Design Theories of Ship and Offshore Plant

Part I. Ship Design

Ch. 3 Hull Form Design

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Contents

Ch. 3 Hull Form Design

3.1 Generation of a Hull Form

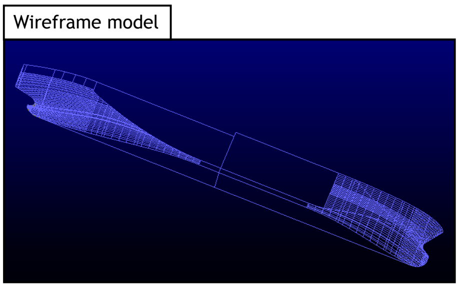
What is a “Hull form”?

☑ **Hull form**
  - **Outer shape of the hull that is streamlined in order to satisfy requirements of a ship owner such as a deadweight, ship speed, and so on**
  - **Like a skin of human**

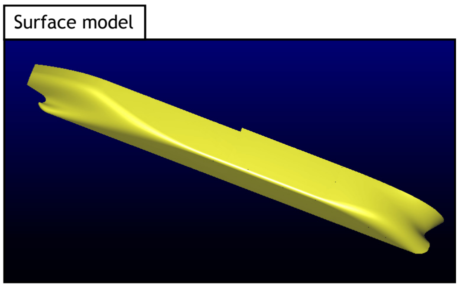
☑ **Hull form design**
  - **Design task that designs the hull form**

Hull form of the VLCC(Very Large Crude oil Carrier)

Wireframe model

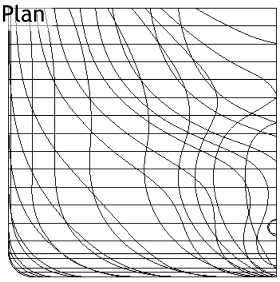


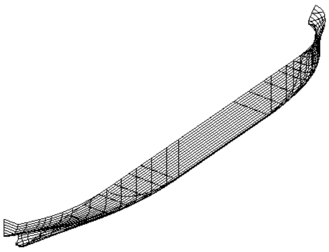
Surface model



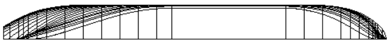
Lines

Body Plan



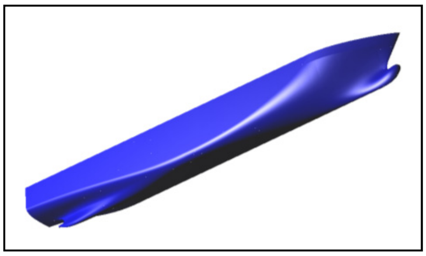


Water Plan



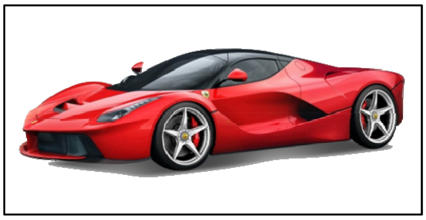
Sheer Plan

Hull Form Design vs. Car Exterior Design



❑ Hull form design

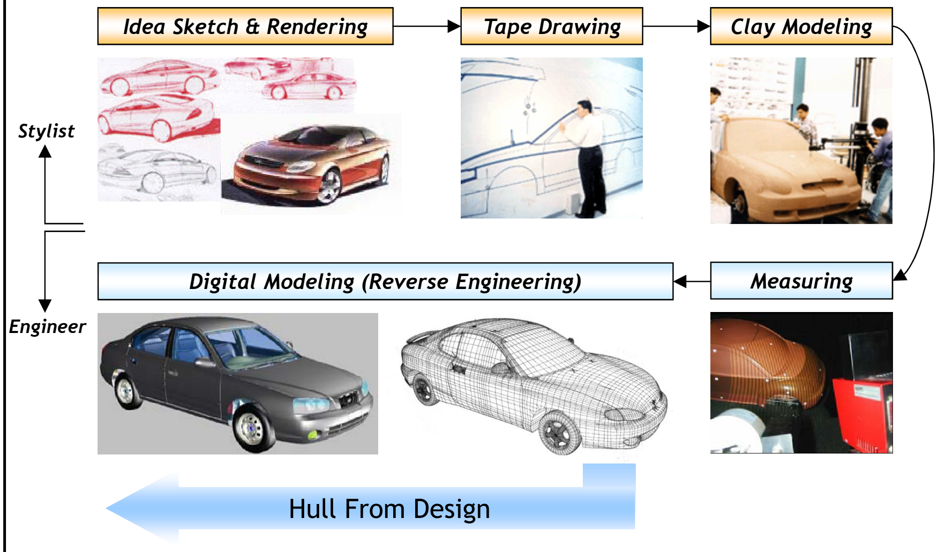
- A hull form is related to **the resistance and propulsion performance** of a ship.
- Order production: new design for each order
- Large structure of about 100~400 m length
- **The performance like speed and deadweight is most important**.



❑ Car exterior design

- A exterior is related to **the air resistance and esthetic design** of a car.
- Mass production: one time design for each model
- **The performance and esthetic design are simultaneously important**.

