Implications of Performing Tugboat Stability Analysis with Fixed Trim Assumptions

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Tugboat and towboat stability analysis may be performed with either "fixed trim" or "free to trim" methodologies under the current Code of Federal Regulations (CFR). The "fixed trim" method allows the vessel's draft to change with increasing heel angle, while maintaining constant trim until the trimming moment is zero. The "free to trim" method is representative of how the vessel will behave, allowing the vessel to trim until the trimming moment is zero, with no restrictions on draft or trim. The use of the fixed trim method originally simplified the calculations performed by naval architects and produced accurate results for traditional model bow tugboats that were predominant. However, as tug styles and computers have evolved, the methodology is no longer as relevant or necessary. The paper quantifies what affect the fixed trim method has on the calculated righting energy at large angles of heel and determines when the method is no longer valid. The analysis looks at tugboats currently in operation representing a range of design characteristics and ages. The results show that the fixed trim method may provide a reasonably accurate righting arm curve for traditional model bow tugboats in some loading conditions. However, the fixed trim method can result in unrealistic and exaggerated righting arm curves for many foc'sle bow tugboat designs particularly in the intermediate and load line conditions. As older tugs are modified and new design trends evolve, it is important that naval architects understand the underlying reasoning behind the regulations that are applied to these vessels. The issue has become particularly relevant as older Load Line tugs are being repowered, modernized and, in many cases, converted into modern articulated tug and barge (ATB) units. These older tugs were not originally designed to the current stability standards and it is often a challenge for these vessels to comply.

KEY WORDS: Tugboat; stability; trim; righting arm

INTRODUCTION

Tugboat stability analysis is crucial in determining safe operational limits for vessels. Tugboat and towboat stability analysis may be performed with either a fixed trim or free trim assumption under current regulations. The fixed trim assumption allows the vessel's draft to change with increasing heel angle, all the while maintaining constant trim until the trimming moment is zero. The free trimming method is representative of how the vessel will behave, when both vessel draft and trim are permitted to change until the trimming moment is zero, at each angle of heel. This paper will examine the suitability of the fixed trim methodology, compared to the realistic free trimming methodology, as it relates to the analysis of tugboat and towboat stability.

BACKGROUND

Early tugboat stability criteria imposed a limiting restriction on the required GM of the vessel. This initially took the form of the USCG proposed criterion as noted by Roach(2) in his work published in 1954.

$$GM = cAh/(\Delta \times f/B) \quad (1)$$

At this time Roach proposed an alternative method for determining the minimum required GM, based upon the overturning moment developed by the rudder deflection of propeller wash, when a tow is abeam of a tugboat in a towline trip condition. He came to this conclusion based upon close examination of casualty reports indicating most tugboat capsizes were due to a towline trip, rather than due to poor weather conditions. The method he proposed is here reproduced:

$$GM = BHP \times 15h/(\Delta \times f/B) \quad (2)$$

Further in the work performed by Argyriadis(3) he makes specific mention of the then proposed revised stability criteria by Capt. C. P. Murphy of the USCG, which then took into account the overturning moment due to the propeller wash on the rudder and the overturning moment of a towline trip, reproduced here:

$$GM = (P \times D)^{2/3}(s)(h)/(K\Delta \times 2f/B) \quad (3)$$

This GM requirement is to this day the static GM requirement within 46 CFR 173.095(b), which is a modified form of the above, in accordance with Argyriadis(3) proposal. This consisted of reducing the least tangent of heel to deck edge in the above equation by half, from 2f/B to f/B.

In dynamic form the heeling arm for the towline tripping force is found in 46 CFR 173.095(c) and the similarity of this dynamic heeling arm with that of the statically required GM above is apparent.

$$HA = 2(N)(P \times D)^{2/3}(s)(h)(\cos\theta)/(K\Delta) \quad (4)$$

Thus, the importance of the righting arm curve is introduced and the naval architect must be concerned with the righting arm curve, its extent and the area contained within its bounds.

In reviewing our predecessors work it is worth putting it in context and having an understanding of the types of towing vessels that were in use at the time, as well as the standard practices of the day. While it is not possible to review the practices of the day in this paper, it is possible to gain understanding of the principal characteristics of the towing vessels in use, by reviewing the work of Dwight[(4)]. Dwight[(4)] generated a rather extensive breakdown of the characteristics of tugboats in use in the 1940-50's summarizing what were then considered desirable characteristics for a towing vessel. It is clear from his work that the hull form and relative volume of superstructure above the main deck was very different than that of today's modern tugboats. Most significantly the superstructures were considerably smaller in size and volume, and therefore one may presume they contributed little to reserve stability.

DISCUSSION

When conducting stability analysis for tugboat and towing vessels subject to the requirements of the USCG, 46 CFR 174.145 – Righting Energy Criterion, 46 CFR 170.170 – Weather Criterion and 46 CFR 173.095 (c) – Towline Criterion, the most common approach today is to utilize one of the various computer programs available. Computer programs such as GHS or HECSALV are generally used to perform stability calculations for vessels utilizing a model that contains information regarding the ship's characteristics. Some of these characteristics may include hull shape, superstructures, compartmentation, and displacement. The computer program allows for rapid analysis of various loading conditions, as well as allowing the operator to investigate numerous alternative vessel configurations in a very short time. A significant advantage of these software programs is that they mitigate the error associated with performing stability analyses by hand, as well as remove the tedium of performing the hand calculations associated with large angle stability. In the past, the naval architect would have to calculate large angle stability information by drawing a waterline on the body plan of the subject vessel, calculating all of the immersed areas, and then integrating to obtain vessel displacement. If the displacement did not match the upright vessel displacement, the waterline would need to be continually relocated until the actual and calculated displacement values matched. As this process was repeated, cross curves would be developed and plotted for future stability calculations. However, this set of cross curves would be specific to the vessel displacement and trim, requiring a different set to be developed for each loading condition.

