Chapter 6 Longitudinal Stability

6.1 Introduction

In the previous chapter, we looked at transverse stability i.e. we considered the resultant angles of heel when heeling moments are applied to the ship. In this chapter, we will consider stability in the longitudinal direction. In this case we will look at the effect of change in trimming moments on the trim of the ship and the resulting draughts at the perpendiculars.

6.2 Trim due to movement of weights

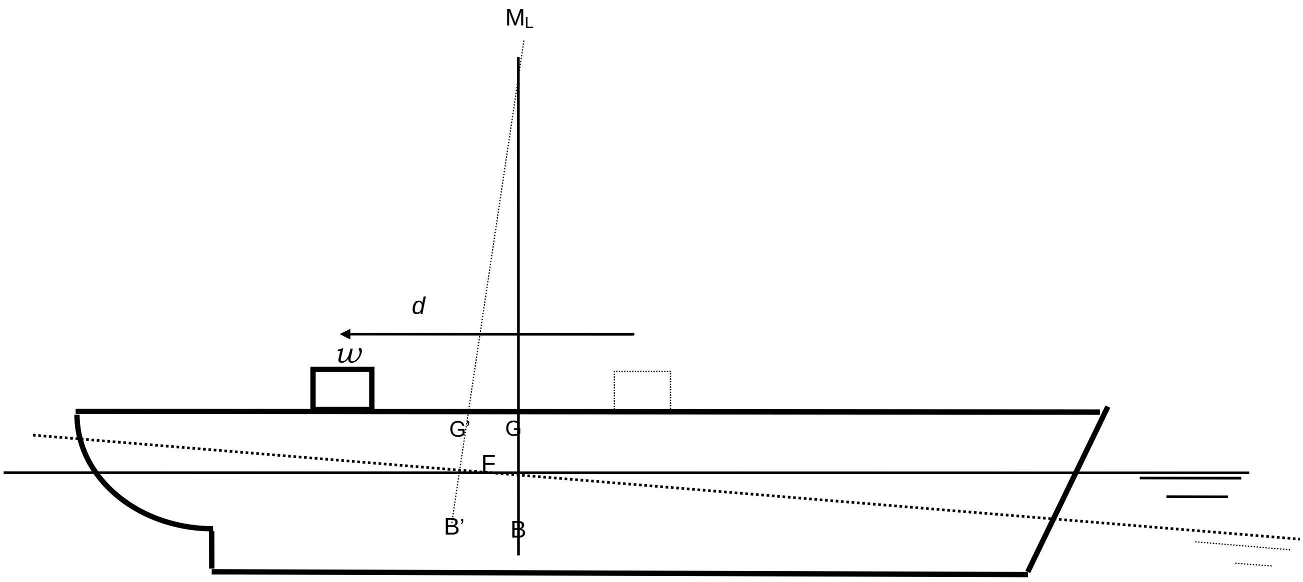


Figure 6.1

Consider the ship as in Figure 6.1. If the weight w is moved a distance d meter, G will move to G' parallel to the direction of movement of w.

$$G\,G' = \frac{w \times d}{\Delta}$$

The shift in weight results in a trimming moment *wd* and the ship will trim until G and B are in line. LCF, the centre of floatation is the centre of area of the water plane. For small trim, the ship is assumed to be trimming about LCF.

The trimming moment causes change in trim and hence change in draughts at AP and FP.

$$\text{Change Trim} = \frac{\text{trimming moment}}{\text{MCTC}}$$

Changes in draught forward, δT_F and aft, δT_A can be obtained by dividing trim in proportion to the distance from LCF to the positions where the draughts are measured, normally AP and FP.