Procedure of Car Exterior Design



Idea Sketch & Rendering → *Tape Drawing* → *Clay Modeling*

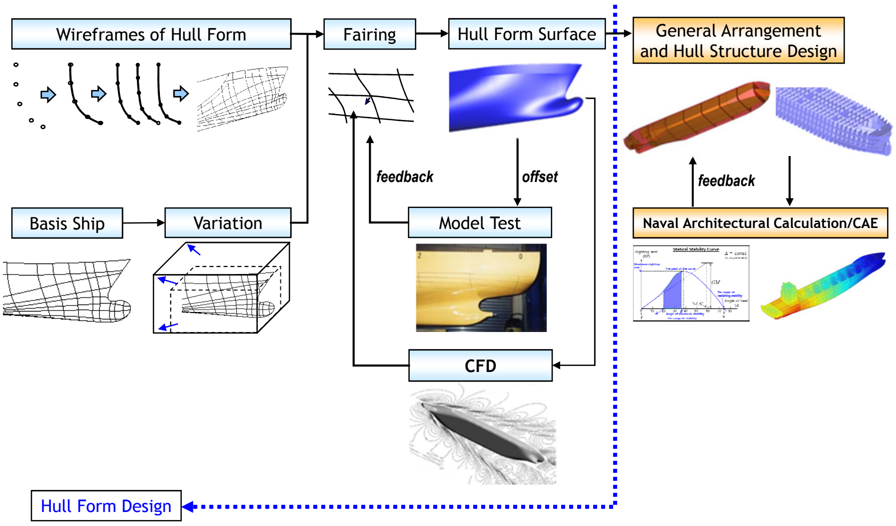
Stylist

Engineer

Digital Modeling (Reverse Engineering) ← *Measuring*

Hull From Design

Procedure of Hull Form Design



Wireframes of Hull Form

Fairing

Hull Form Surface

General Arrangement and Hull Structure Design

feedback

offset

feedback

Basis Ship

Variation

Model Test

Naval Architectural Calculation/CAE

CFD

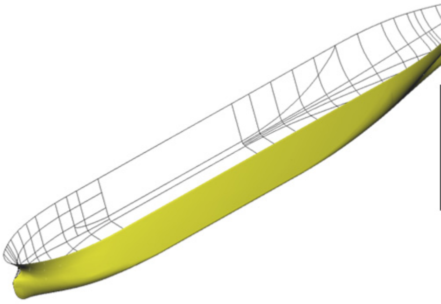
Hull Form Design

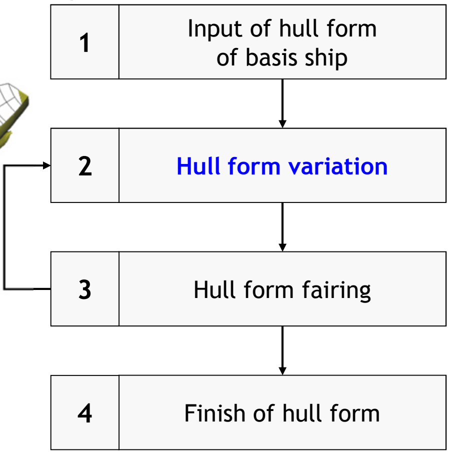
* CFD: Computational Fluid Dynamics, CAE: Computer-Aided Engineering

Overview of Hull Form Design

☑ Procedures of hull form (wire frame) design

- Input or generation of hull form of basis ship
- Variation from basis ship to design ship
- Fairing of varied hull form





1 Input of hull form of basis ship

2 Hull form variation

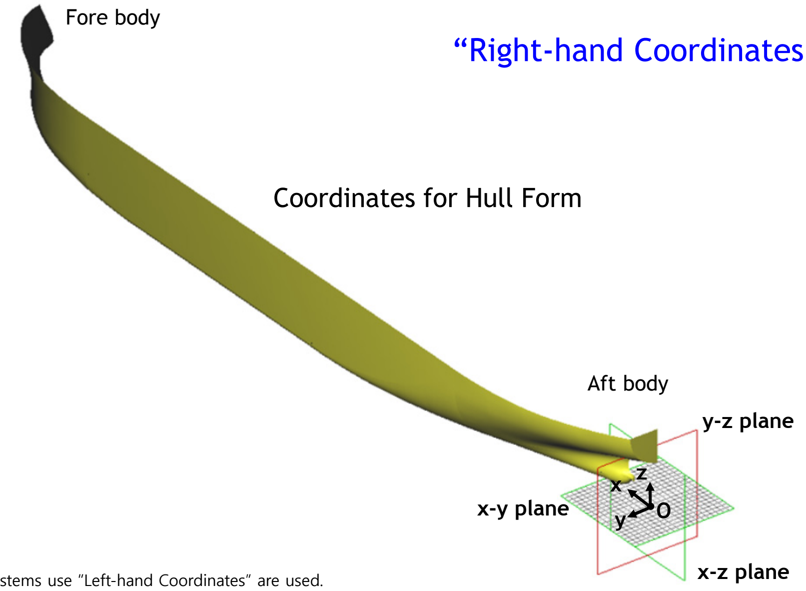
3 Hull form fairing

4 Finish of hull form

Coordinates for Hull Form Representation

"Right-hand Coordinates"

Coordinates for Hull Form



* Some systems use "Left-hand Coordinates" are used.

Composition of Wireframes of Hull Form

☑ Hull form curves

- Primary curves
  - They define the outer shape of a hull form.
  - Profile line, bottom tangent line, side tangent line, etc.
- Secondary curves
  - They define the inner shape of a hull form under the outer shape defined by primary curves.
  - Section line, buttock line, water line, space line, etc.

☑ Wireframes

- Group of hull form curves which are generated from primary and secondary curves, and intersection curves among them
- They contain a number of closed regions of triangle, quadrilateral, pentagon, etc.
- Basis for generating a hull form surface

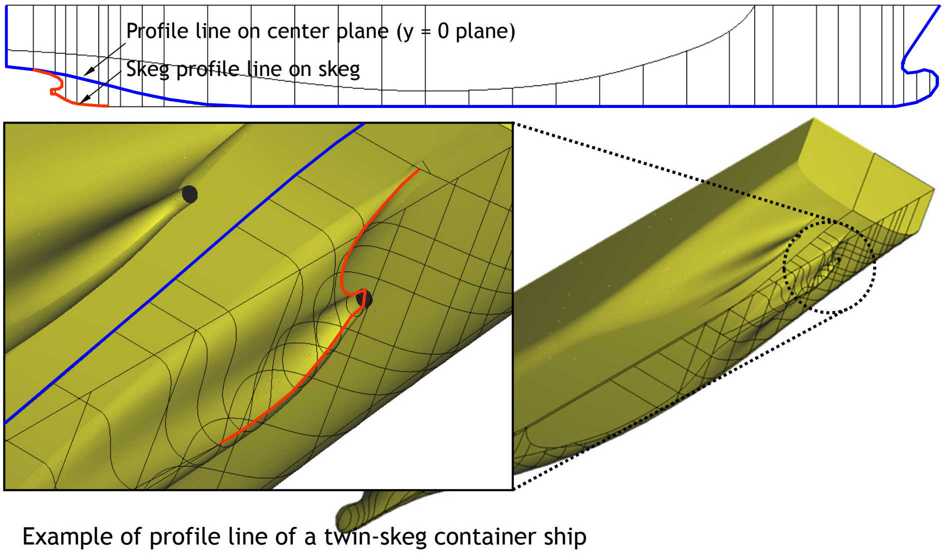
Primary Curves for Hull Form Representation - Profile Line (1/2)

☑ **Profile line is an intersection (or tangent) curve between hull form surface and center plane (center plane, y = 0 plane) except for deck.**

☑ **Also called center line**

Example of profile line of a 320K VLCC

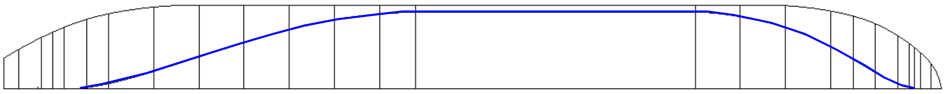
Primary Curves for Hull Form Representation - Profile Line (2/2)



Example of profile line of a twin-skeg container ship

Primary Curves for Hull Form Representation
- Bottom Tangent Line

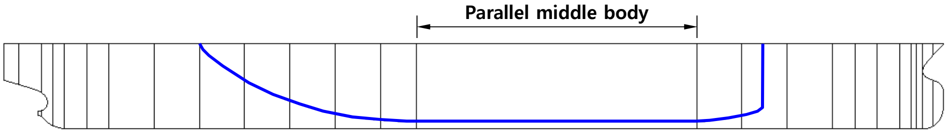
☑ **Bottom tangent line is an intersection (or tangent) curve between hull form surface and base plane (z = 0 plane)**