Today, computer programs allow for the accurate determination of the righting arm of a vessel, at each angle of heel. The free trimming calculation method is used, as it represents the vessel in the actual environment. As it heels to each angle the computer checks that the vessel displacement remains constant, and as the immersed hull shape changes it checks that the trimming moment is resolved to zero (i.e. if, as the vessel heels, the immersed volume aft is less than forward, the vessel will trim by the stern to equilibrium). The righting arm is then calculated in this condition. This method is representative of how the vessel would react in reality when subjected to increasing angles of heel.

Many of the computer based vessel stability programs also maintain the ability to control how the stability analysis will be performed. And in many instances allow the operator to conduct the analysis with what is referred to as a fixed trim assumption. This is an assumption that in the past was often used for large vessel stability calculations to alleviate the complications associated with the process of performing the hand calculations previously outlined above. As a result, it is a dated methodology still used today, whose principal reason for inception is no longer relevant.

The 46 CFR regulations continue to permit the vessel's righting arm to be calculated at each angle of heel as though the vessel does not trim as it heels. This approach requires that the vessel be loaded to the condition under consideration, as defined in McGowan and Meyer[(1)]. The vessel is allowed to trim in this initial condition, and then this trim remains constant as the vessel heels. The righting arm is then calculated at each subsequent angle of heel. This method of fixed trim analysis has been used throughout this paper and is compared directly with the results obtained using the freely trimming method. Both analyses were performed in HECSALV, with a fixed trim macro utilized to perform the applicable fixed trim calculations in accordance with 46 CFR requirements.

DATA

A wide range of tugboats common to the coastal and harbor towing industries in the Eastern United States were used to form the pool of characteristic vessels. More than 25 vessels were looked at for inclusion, but due to available information, inaccuracies of available information, and various other factors, 10 were used to form the database at the heart of this study. These vessels are generally one of two configurations: foc'sle bow and model bow. (Fig. 1) below shows the general foc'sle bow configuration, with (Figs 2 ~ 4) comparing the fixed trim and free trim righting arm curves for the subject vessel.

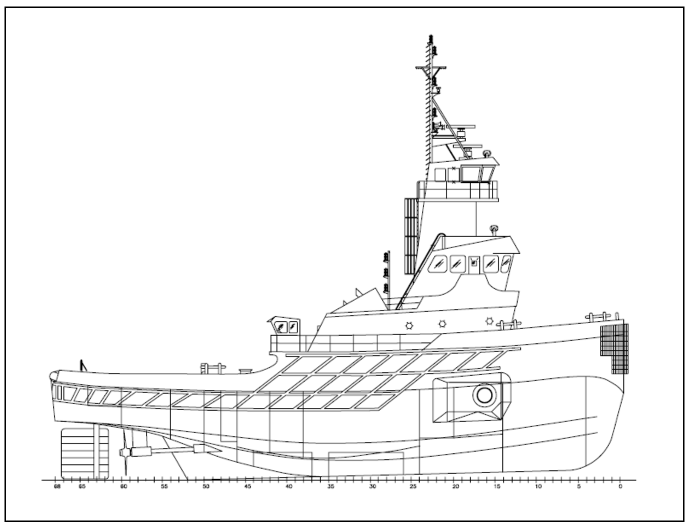

Fig. 1 Foc'sle Bow 1 Tugboat

The vessel for which these plots have been generated is a 4,000 hp, foc'sle bow type tugboat that has recently been converted to an Articulated Tug and Barge (ATB) configuration. What this set of plots demonstrates is characteristic of what has been found for the majority of foc'sle bow type tugboats that the authors have investigated.

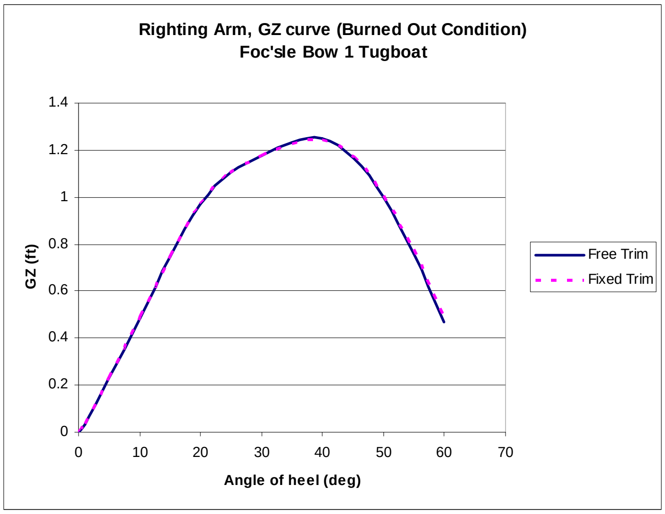

Fig. 2 Burned Out Condition Righting Arm Curves

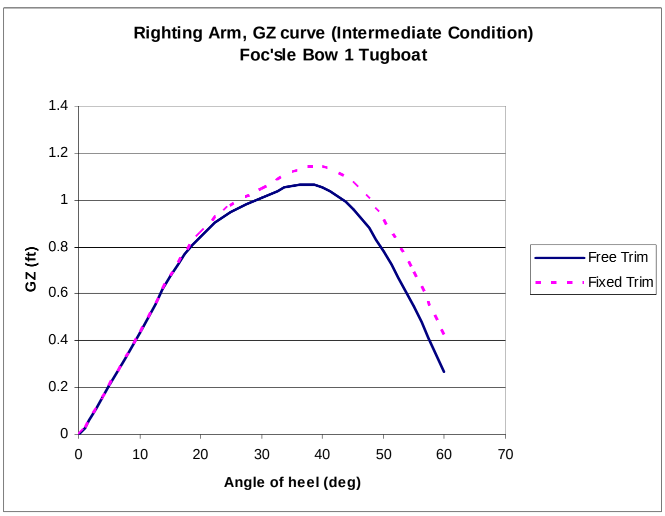

Fig. 3 Intermediate Condition Righting Arm Curves.