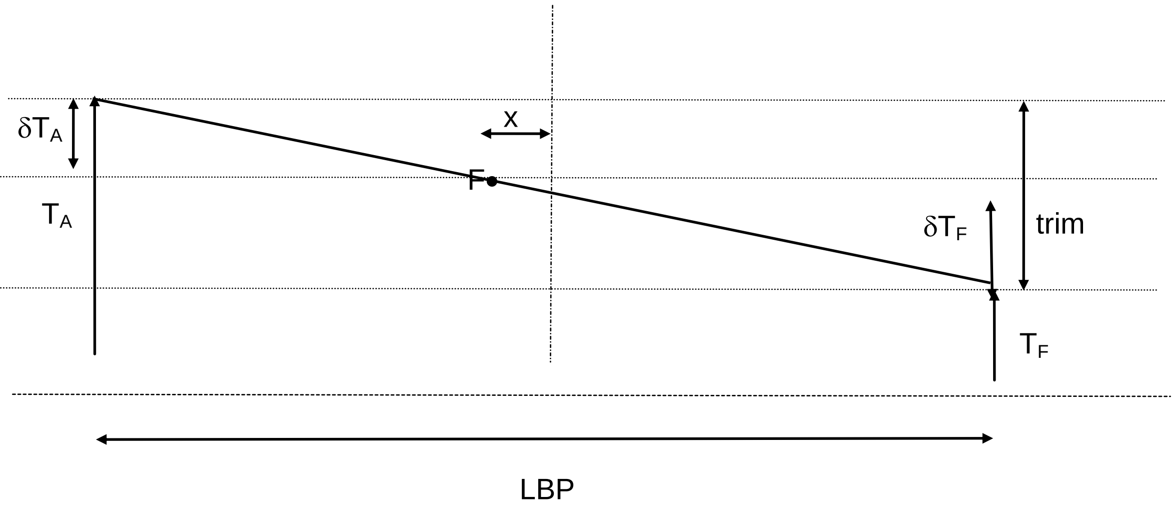


Figure 6.2

$$\text{trim} = \delta T_A + \delta T_F$$

$$\delta T_A = \text{trim x} \left(\frac{\frac{LBP}{2} - x}{LBP} \right) \qquad \delta T_F = \text{trim x} \left(\frac{\frac{LBP}{2} + x}{LBP} \right)$$

Example 6.1

A ship LBP 100 m has MCTC 125 tonne-m while its LCF is 2.0 m aft of amidships. Its original draughts are 4.5 m at AP and 4.45 m at FP.

Find new draughts when a 100 tonne weight already on board is moved 50m aft.

$$\text{Change Trim} = \frac{\text{trimming moment}}{\text{MCTC}}$$

$$\text{Change in trim} = \frac{100 \times 50}{125} = 40 \text{ cm} = 0.4 \text{ m by stern}$$

$$\delta T_F = 0.4 \times \left[\frac{50 + 2.0}{100} \right]$$

$$= \underline{-\ 0.208 \text{ m}}$$

(since ship trims aft, forward draught is reduced i.e. negative) and similarly,

δT_A = <u>+ 0.192 m</u>, positive due to increase in draught aft.

Final draught table;

	T_A	T_F
Original δT	4.5 + 0.192	4.45 - 0.208
New	4.692 m	4.242 m

Exercise:

A ship LBP 50m is floating at Ta= 5.1m and Tf =5.3m. In this condition its MCTC is 30 tonne-m, LCF 5m fwd of amidships.

Find new draughts at Ap and FP when 50 tonne weight is moved 15m forward.

6.3 Small Weight Changes

If a small weight w is added or removed from a ship, the draught of the ship will change as follows:

i. Parallel sinkage/rise $\dfrac{w}{TPC}$

ii. Change in trim = $\dfrac{\text{trimming moment}}{MCTC} = \dfrac{w \text{ x distance to LCF}}{MCTC}$

Once trim is obtained, the changes δT_F and δT_A can be calculated and the final draughts will include the parallel rise/sinkage and δT_F & δT_A.

Example 6.2

A ship LBP 100 m has LCF 3 m aft of amidships and floats at 3.2 m and 4.4 m at FP and AP respectively. Its TPC is 10 tonne while MCTC 100 tonne-m. 50 tonne cargo is removed from 20 m forward of amidships while 30 tonne is unloaded from cargo hold 15 m aft of amidships. Find the final draughts at the perpendiculars.