Example of bottom tangent line of a 320K VLCC

Primary Curves for Hull Form Representation
- Side Tangent Line

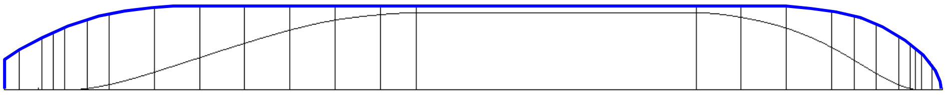
☑ **Side tangent line is an intersection (or tangent) curve between hull form surface and y = $B_{mld}/2$ plane.**



Example of side tangent line of a 320K VLCC

Primary Curves for Hull Form Representation
- Deck Side Line

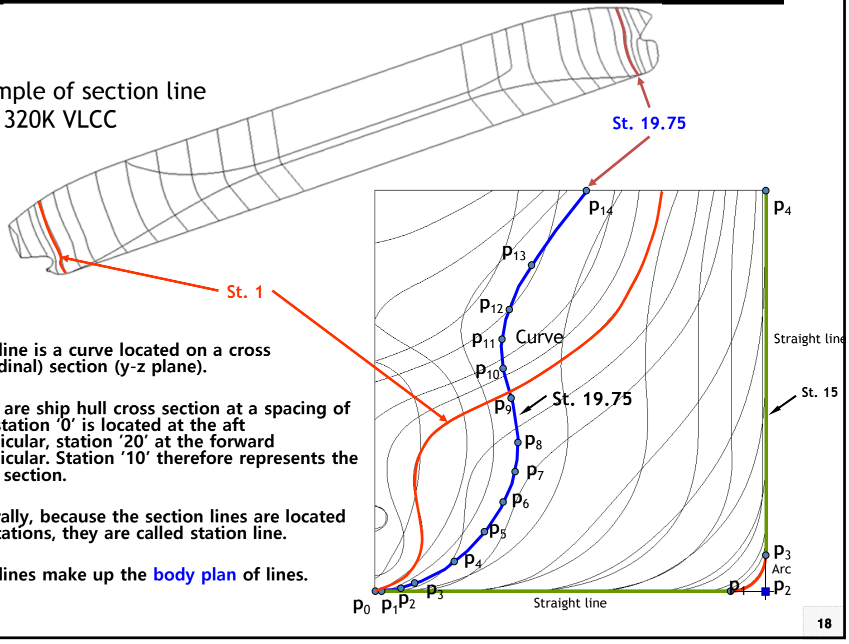
- ☑ **Deck side line is a curve representing the side of upper deck**
- ☑ **Both ends of the curve contact with profile line.**



Example of deck side line of a 320K VLCC

Secondary Curves for Hull Form Representation
- Section Line

Example of section line of a 320K VLCC

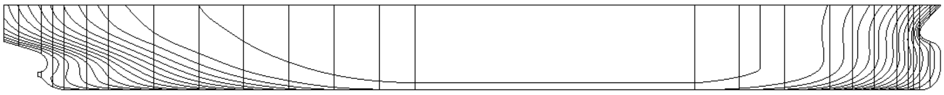


- ☑ **Section line is a curve located on a cross (longitudinal) section (y-z plane).**
- ☑ **Stations are ship hull cross section at a spacing of L_{BP}/20, station '0' is located at the aft perpendicular, station '20' at the forward perpendicular. Station '10' therefore represents the midship section.**
- ☑ **In generally, because the section lines are located at the stations, they are called station line.**
- ☑ **Section lines make up the body plan of lines.**

Secondary Curves for Hull Form Representation - Buttock Line

☑ **Buttock line is a curve located on a profile (lateral) section (x-z plane).**

☑ **Buttock lines make up the sheer plan or buttock plan of lines.**

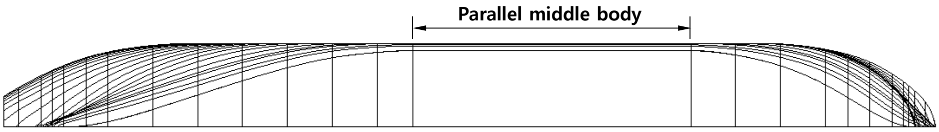


Example of buttock line of a 320K VLCC

Secondary Curves for Hull Form Representation - Water Line

☑ **Water line is a curve located on a water plane (vertical) section (x-y plane).**

☑ **Water lines make up the water plan or half-breadth plan of lines.**

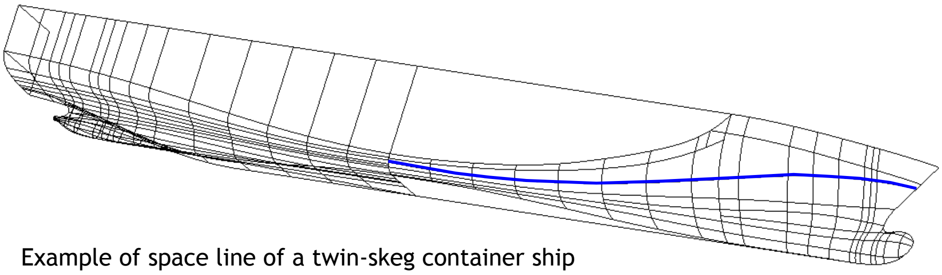


Example of water line of a 320K VLCC

Secondary Curves for Hull Form Representation
- Space Line (1/2)

☑ **Space line is a curve located on a 3D space, as compared with plane curve such as section line, buttock line, water line, etc.**

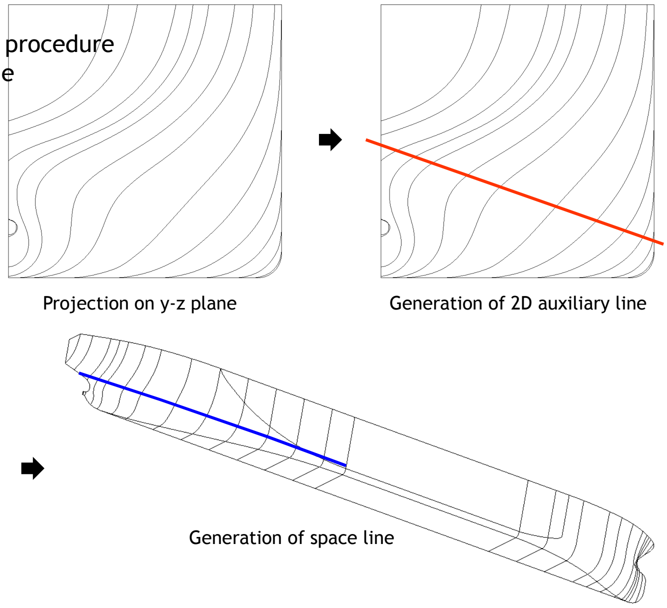
☑ **For the complicated hull form, space lines are additionally required with plane curves for defining the hull form.**



Example of space line of a twin-skeg container ship

Secondary Curves for Hull Form Representation
- Space Line (2/2)