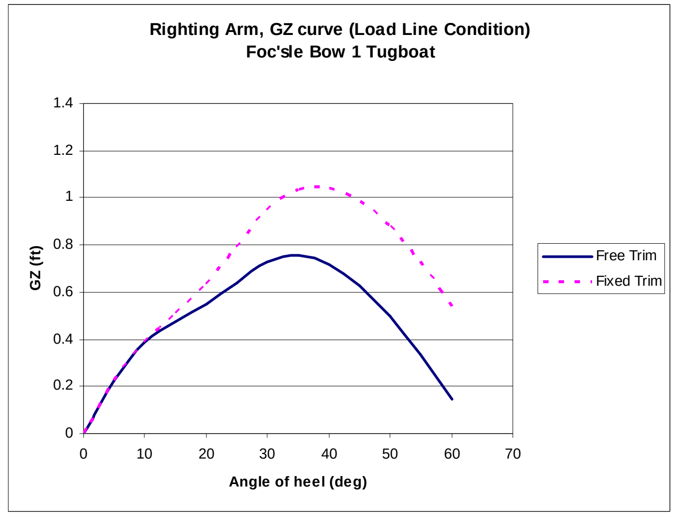

Fig. 4 Loaded Condition Righting Arm Curves.

The righting arm calculations for the vessel using a free trimming and fixed trimming method of analysis are in very close agreement for the burned out condition depicted in (Fig. 2) These two methods no longer match in the intermediate condition at angles of heel above 20-30 degrees, as may be seen in Figure 3. In the case of the load line condition, (Fig. 4), the correlation is extremely poor and the two methods produce widely varying results for the righting arm, particularly as heel angle approaches 30 degrees. It is this difference in righting arm calculated between the two methods that raises some question about the validity of the fixed trim method currently accepted by the USCG and therefore still utilized by industry.

To characterize the difference in righting arm calculated in the preceding plots, the ratio of the area under the righting arm curves, in 5 degree increments, have been calculated and plotted in (Fig. 5). This plot demonstrates the rate at which the area under the righting arm curves differ as heel angle is increased for each loading condition, and it serves to illustrate that at small angles of heel, in the near upright condition, the differences are minimal.

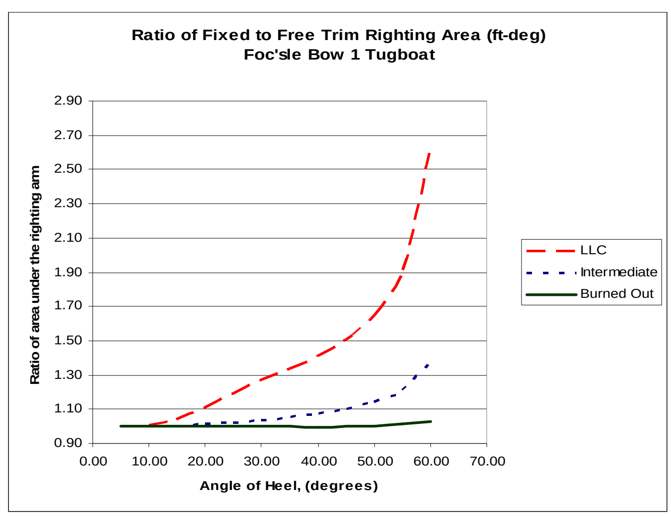

Fig.5 Ratio of Righting Arm Curves.

In support of the above findings, following is another foc'sle bow tugboat of equivalent horsepower and comparable displacement. The vessel profile below, (Fig. 6), indicates it is a highly specialized vessel, retrofitted to have a coupling system for an ATB configuration with a raised wheelhouse.

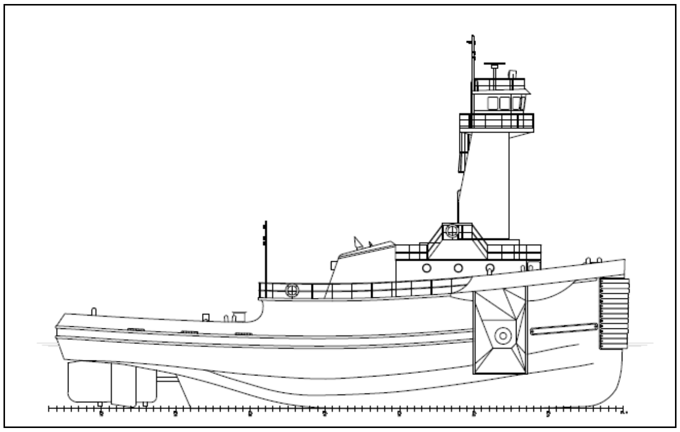

Fig. 6 Foc'sle Bow 2 Tugboat

Examination of the righting arm plots for this vessel in (Figs. 7 ~ 9) illustrates a similar pattern to that of the previous foc'sle bow tugboat in (Figs. 2 ~ 4). Namely that the relationship between the two methods of calculating the righting arm curves for the vessel is reduced as vessel loading increases and is a maximum in the loaded condition. Again a plot of the ratio of the righting arm curves for the two methods employed is included in (Fig. 10). This plot shows how quickly the area under the righting arm curve for the two methods of calculation diverges in the case of the load line condition.