When cargo is removed, draught reduces i.e. the ship rise.

$$\text{Parallel rise} = \frac{80}{10} = 8 \text{ cm} = 0.08 \text{ m}$$

At the same time, the ship trims because there is a change of moment about LCF.

Change in Moment = sum of moment of weight about LCF
= 50 x (20 + 3) – 30 x (15 – 3)
(aft) = <u>790 tonne-m</u>

$$\text{Change in trim} = \frac{790}{100} = 0.079 \text{ m}$$

$$\delta T_A = 0.079 \left(\frac{\frac{100}{2} - 3}{100} \right) = +\ 0.037 \text{ m}$$

$$\delta T_F = 0.079 \left(\frac{\frac{100}{2} - 3}{100} \right) = -\ 0.042 \text{ m}$$

	T_A	T_F
Original	4.4 m	3.2 m
Rise	- 0.08	- 0.08
δT	+ 0.037	- 0.041
	4.357 m	3.089 m

6.4 Effect of Large Changes in Mass

The effects discussed in Section 6.3 are related to small changes in weights. These small changes lead to small changes in draughts and the hydrostatic particulars are assumed unchanged.

If the weight changes are big, draughts will change significantly. Hydrostatic data such as TPC and MCTC will also change and therefore the simple formula used in Section 6.3 can no longer be used.

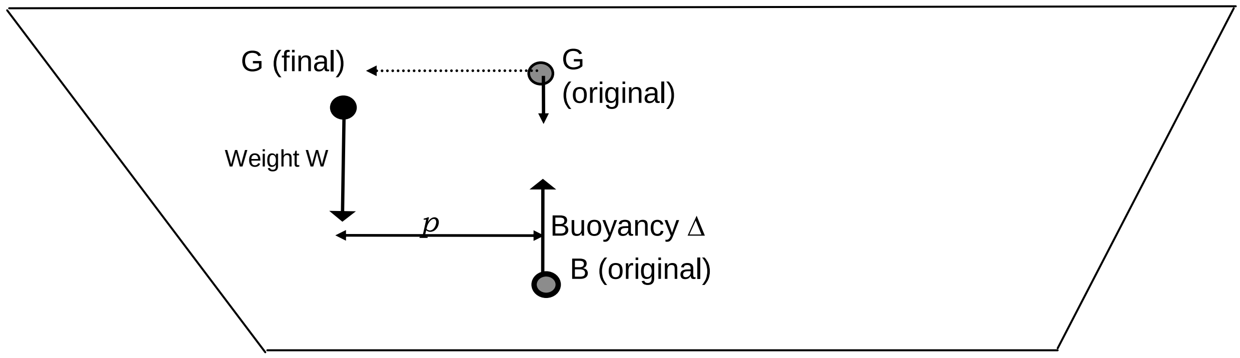


Figure 6.3 Relative Positions of G and B

Consider the relative positions of centre of gravity and centre of gravity as shown in Figure 6.3. Before addition or removal of weight, B is directly under G and in equilibrium, buoyancy Δ equals weight W.

When weights are added, the draught of the ship can be considered to change as follows:

i.) The effect of additional weight will cause the vessel to sink to new draught. But since there is a big change in draught, TPC cannot be used. Instead, the mean draught of the ship must be obtained from hydrostatic particulars. At this mean draught, also obtain LCB, MCTC and LCF.

ii.) From the way the vessel is loaded, the final LCG can be calculated. The new location of G is no longer directly under the new LCB of the ship i.e. a trimming moment is created which will trim the vessel. If the longitudinal separation between G and B is *p*, then trim can be calculated:

$$\text{Trim (m)} = \frac{\Delta \text{ x } p}{MCTC \text{ x} 100}$$

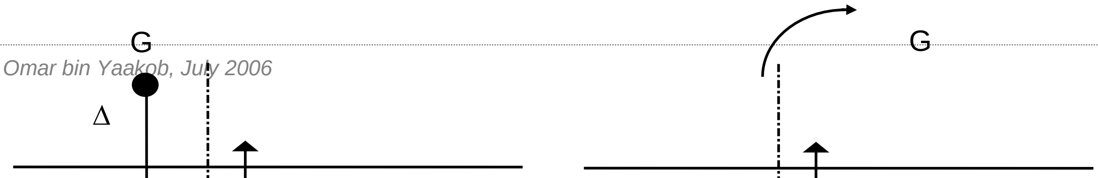
LCG, LCB, MCTC and Δ in this formula are for the final condition of equilibrium.