Generation procedure of space line



Projection on y-z plane

Generation of 2D auxiliary line

Generation of space line

Generation of Wireframes of Hull From

① Input

- Primary curves, secondary curves

② Intersection

- Generation of intermediate curves such as water lines and buttock lines through intersection between primary and secondary curves

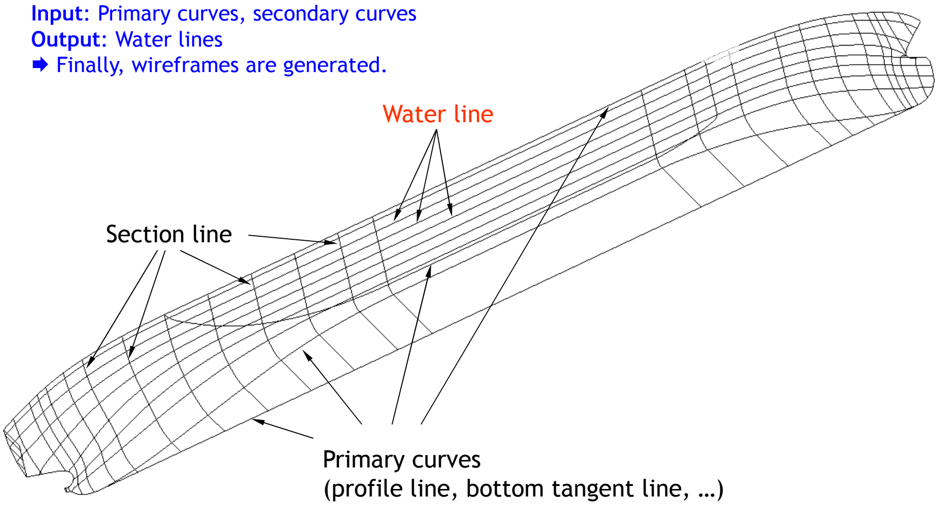
③ Wireframes generation

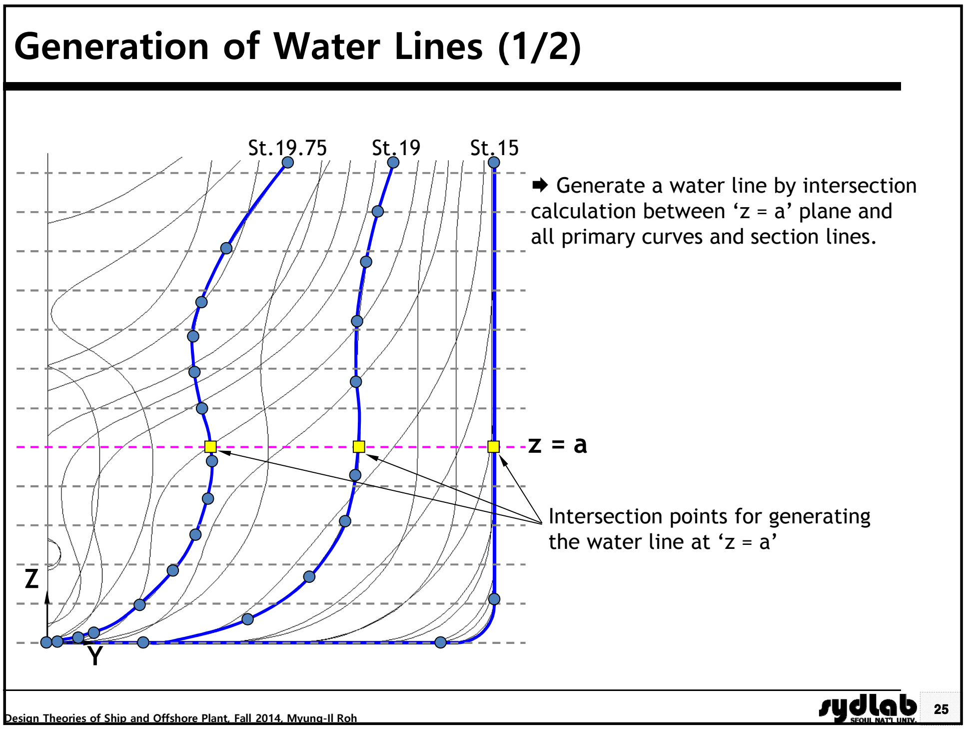
- Generation of wireframes using ① and ②

Wireframes Generation

Wireframes generation using primary & secondary curves and water lines

Input: Primary curves, secondary curves
Output: Water lines
➧ Finally, wireframes are generated.

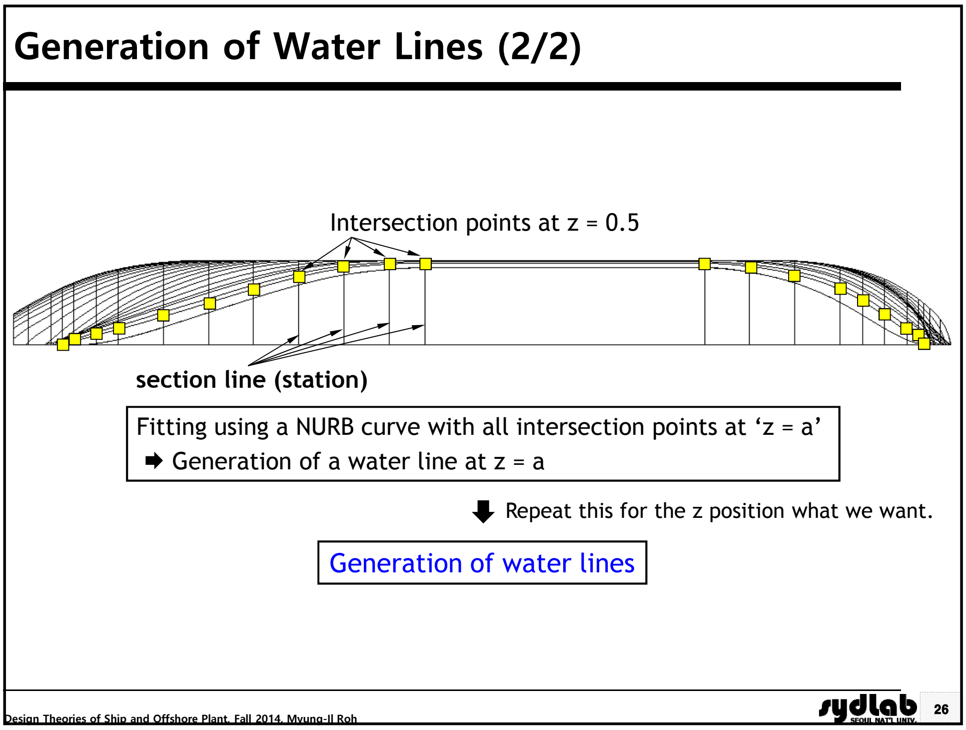




Generation of Water Lines (1/2)

➡ Generate a water line by intersection calculation between ‘z = a’ plane and all primary curves and section lines.