Fig. 7 Burned Out Condition Righting Arm Curves

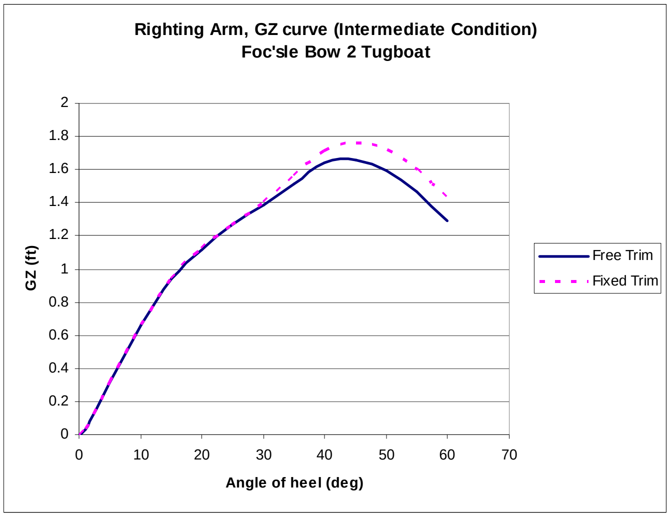

Fig. 8 Intermediate Condition Righting Arm Curves

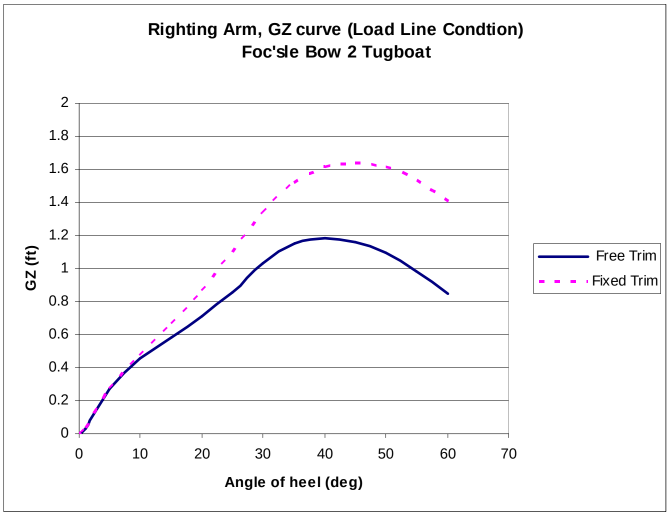

Fig. 9 Loaded Condition Righting Arm Curves

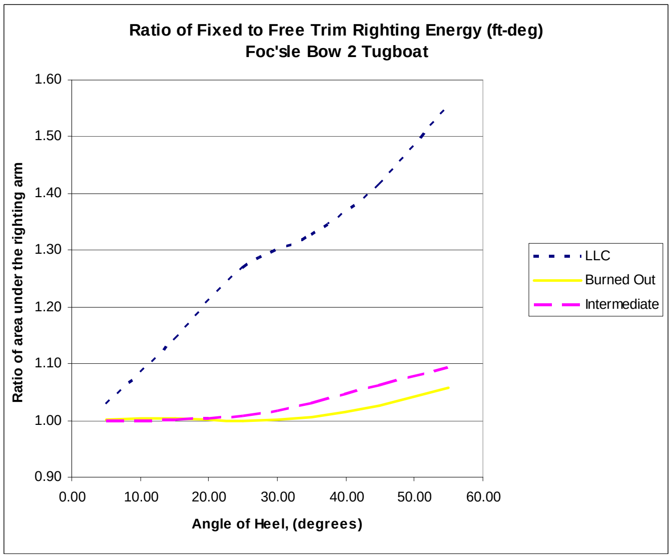

Fig.10 Ratio of Righting Arm Curves

When the analysis is extended to more traditional model bow type tugboats the results have been found to be very different from those presented here. Principally, the righting arm results for the two methods are in much closer agreement throughout the range of heel angles and loading conditions considered.

The vessel for which these plots have been generated is a 4,000 HP, model bow tugboat that has recently been converted to an ATB configuration. The data presented is for the vessel in its original as built condition, as a model bow, hawser tugboat, prior to conversion to an ATB. What the following set of plots demonstrates is characteristic of what has been found for the model bow type tugboats (Fig. 11) that the authors have investigated.

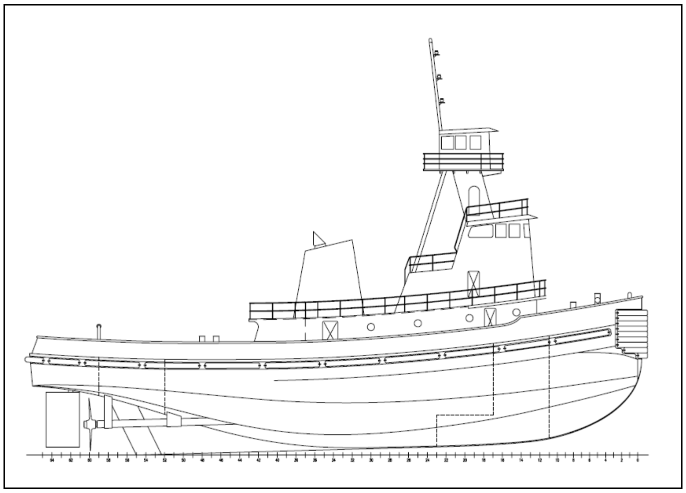

Fig. 11 Model Bow 1 Tugboat

Reference is made to (Figs. 12 ~ 14) which demonstrate the free trim and fixed trim righting arm curves for a model bow tugboat in the burned out, intermediate and load line conditions. These figures show very good agreement even at large angles of heel for the two methods, to over 40 degrees, at which point this particular vessel's righting arm is rapidly deteriorating. Other model bow type tugboats investigated have shown good agreement with the tug illustrated here.