This formula is important for two cases:

i) If we know the condition of the ship in terms of its weight and LCG as well as its hydrostatic particulars (LCB, LCF, MCTC) we can find its trim and the draughts at the perpendiculars.

ii) If we know ships draughts, we can find trim and hydrostatic particulars (LCB, MCTC, LCF, displacement). Using the above formula, we can find LCG.

Direction of trim (by stern or bow) can be derived by considering the relative position of LCG and LCB giving the direction of the trimming moment.



Trim by Stern Trim by Bow

Figure 6.4

6.5 Loading Calculations

Loading calculation is an important step in the ship design process. Through this calculation, we are able to calculate the final displacement of the ship, its KG, LCG and final draughts at the perpendiculars. Also, the value of GM can be estimated. The calculation is done for a number of ship loading conditions.

A loading table is used where the weights of the ship and any additional deadweight and the respective kg and lcg are tabulated. Finally the total weights, KG and LCG can be obtained. By using hydrostatic table, values of mean draught, MCTC, LCF, KMT and LCB are obtained. The formula above is used to calculate ships draughts at AP and FP. Also, since KG and KMT are known, the value of GM can be obtained.

The above calculations are carried out while the ship is still on the drawing board.

Loading calculation is also important for the ship's master to know the current condition of his ship. Calculations can be done to determine the current level of stability and draughts when some loading and unloading are done on the ship.

To undertake loading calculations, the following items are required:

a) Hydrostatic data, table or particulars.

b) The weight, KG and LCG of the original ship whether lightship or already loaded.

c) A list of loads to be added or removed from the ship; their masses, kg and lcg.

Example 6.3

A ship LBP 125m having lightship mass 4000 tonne, LCG 1.6m aft of amidships is loaded with the following:

8500 tonne cargo lcg 3.9m forward of amidships
1200 tonne fuel lcg 3.1m aft of amidships
200 tonne water lcg 7.6m aft of amidships.
100 tonne store lcg 30.5m fwd of amidships

Hydrostatic particulars indicate that at 14000 tonne displacement, mean draught is 7.8m, MCTC 160 tonne-m, LCB 2.00m forward of amidships and LCF 1.5m forward of amidships. Find the final draughts at the perpendiculars.

Item	**Mass (tonnes)**	**LCG (m from amidships)**	**Fwd Moment about amidships (tonne-m)**	**Aft Moment about amidships (tonne-m)**
Lightship	4000	1.6A		6400
Cargo	8500	3.9F	33150	
Fuel	1200	3.1A		3720
Water	200	7.6A		1520
Store	100	30.5F	3050	
TOTAL	**14000**		**36200**	**11640**

Forward Excess Moment = 36200 - 11640
= 24560 tonne m

$$\text{LCG from amidships} = \frac{24560}{14000}$$
= 1.754m fwd of amidships

From hydrostatics, LCB 2.00m forward of amidships

$$\text{Trim} = \frac{0.246 \times 14000}{160 \times 100}$$

$$= \underline{0.215\text{m aft}}$$

$$\delta T_A = 0.215 \times \left(\frac{\frac{125}{2} - 1.5}{125}\right) = +0.11\text{m}$$

$$\delta T_F = 0.215 \times \left(\frac{\frac{125}{2} + 1.5}{125}\right) = -0.105\text{m}$$

	Aft	Fwd

T (Original)	7.8m	7.8m
δT	0.11	-0.105
T (Final)	7.91m	7.695m

6.6 Finding LCG of a Ship by measuring draughts

If we have the hydrostatic particulars of the vessel and we can measure the draughts of the floating ship, we can know the ships weight and LCG.