Intersection points for generating the water line at ‘z = a’



Generation of Water Lines (2/2)

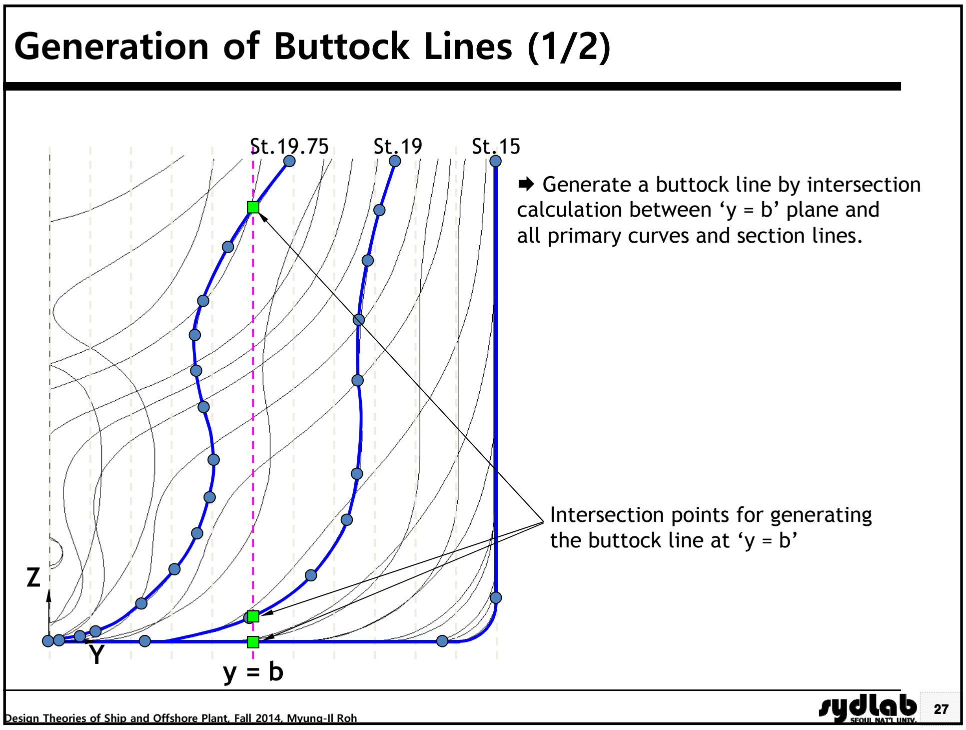
Intersection points at z = 0.5

section line (station)

Fitting using a NURB curve with all intersection points at ‘z = a’
➡ Generation of a water line at z = a

⬇ Repeat this for the z position what we want.

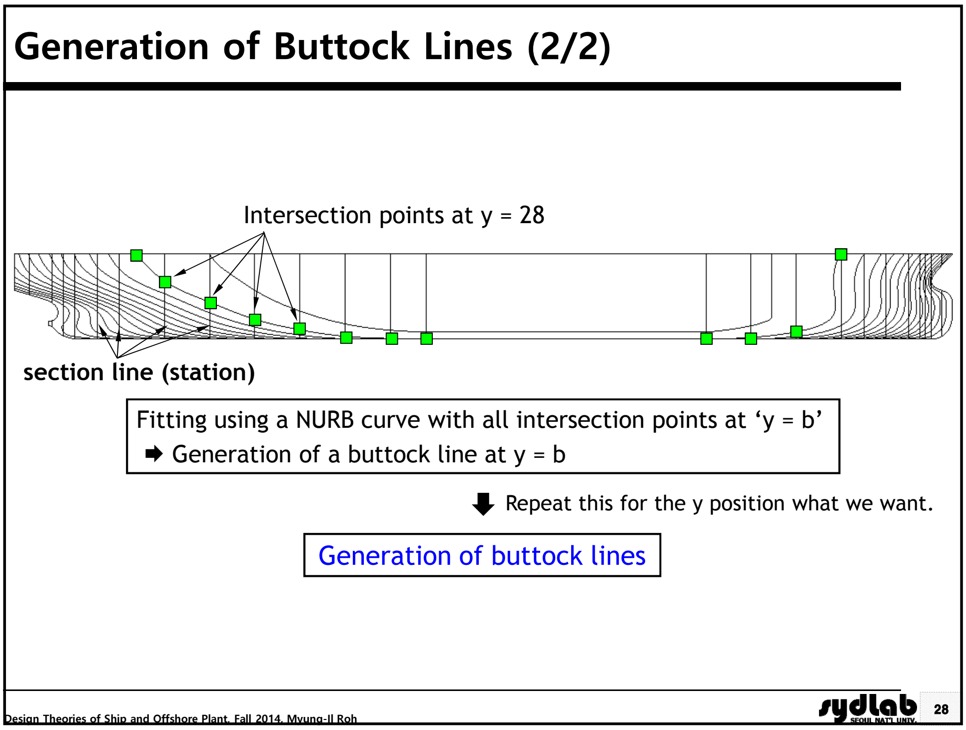
Generation of water lines



Generation of Buttock Lines (1/2)

➡ Generate a buttock line by intersection calculation between ‘y = b’ plane and all primary curves and section lines.

Intersection points for generating the buttock line at ‘y = b’



Generation of Buttock Lines (2/2)

Intersection points at y = 28

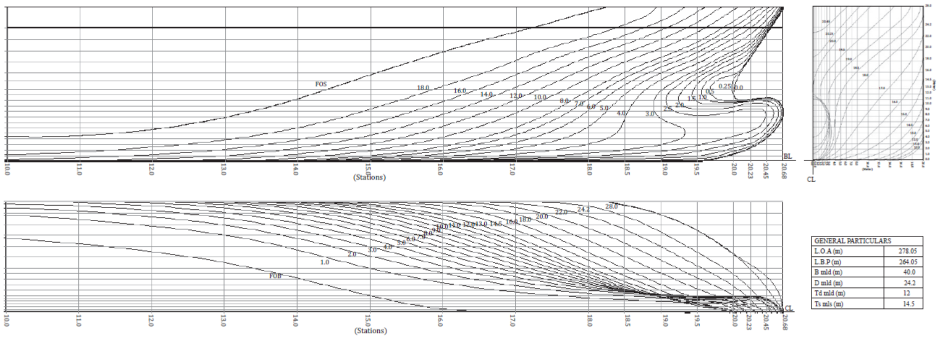
section line (station)

Fitting using a NURB curve with all intersection points at ‘y = b’
➡ Generation of a buttock line at y = b

⬇ Repeat this for the y position what we want.