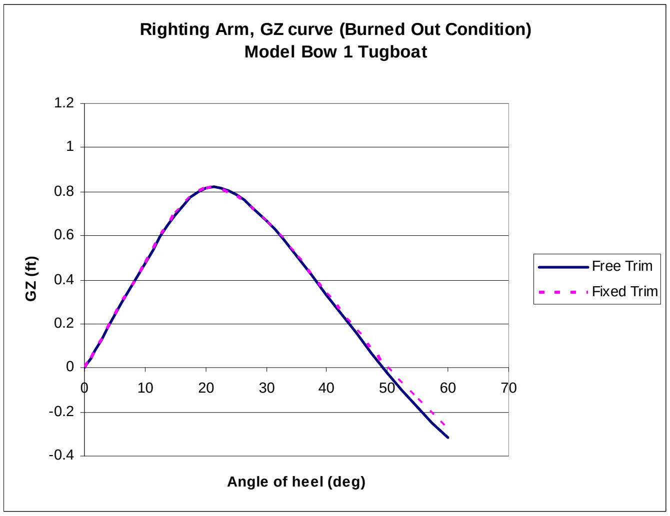

Fig. 12 Burned Out Condition Righting Arm Curves

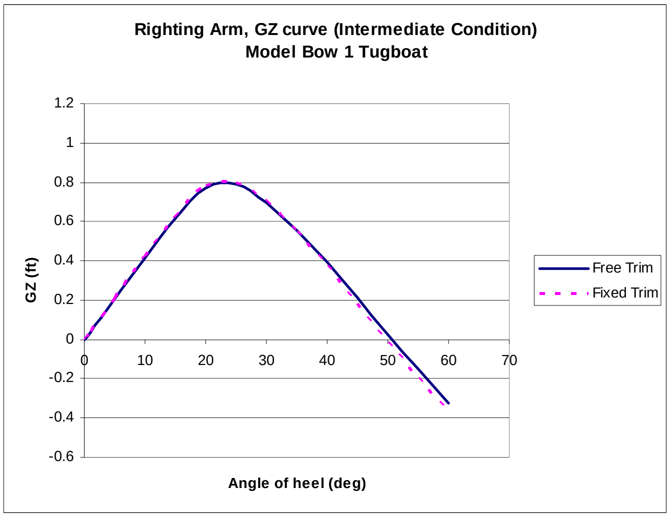

Fig. 13 Intermediate Condition Righting Arm Curves

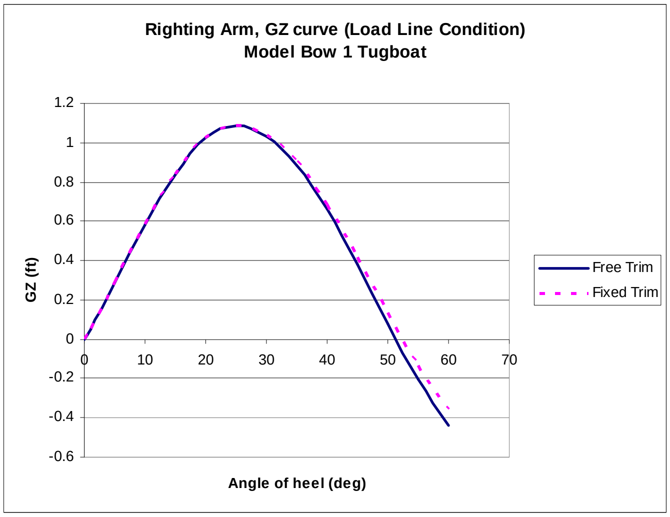

Fig. 14 Loaded Condition Righting Arm Curves

The foc'sle bow vessels that were examined briefly in (Figs. 1 ~ 10) have extended foc'sle bows which terminate in the vicinity of or aft of amidships. This length of foc'sle bow may not be considered typical of the foc'sle bow tugboats currently in operation, as it is rather more at the extremity of the foc'sle bow fleet. To address this, a further analysis of the model bow tugboat previously presented in (Figs. 11 ~ 14) has been conducted. The subject model bow tugboat has been modified to have a foc'sle bow with a limited extent and volume. The total enclosed height was 4.5 ft and from the stem aft to frame 23, consistent with where one might expect such a modification to have been performed on model bow tugboats. See the modified vessel profile in (Fig. 15) below.

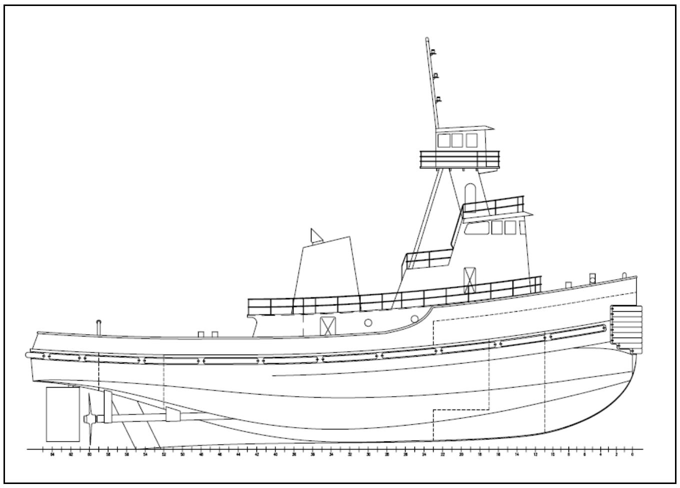

Fig.15 Model Bow 1 Tugboat w/Foc'sle Bow

The resulting righting arm curves follow in (Figs 16 ~ 18).