The steps are as follows:

- Read T_F, T_A
- Calculate trim = $| T_F - T_A |$
- Calculate Tmean = $\frac{T_F + T_A}{2}$
- Use T_{mean} to obtain Δ, MCTC and LCB from hydrostatic table.
- Use trim formula to calculate the value of *p* i.e.

$$p = \frac{MCTC \times 100 \times Trim}{\Delta}$$

since p= Distance (LCB ~ LCG), the location of LCG can be determined.

Note that the value of p is the actual distance between B and G in the longitudinal direction. The actual position of G will depend on the direction of trim as discussed earlier, see Figure 6.4.

6.7 Lightship survey or Inclining Experiment

The process to obtain the actual mass, KG and LCG of a ship is called **lightship survey** and **inclining experiment** is the part in which the ship is inclined to obtain KG.
It consists of taking a set of measurements and conducting analysis to obtain the required objectives. Although sometimes the whole process is called an inclining experiment, inclining the ship is only a part of the whole procedure and will achieve only one aspect of the whole objectives. Inclining experiment itself is very important and required to be done on every ship under the Merchant Shipping Ordinance 1952.

The main objectives of the lightship survey are to determine for the ship in as inclined condition and lightship condition:

i. Displacement
ii. KG
iii. LCG

When the three particulars are known for a lightship condition, displacement and centre of gravity for other conditions can be determined by using loading calculation as explained in Section 6.5.

Preparation

The measurements are carried out when the ship is completed or nearly complete. The vessel should be floating freely, not touching the bottom. Gangways and ladders should be removed. Any loose cables and equipment must be secured while tanks should either be fully pressed or emptied to reduce free surface effects.

The draughts are measured at six locations around the ship. Mean draught is calculated and is used to enter the hydrostatic tables to obtain the hydrostatic particulars of Δ, MCTC, KMT and LCB. The density of water is also measured.

The inclining experiment itself is carried out by moving weights across the ship. The weights are chosen such that the total weight on one side will give about two degrees of heel. The angles of heel are usually measured using three pendulums. If other devices are used, one pendulum must still be used. To increase accuracy, the pendulum should be the longest possible and to facilitate pendulum deflection reading, the pendulum bob may be immersed in oil.

Movement of weights

Weights are moved one by one across the deck and after each move pendulum reading is taken. When all three weights have been moved across, readings are again taken each time the weights are returned to the original position.

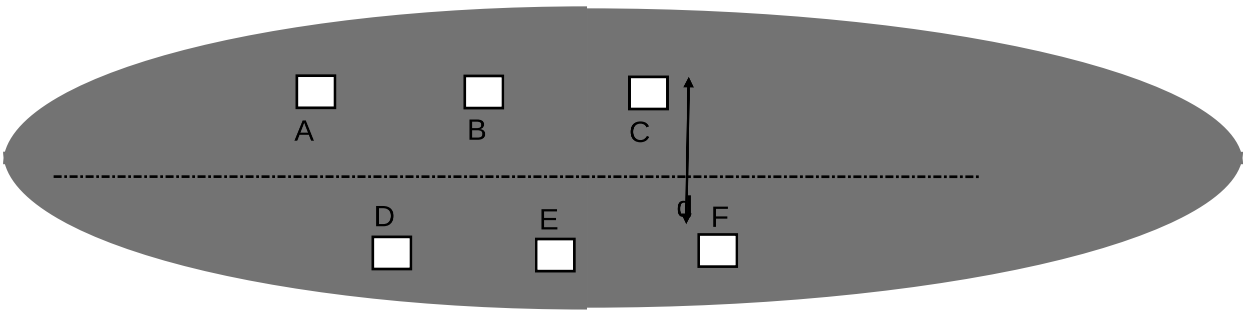


Figure 6.5

Processing Results

The results are first processed for the ship in the condition at which the measurements are taken. This is known as the ‘ as inclined condition’. This condition is different from the final lightship conditions and therefore corrections will have to be made later.

a. To obtain Δ and other hydrostatic particulars in as inclined condition

- From six draughts, obtain Tmean.
- Use T mean to read KM_T, LCB, MCTC, Δ and LCF from hydrostatic tables.
- Hydrostatic tables are prepared normally using the assumed density of 1.025 tonnes/m^3. Correction must be made to Δ and MCTC for density difference.
  For example:
  $$\Delta_{actual} = \frac{\Delta_{table}\ \rho_{actual}}{\rho_{table}}$$

b. To obtain KG as inclined

Based on the formula:

$$\frac{wd}{\Delta} = GM \tan \phi$$

By plotting $\frac{wd}{\Delta}$ vs $\tan \phi$, a straight line is expected as shown in Figure 6.6.