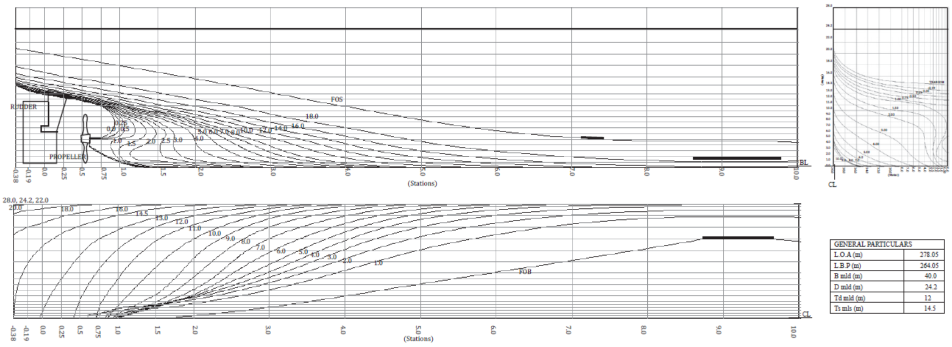
Generation of buttock lines

Example of Lines of a 6,300TEU Container Ship - Fore Body



GENERAL PARTICULARS	
L.O.A (m)	278.05
L.B.P (m)	264.05
B mld (m)	40.0
D mld (m)	24.2
Td mld (m)	12
Ts mls (m)	14.5

Example of Lines of a 6,300TEU Container Ship - After Body



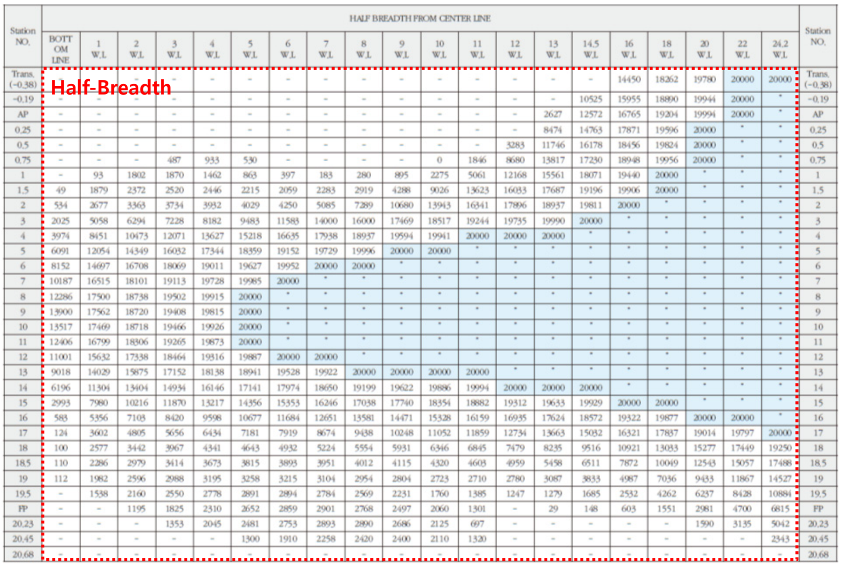
GENERAL PARTICULARS	
L.O.A (m)	278.05
L.B.P (m)	264.05
B mld (m)	40.0
D mld (m)	24.2
Td mld (m)	12
Ts mls (m)	14.5

Example of Offsets Table of a 6,300TEU Container Ship

Waterline

Stations

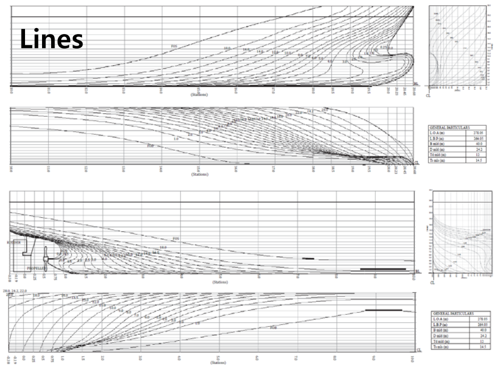
* Unit: mm



Half-Breadth

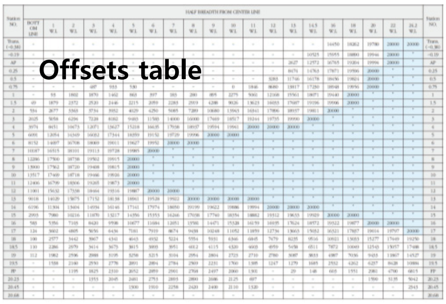
Station NO.	HALF BREADTH FROM CENTER LINE																				Station NO.
	BOTTOM LINE	1 W.L	2 W.L	3 W.L	4 W.L	5 W.L	6 W.L	7 W.L	8 W.L	9 W.L	10 W.L	11 W.L	12 W.L	13 W.L	14.5 W.L	16 W.L	18 W.L	20 W.L	22 W.L	24.2 W.L	
Trans. (−0.38)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	14450	18262	19780	20000	20000	Trans. (−0.38)
−0.19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10525	15955	18890	19944	20000	*	−0.19
AP	-	-	-	-	-	-	-	-	-	-	-	-	-	2627	12572	16765	19204	19994	20000	*	AP
0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	8474	14763	17871	19596	20000	*	*	0.25
0.5	-	-	-	-	-	-	-	-	-	-	-	-	3283	11746	16178	18456	19824	20000	*	*	0.5
0.75	-	-	-	487	933	530	-	-	-	-	0	1846	8680	13817	17230	18948	19956	20000	*	*	0.75
1	-	93	1802	1870	1462	863	397	183	280	895	2275	5061	12168	15561	18071	19440	20000	*	*	*	1
1.5	49	1879	2372	2520	2446	2215	2059	2283	2919	4288	9026	13623	16033	17687	19196	19906	20000	*	*	*	1.5
2	534	2677	3363	3734	3932	4029	4250	5085	7289	10680	13943	16341	17896	18937	19811	20000	*	*	*	*	2
3	2025	5058	6294	7228	8182	9483	11583	14000	16000	17469	18517	19244	19735	19990	20000	*	*	*	*	*	3
4	3974	8451	10473	12071	13627	15218	16635	17938	18937	19594	19941	20000	20000	20000	*	*	*	*	*	*	4
5	6091	12054	14349	16032	17344	18359	19152	19729	19996	20000	20000	*	*	*	*	*	*	*	*	*	5
6	8152	14697	16708	18069	19011	19627	19952	20000	20000	*	*	*	*	*	*	*	*	*	*	*	6
7	10187	16515	18101	19113	19728	19985	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	7
8	12286	17500	18738	19502	19915	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	8
9	13900	17562	18720	19408	19815	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	9
10	13517	17469	18718	19466	19926	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	10
11	12406	16799	18306	19265	19873	20000	*	*	*	*	*	*	*	*	*	*	*	*	*	*	11
12	11001	15632	17338	18464	19316	19887	20000	20000	*	*	*	*	*	*	*	*	*	*	*	*	12
13	9018	14029	15875	17152	18138	18941	19528	19922	20000	20000	20000	20000	*	*	*	*	*	*	*	*	13
14	6196	11304	13404	14934	16146	17141	17974	18650	19199	19622	19886	19994	20000	20000	20000	*	*	*	*	*	14
15	2993	7980	10216	11870	13217	14356	15353	16246	17038	17740	18354	18882	19312	19633	19929	20000	20000	*	*	*	15
16	583	5356	7103	8420	9598	10677	11684	12651	13581	14471	15328	16159	16935	17624	18572	19322	19877	20000	20000	*	16
17	124	3602	4805	5656	6434	7181	7919	8674	9438	10248	11052	11859	12734	13663	15032	16321	17837	19014	19797	20000	17
18	100	2577	3442	3967	4341	4643	4932	5224	5554	5931	6346	6845	7479	8235	9516	10921	13033	15277	17449	19250	18
18.5	110	2286	2979	3414	3673	3815	3893	3951	4012	4115	4320	4603	4959	5458	6511	7872	10049	12543	15057	17488	18.5
19	112	1982	2596	2988	3195	3258	3215	3104	2954	2804	2723	2710	2780	3087	3833	4987	7036	9433	11867	14527	19
19.5	-	1538	2160	2550	2778	2891	2894	2784	2569	2231	1760	1385	1247	1279	1685	2532	4262	6237	8428	10884	19.5
FP	-	-	1195	1825	2310	2652	2859	2901	2768	2497	2060	1301	-	29	148	603	1551	2981	4700	6815	FP
20.23	-	-	-	1353	2045	2481	2753	2893	2890	2686	2125	697	-	-	-	-	-	1590	3135	5042	20.23
20.45	-	-	-	-	-	1300	1910	2258	2420	2400	2110	1320	-	-	-	-	-	-	-	2343	20.45
20.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.68