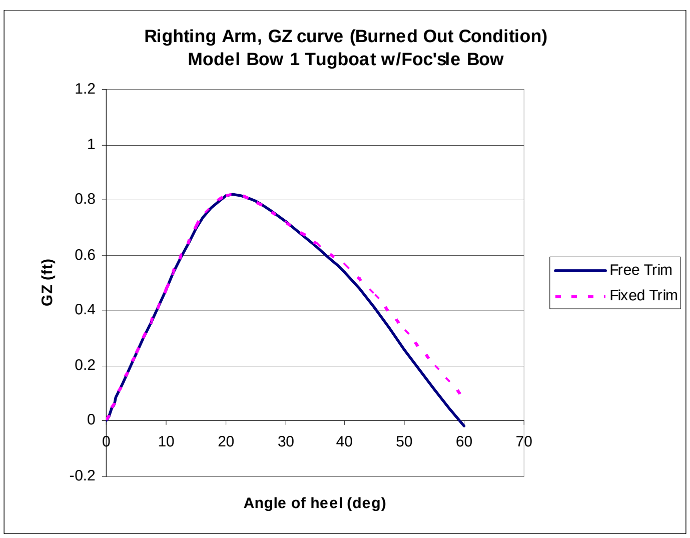

Fig. 16 Burned Out Condition Righting Arm Curves

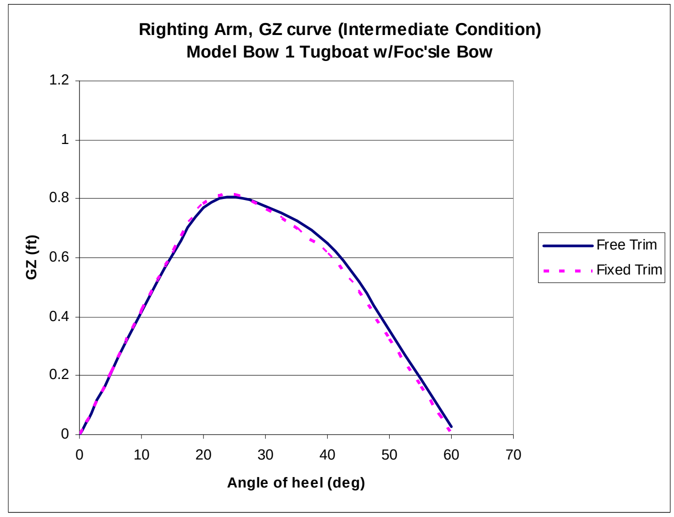

Fig. 17 Intermediate Condition Righting Arm Curves

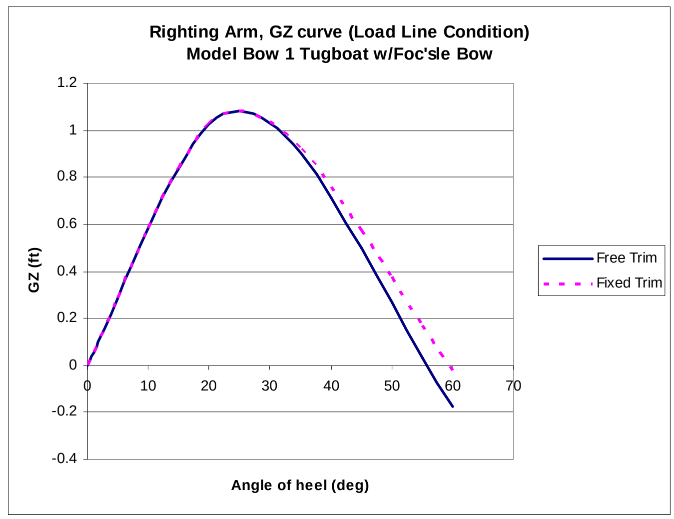

Fig. 18 Loaded Condition Righting Arm Curves

By comparing the model bow tugboat righting arm curve plots in (Figs. 12 ~ 14) with those of the modified model bow tugboat in (Figs. 16 ~ 18) it can be seen that the addition of the low volume foc'sle bow has had a positive effect on the righting arm curves. It has resulted in an extension of the positive range of stability of approximately 10 degrees for all load cases. While the disparity between the fixed and the free trim curves has increased, it is still of rather limited extent.

Of note in comparing (Figs. 12 ~ 14) with those of (Figs. 16 ~ 18) is that there is no difference in the righting arm curves, prior to deck edge immersion, as one might expect. The significance of the foc'sle bow is primarily at larger angles of heel. Another similar model bow tugboat is also similarly modified to have a foc'sle bow and the data for this vessel is presented below. This analysis resulted in similar results to those noted above for model bow tugboat 1. (Figs. 20 ~ 22) are for the model bow tugboat without the additional of a foc'sle bow, as shown in (Fig. 19) below.

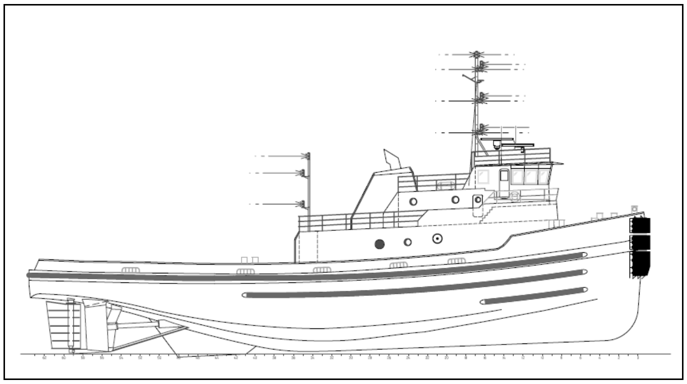

Fig. 19 Model Bow Tugboat 2.

Fig. 20 (Burned Out Condition Righting Arm Curves)

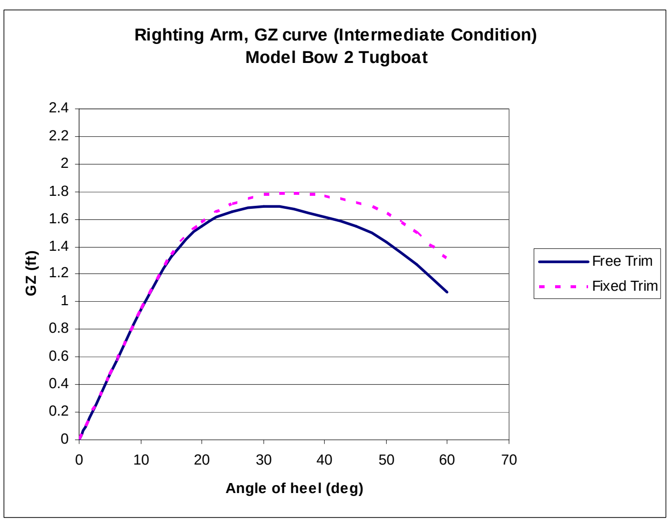

Fig. 21 (Intermediate Condition Righting Arm Curves)

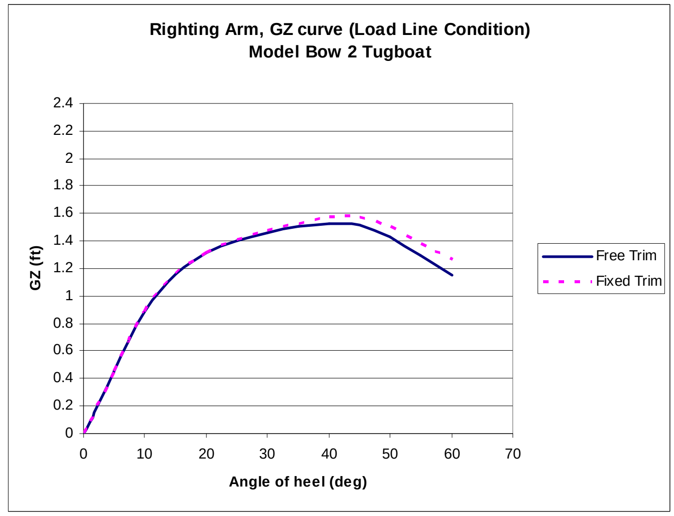

Fig. 22 (Loaded Condition Righting Arm Curves)

(Fig. 23) now illustrates model bow tugboat 2 suitably modified to include a foc'sle bow addition, with (Figs 24 ~ 26) now showing the resulting righting arm curves.