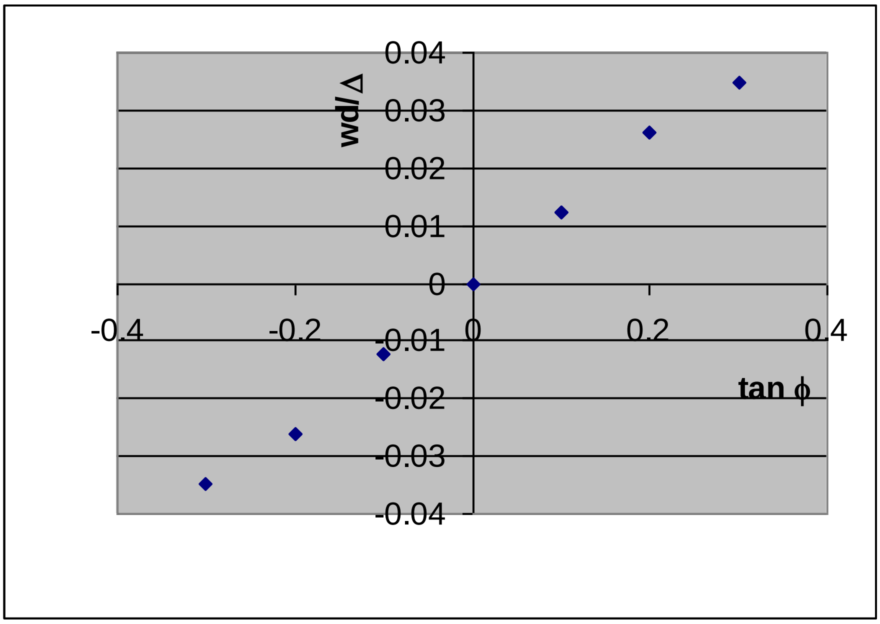


Figure 6.6

Since KM is known from hydrostatic data, the height of centre of gravity above keel,

$$KG = KM - GM$$

c. To obtain LCG as inclined

The position of LCG is obtained using methods described in Section 6.6 i.e. by using the trim formula to calculate the value of *p* i.e.

$$p = = \frac{\text{MCTC x100 x Trim}}{\Delta}$$

since p= Distance (LCB ~ LCG), the location of LCG can be determined.

d. Obtaining final Δ, KG and LCG for lightship

A detailed record must be made of items that have yet to be installed on the ship as well as items that are not part of the ship but present on the ship during the lightship survey. Examples of the former are deck equipment, cranes or any other equipment yet to be installed. Items to be excluded include personnel, inclining weights and other equipment.

The following format may be used:

Item	**Mass (tonnes)**	**Kg (m)**	**Vertical Moment (tonne-m)**	**Lcg (m from amidships)**	**Fwd Moment (tonne-m)**	**Aft Moment (tonne-m)**
Ship as inclined						
Items to remove						
Incl.weights	-12	12				
Personnel	-0.7	12.5				
Items to add						
Deck cranes	+5	17				
Generator	+2	1.3				
LIGHTSHIP						

Example 6.4

Hydrostatic Particulars of *MV Penyu* LBP 50m is given below:

Drauf	Displacement tonnes	Cb	MCTC (tonne-m)	LCB (m from O)	LCF (m dari O)
4.00	5000	0.75	100.00	-2.00	3.0
5.00	6000	0.76	110.00	-1.5	2.0

6.00	7000	0.77	120.00	0.0	0.0
7.00	8000	0.78	130.00	0.0	0.0

The ship M.V. Penyu is floating at level keel draught of 4.50m.