Relationship Between Lines and Offsets Table (1/2)



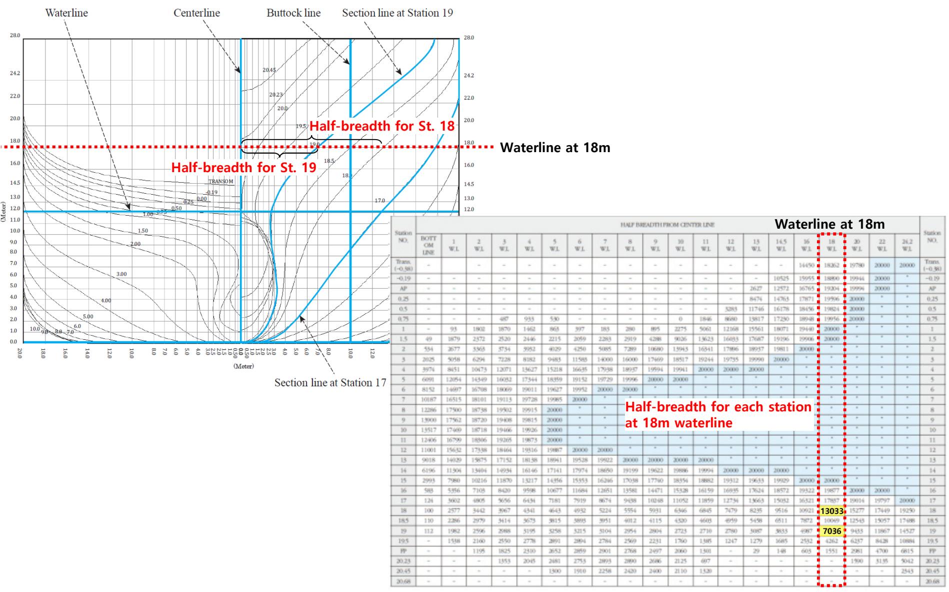
Lines

Generation of offsets table from the lines



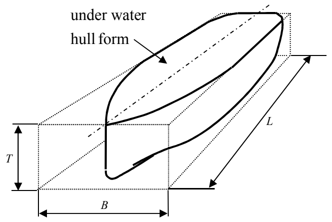
Offsets table

Relationship Between Lines and Offsets Table (2/2)



Hull Form Coefficients
- C_B (Block Coefficient) and C_P (Prismatic Coefficient)

C_B (Block coefficient)



$$C_B = \frac{\nabla}{L \cdot B \cdot T}$$

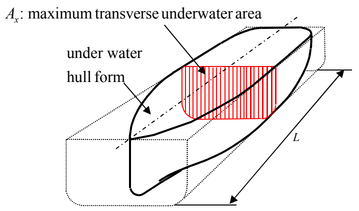
∇ = moulded volume of displacement

L = length of the ship (L_{BP} or L_{WL})

B = moulded breadth

T = moulded draft

C_P (Prismatic coefficient)



$$C_P = \frac{\nabla}{L \cdot A_M} = \frac{C_B}{C_M}$$

∇ = moulded volume of displacement

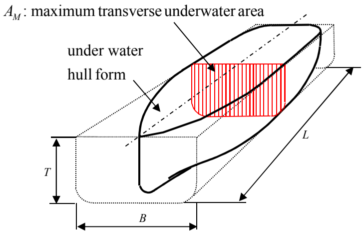
L = length of the ship (L_{BP} or L_{WL})

A_M = midship section area

C_M = midship coefficient

Hull Form Coefficients
- C_M (Midship Section Coefficient) and C_{WP} (Water Plane Area Coefficient)

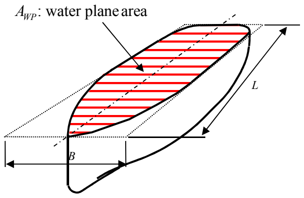
C_M (Midship Section Coefficient)



$$C_M = \frac{A_M}{B \cdot T}$$

A_M = midship section area
B = moulded breadth
T = moulded draft

C_{WP} (Water Plane Area Coefficient)

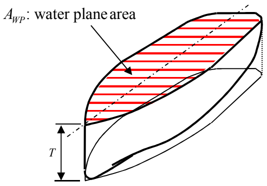


$$C_{WP} = \frac{A_{WP}}{L \cdot B}$$

A_W = water plane area
L = length of the ship (LWL or LBP)
B = moulded breadth

Hull Form Coefficients
- C_{VP} (Vertical Prismatic Coefficient)

C_{VP} (Vertical Prismatic Coefficient)