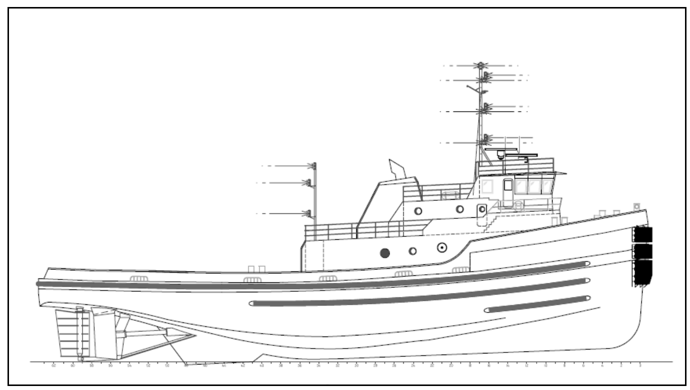

Fig. 23 Model Bow Tugboat 2, w/Foc'sle Bow.

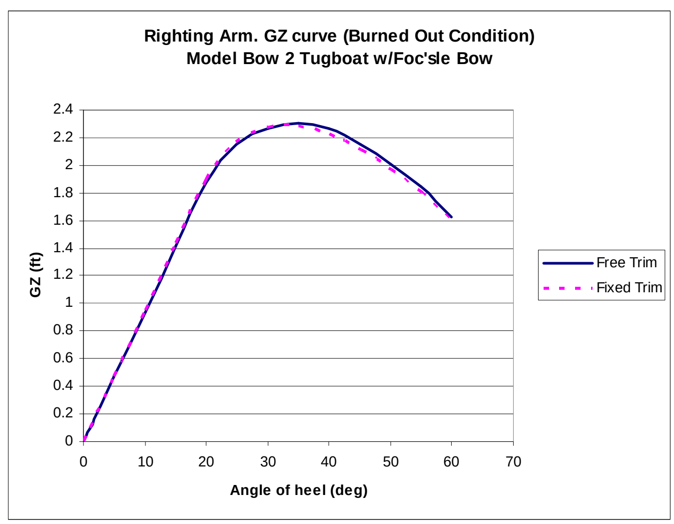

Fig. 24 (Burned Out Condition Righting Arm Curves)

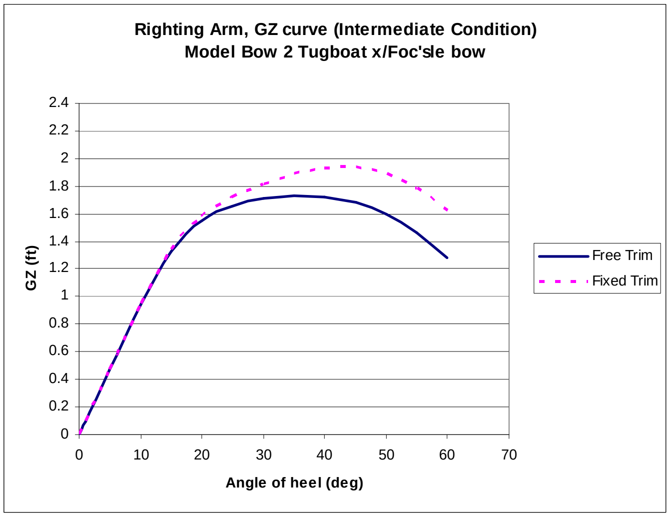

Fig. 25 (Intermediate Condition Righting Arm Curves)

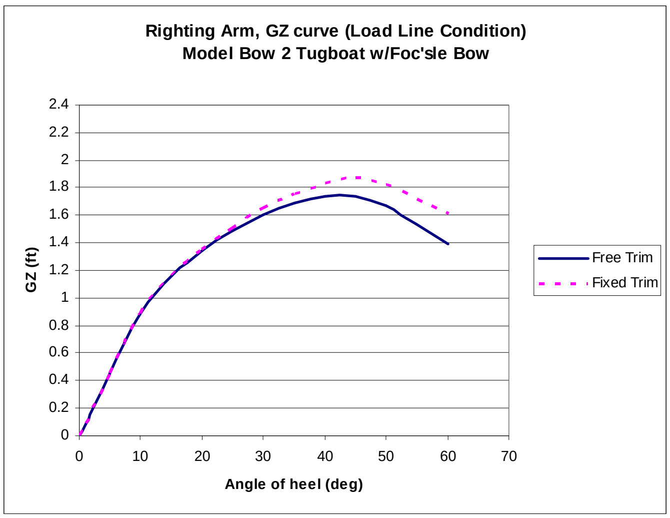

Fig. 26 (Loaded Condition Righting Arm Curves)

In the case of the foc'sle bow tugboats' righting arm plots, (Figs. 2 ~ 4) and (Figs. 7 ~ 9), it appears that the fixed trim method agrees well with the free trim method in the burned out condition, and less so as the vessel is loaded to its load line draft. This appears to be linked directly to the distribution of the first tier superstructure volume relative to the volume of immersed hull in the load line condition. When one considers the model bow tugboat again, this appears to bear out, as the first tier superstructure volume in the case of a model bow tugboat is typically of less enclosed volume than that of a foc'sle bow tugboat, it is more closely centered about amidships and the load line freeboard is greater, ensuring a more evenly distributed above waterline hull volume.