Cargo are loaded as follows:

500 tonnes at lcg 10m Aft of amidships
500 tonnes at lcg 10m Fwd of amidships
500 tonnes at lcg 20m Fwd of amidships
500 tonnes at lcg 15m Aft of amidships

Find its final draughts at the perpendiculars.

SOLUTION:

i. Find displacement (5500)and LCB (-1.75) of original ship. Since ship is level keel, trim = 0, p= 0 therefore LCG= LCB.

ii. Construct table to find final displacement and LCG.

Item	Weight (tonnes)	Lcg (m from amidships)	Moment about amidship (tonne-m)
Ori. ship	5500	-1.75	
Cargo 1			
Cargo 2			
Cargo 3			
Cargo 4			
TOTAL			

$$LCG = \frac{\text{Total moment amidship}}{\text{Total weight}} = 0.95 \text{ m aft of amidship}$$

iii. Use total weight to go into Hydrostatic Table and get
Tmean, MCTC, LCB, LCF
6.50m, 125tm, 0, 0

iv. find distance p where p is longitudinal distance between LCB and LCG.

p = 0.95m

v. Use formula

$$trim = \frac{displacement \ x \ p}{MCTC \ x \ 100}$$

Trim= 0.57m

vi. Use normal formula to calculate delta Ta and delta Tf. Since LCF is at amidships, delta Ta= delta Tf = trim/2 =

vii. Make final table:

	Aft	Fwd
Tmean		
Delta T		
Final	6.785	6.215

Exercise 6

1. A ship LBP 60m has lightship 500 tonnes, KG 3.7m and LCG 2.0m aft of amidships. The following are loaded:

Item	Mass (tonnes)	Kg (m)	LCG from ⊗ (m)
Fuel Tank	50	0.7	1.5A
Fresh Water	10	3.6	26.2F
Cargo	735	3.2	1.5F
Crew and Store	5	5.5	20.0A

Find Final KG and LCG

2. A ship LBP 100 m has LCF 3 m aft of amidships and floats at 3.2 m and 4.4 m at FP and AP respectively. Its TPC is 10 tonne while MCTC 100 tonne-m.

The following cargo is added and removed:

UNLOAD 50 tonne cargo from 20 m forward of amidships
30 tonne cargo from 15 m aft of amidships.
10 tonne cargo at amidships.

LOAD 20 tonne cargo at 10m fwd of amidships
5 tonne fuel at 10m aft of amidships

Find the final draughts at the perpendiculars.

Item	*Weight*	*Lcg (from amidships)*	*D (m from LCF)*	*Moment about LCF (tonne-m)*
Cargo1				
Cargo2				
Cargo3				

Cargo4				
Fuel				
TOTAL				

Use TPC, net weight reduced Rise =
Net moment = tm aft

Trim =

Find deltaTa and deltaTf

δT_A = m
δT_F = m

Make final table:

	T_A	T_F
Original *Rise* δT	*4.4*	
FINAL		

2. A ship is being loaded in port. At one point, its draughts are 10.5m A and 12.2m F, MCTC 200tonne-m and LCF 2m fwd of amidships. A further 5000 tonnes cargo is to be loaded at locations 10m fwd of amidships and 10m aft of amidships. Determine how the cargo should be distributed to complete loading with an even keel.

3. A ship arrives in port trimmed 25cms by stern. The centre of floatation is amidships, MCTC 100 tm. A total of 1000 tonnes is to be discharged from No1 hold (lcg 50m fwd of LCF) and No 4 Hold (lcg 45m aft of LCF). Find how much to be discharged from each hold for the ship to complete loading on even keel.

{Solution guide: Find trimming moment currently trimming ship using
Trim (cm) = trimming mmt/ MCTC
Remove weights such that net moment from removal will counteract the trimming moment.}

4. A ship is floating at draughts of 6.1m F and 6.7m A. The following cargo is then loaded:

20 tonnes with lcg 30m forward of amidships.
45 tonnes 25m forward of amidships
60 tonnes 15m aft of amidships
30 tonnes 3m aft of amidships

If LCF is at amidships, MCTC 200 tonne-m and TPC 35 tonne, find final draughts.

