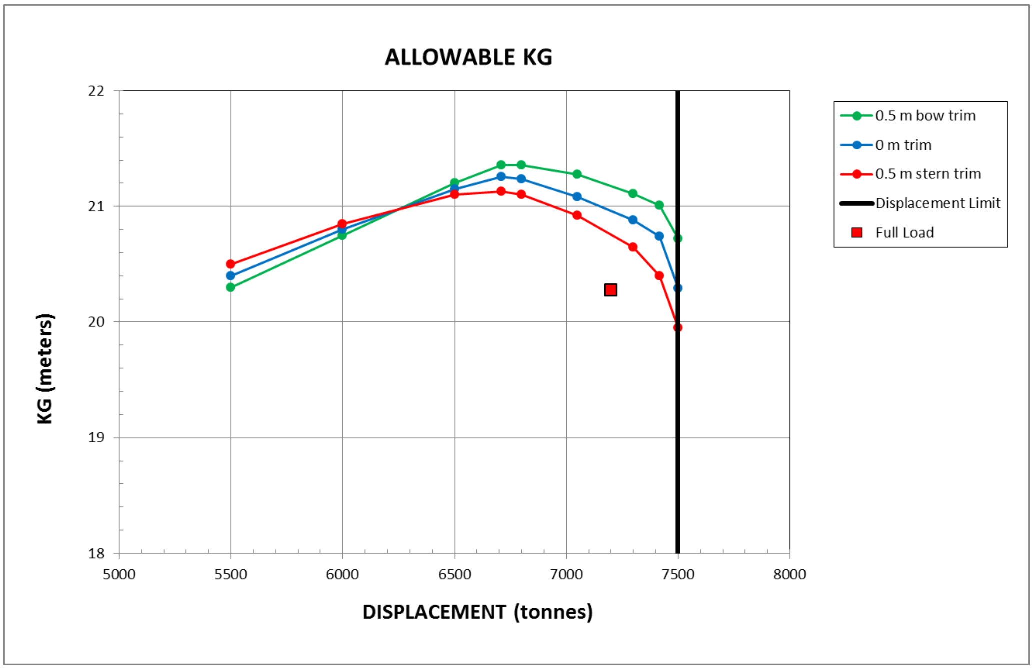

Figure 6: Allowable KG for various trims

Conclusion

The Load Shift Method is used to calculate the damage KG_A curve based on the expected limiting case loading condition of the operating range yielding the highest KG. The family of trim-based KG_A curves approach should only be considered when a single composite KG_A curve can be used to evaluate the current status of a ship's stability and the ship's hullform type also exhibits trim sensitivity (such as SWATHs, Off Shore Supply Vessels, etc). By shifting the LCG in addition to the displacement and KG, an equitable comparison can be made between liquid loading conditions, such as MinOp and Full Load, at a given displacement and trim to determine the limiting KG in a family of allowable curves.

By not shifting the trim along with the displacement and KG, the damage stability analysis would not be performed at an approximately equivalent LCG in the alternate loading condition and would contradict the intent of performing the load shift in the first place, which is to create an equitable comparison of conditions. This also means that by not shifting the trim between liquid loading conditions for ships that are trim sensitive, the final KG_A curves for multiple, different trims provide an inaccurate representation of the safe operating range for the ship's KG.

Acknowledgements

The authors would like to thank those who contributed to updating T9070-AF-DPC-010/079-1 as well as those who provided feedback on this paper. Specifically, John Rosborough of NSWCCD, and Chris Filiopoulos and Tapan Mazumdar of NAVSEA.

6. REFERENCES

Naval Sea Systems Command. (2016). *DESIGN PRACTICES AND CRITERIA FOR U.S. NAVY SURFACE SHIP STABILITY AND RESERVE BUOYANCY.* T9070-AF-DPC-010/079-1 (Approved for public release).