Table 1 illustrates that for the foc'sle bow tugboats the volume of reserve buoyancy in tier one is approximately 40% to 70% of the vessel's loaded displacement. While for the model bow tugboat this is on the order of less than 30%. Further, the relative location of this volume as a percentage of length between perpendiculars, is further forward for the foc'sle bow tugboats, as might be expected. Thus, a trimming moment will be developed as the volume of tier one structure is immersed with increasing heel angle beyond deck edge immersion.

Table 1. First Tier Volume Comparison

	Immersed Hull @ Load Line Condition				**Tier 1 Abv LL draft**		Ratio of Tier 1 volume to Loaded condition Immersed Hull volume (%)
	Draft (m)	Trim (m)	*Volume (ft^3)*	*LCB % aft FP*	*Volume (ft^3)*	*LCB % aft FP*	
Foc'sle Bow 1	5.46	0.15 Fwd	1087	50.4	434	34.9	40.0
Foc'sle Bow 2	4.27	0.29 Aft	679	50.6	463	33.0	69.4
Model Bow 1	4.36	0.41 Fwd	621	49.5	181	38.2	29.1
Model Bow 1 w/Foc'sle	4.36	0.41 Fwd	621	49.5	246	32.4	39.6
Model Bow 2	4.45	1.19 Fwd	844	51.1	250	39.9	29.7
Model Bow 2 w/Foc'sle	4.45	1.19 Fwd	844	51.1	316	34.8	37.4

Table 2. Principle Characteristics

Vessel		LBP (m)	Beam (m)	Depth (m)	L.L. Δ (MT)	L.L. Draft (m)
		Principle Characteristics				
Foc'sle Bow	1	36.57	10.67	5.73	1114.5	5.46
	2	36.27	9.30	4.42	584.2	3.81
	3	36.57	1067	5.73	1141.8	5.55
	4	33.28	9.75	5.18	767.0	4.79
	5	38.40	10.36	4.88	929.5	4.48
	6	33.22	9.48	4.88	699.2	4.63
	7	41.61	11.28	6.31	1449.1	5.67
	8	41.61	11.25	7.89	1264.2	5.27
	9	41.61	11.28	6.22	1444.2	5.67
Model Bow	1	33.28	9.75	5.18	767.0	4.79
	2	38.40	10.36	4.88	929.5	4.48
	3	30.63	8.23	4.27	479.6	3.66
	4	35.63	10.67	5.49	1304.7	4.97

CONCLUSION

The data presented here indicates that using a fixed trim assumption when performing stability analysis for tugboats may not be an accurate assumption. The fixed trim assumption may provide a reasonably accurate stability analysis when compared to the fixed trim assumption for some vessels, principally model bow tugboats of traditional form. This statement may also be made to include a wider array of tugboats in the burned out condition. However, for many foc'sle bow tugboat designs the fixed trim assumption does not provide an accurate analysis of the stability characteristics of these tugboats in the intermediate and particularly the load line conditions. Naval Architects should be aware of this, and apply this knowledge when performing stability analysis on tugboats and particularly foc'sle bow tugboats.

The work of Francescutto[5], first discussed at the International Conference on Marine Research and Transportation, makes specific reference to the fact that the Intact Stability Code (ISC) is aware of deficiencies in stability calculations performed using fixed trim assumptions. Francescutto's presentation mentioned that portions of the ISC are being modified to reflect trim effects in stability calculations. "The fixed-trim calculations accepted up to now were not on the side of safety with respect to the more realistic calculations."[5] This indicates that the discrepancies between the fixed and free trim assumptions utilized for the tugboat analysis presented here are not an anomaly. This problem has been recognized world wide and has been shown to present enough of a discrepancy in results to change the way that the International Maritime Organization approaches stability requirements for vessels.

The USCG Marine Safety Manual, Volume IV also makes mention of the discrepancy between the fixed trim and free trim analysis, specifically with offshore supply vessels (OSV's) and tugboats. The manual states that "the traditional method to calculate righting arms is to maintain a given trim…it is quick and causes negligible error for traditional ships."[6] The manual continues, stating "however, [this method] is misleading at best when the buoyancy of the hull form is not uniformly balanced longitudinally"[6]. Essentially, vessels with superstructures that are not centrally located trim much more substantially than the traditional vessels used to develop the fixed trim stability approximation. This causes the maximum righting arm to artificially increase, making the vessel seem more stable than it actually is. The Marine Safety Manual, Volume IV, section 6.E.20.i. concludes by stating that "due to the tradition of using this method, it is allowed for OSV's and tugboats, the two general hull forms where it introduces the largest error."[6] However, the paragraph further mentions that updates to the righting arm criteria specify that the free trim methodology must be used to ensure accuracy.

With the availability of sophisticated computer software for performing the stability analysis of new build vessels, as well as vessels currently operating, it is necessary to re-evaluate the reliability of assumptions made in the past regarding trim and vessel stability. As demonstrated while the fixed trim assumption provides good agreement with the free trim method in the case of a model bow tugboat, it does not do so for a foc'sle bow tugboat. This is of interest, as many new build coastal towing and ATB tugboats are now built with foc'sle bow configurations. As a result in some cases, the difference in righting energy of the foc'sle bow vessels is so great between fixed and free trim assumptions that the naval architect must be cautious when determining which to use to develop safe operating parameters.

The USCG is aware of this issue, as evidenced by the inclusion in the Marine Safety Manual referenced above. The two types of vessels mentioned are most likely not the only ones that experience significant discrepancies between the free trim and fixed trim calculations. Despite the "tradition" in performing fixed trim calculations, it is not safe to assume that a vessel, especially those with inconsistent longitudinal buoyancy, will perform as the fixed trim calculation predicts. As vessels are constantly being updated and replaced, it is important for the naval architect to understand the detriment of performing stability calculations to an outdated standard. The tugboats analyzed in this paper are just one of the many types of vessels that have the potential to be adversely affected by this fixed trim assumption. As such, the rules dictating their stability criteria should be updated to ensure that a free trim analysis depicting real world response of the vessel is completed.

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