5. An oil tanker 150m long, displacement 12,500 tonnes, LCF 1m aft of amidships, MCTC 200 tonnes-m leaves port with draughts 7.2m F and 7.4m A. There are 550 tonnes of fuel oil in the forward deep tank (centre of gravity 70m forward of LCF) and 600 tonnes in the after deep tank (centre of gravity 60m aft of LCF). During the sea passage, 450 tonnes of oil is consumed from the aft tank. Find how much oil must be transferred from the forward to the aft tank if the ship is to arrive on an even keel.

6. A ship arrives in port trimmed 0.3 m by the stern and is to discharge 4,600 tonnes of cargo from 4 holds. 1,800 tonnes of cargo is to be discharged from No.2 and 800 tonnes from No.3 hold. Centre of floatation is amidships. MCTC=250 tonne-m.

Centre of gravities of the holds No 1, 2, 3 and 4 from amidships are 45m forward, 25m forward, 20m aft and 50m aft respectively.

Find the amount of cargo to be discharged from Nos. 1 and 4 holds if the ship is to sail on an even keel.

7. MV Bulker LBP 100 m is floating at a level keel draught of 7m. Its LCG is 4m fwd of amidships.

The following cargo are loaded:

2000 tonne lcg 10m aft of amidships

2000 tonne lcg 10m fwd of amidships 1000 tonne lcg 5m aft of amidships

Find the final draughts at the perpendiculars. Use the provided hydrostatic curves.

8. MV bulker is floating at draughts of 7.8m F and 7.1m A. Find its displacement and LCG.

9. Bunga Kintan is floating at draught of 6.2mF and 5.8mA. Its GM was measured and found to be 0.15m. Find its displacement , LCG and KG.

10. Some weights (w=200 tonnes,lcg= 2m fwd of amidships, kg=5.0m) are taken off. What is its final displacement , LCG and KG ?

11. Pemerhatian berikut diperolehi daripada ujikaji sendeng. Kirakan **sesaran** serta **kedudukan pusat graviti membujur (LCG)** bagi keadaan kapal kosong.

Drauf:	FP	4.92m
	Peminggang	5.50m
	AP	6.08m

Ketumpatan air laut 1025 kg/m³. Jumlah beban (termasuk pemberat dan air balas) yang perlu dikeluarkan bagi mendapatkan kapal kosong ialah 354 tonne pada lokasi 4.0m di depan peminggang dan 10.5m di atas lunas. Panjang kapal ialah 125m dan butiran hidrostatiknya di dalam air berketumpatan 1025 Kg/m³ adalah seperti berikut;

Drauf (m)	**Sesaran (tonne)**	**KMT (m)**	**MCTC (tonne-m)**	**LCB (m dari ⊗)**	**LCF (m dari ⊗)**
6.00	10300	8.4	141.0	3.8m Fwd	0.0 m
5.00	8200	9.0	131.0	4.0m Fwd	0.0 m

HOMEWORK

1. A ship LBP 60m has lightship 500 tonnes, KG 3.7m and LCG 2.0m aft of amidships.
   The following are loaded:

Item	Mass (tonnes)	Kg (m)	LCG from ⊗ (m)	FSM (tonne-m)
Fuel Tank	50	0.7	1.5A	40
Fresh Water	10	3.6	26.2F	15
Cargo	735	3.2	1.5F	
Crew and Store	5	5.5	20.0A	

Extracts from Hydrostatic Table as follows:

Drauf (m)	Sesaran (tonnes)	MCTC (tonne-m)	LCB dari ⊗ (m)	LCF from ⊗ (m)	KMT (m)
3.6	1280	14.5	0.30A	0.0	4.29
3.8	1320	14.7	0.20A	0.0	4.15

1. Find the final Displacement, KG, LCG and GM_T
2. Find Trim
3. Find new Draughts at AP and FP.
4. A 50 tonne weight is moved 6 m across. Find the resulting angle of heel.