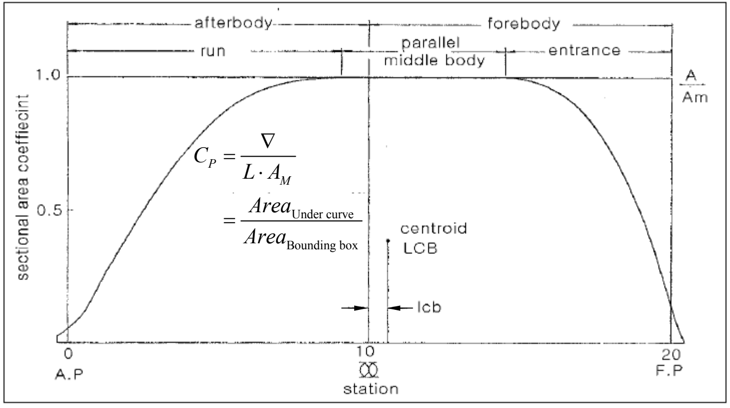


$$C_{VP} = \frac{\nabla}{T \cdot A_{WP}}$$

∇ = moulded volume of displacement
A_{WP} = water plane area
T = moulded draft

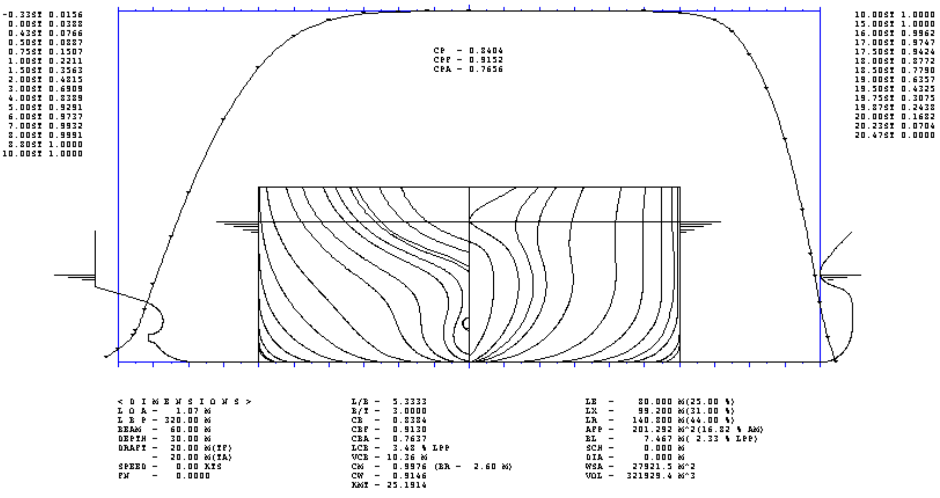
C_P Curve (Sectional Area Curve)

- C_P curve (or sectional area curve) is a diagram of transverse section areas up to the designed water line, plotted on a base on length.
- This diagram may be made dimensionless by plotting each ordinate as the ratio of the area A of any section to the area of the maximum section.
- This diagram represents the distribution of underwater volume along the length of a ship.



Sectional area curve or C_P-curve and LCB (Longitudinal Center of Buoyancy)

Example of C_P Curve of a 320K VLCC



```
-0.33ST 0.0156
 0.00ST 0.0388
 0.43ST 0.0766
 0.50ST 0.0887
 0.75ST 0.1507
 1.00ST 0.2211
 1.50ST 0.3563
 2.00ST 0.4815
 3.00ST 0.6909
 4.00ST 0.8389
 5.00ST 0.9291
 6.00ST 0.9737
 7.00ST 0.9932
 8.00ST 0.9991
 8.80ST 1.0000
10.00ST 1.0000
```

```
CP  - 0.8404
CPF - 0.9152
CPA - 0.7656
```

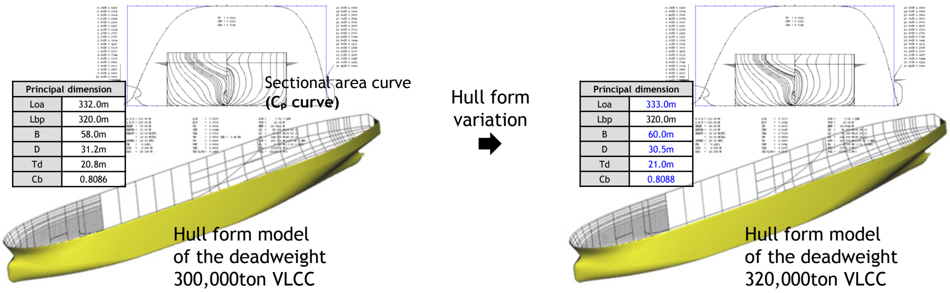
```
10.00ST 1.0000
15.00ST 1.0000
16.00ST 0.9962
17.00ST 0.9747
17.50ST 0.9424
18.00ST 0.8772
18.50ST 0.7790
19.00ST 0.6357
19.50ST 0.4325
19.75ST 0.3075
19.87ST 0.2438
20.00ST 0.1682
20.23ST 0.0704
20.47ST 0.0000
```

```
< D I M E N S I O N S >           L/B -   5.3333                       LE  -    80.000 M(25.00 %)
L O A -    1.07 M                 B/T -   3.0000                       LX  -    99.200 M(31.00 %)
L B P - 320.00 M                  CB  -   0.8384                       LR  -   140.800 M(44.00 %)
BEAM  -  60.00 M                  CBF -   0.9130                       AFP -   201.292 M^2(16.82 % AM)
DEPTH -  30.00 M                  CBA -   0.7637                       BL  -     7.467 M( 2.33 % LPP)
DRAFT -  20.00 M(TF)              LCB -   3.48 % LPP                   SCH -     0.000 M
      -  20.00 M(TA)              VCB - 10.36 M                        DIA -     0.000 M
SPEED -   0.00 KTS                CM  -   0.9976 (BR -   2.60 M)       WSA -   27921.5 M^2
FN    -   0.0000                  CW  -   0.9146                       VOL -  321929.4 M^3
                                  KMT - 25.1914
```

3.2 Hull Form Variation

Hull Form Variation (1/2)

☑ **Design task for obtaining a hull form of a design ship from the variation of that of a basis ship**



Principal dimension	
Loa	332.0m
Lbp	320.0m
B	58.0m
D	31.2m
Td	20.8m
Cb	0.8086

Sectional area curve **(C_p curve)**

Hull form model of the deadweight 300,000ton VLCC

Hull form variation ➡

Principal dimension	
Loa	333.0m
Lbp	320.0m
B	60.0m
D	30.5m
Td	21.0m
Cb	0.8088

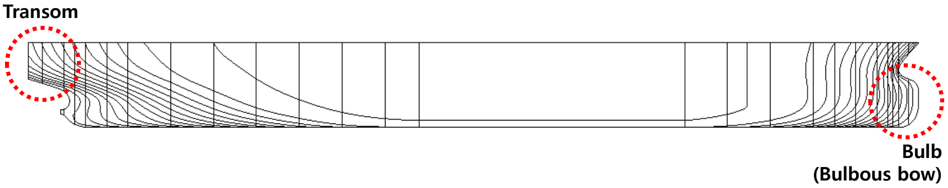
Hull form model of the deadweight 320,000ton VLCC

Hull Form Variation (2/2)

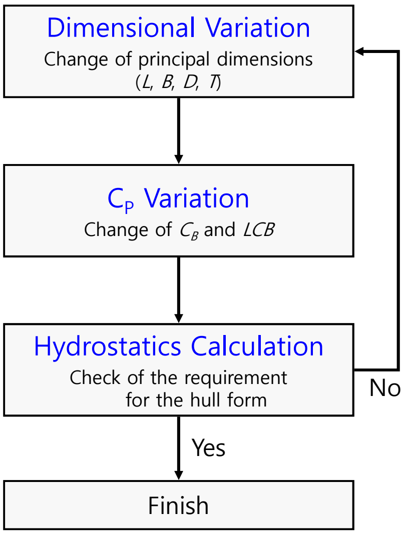
☑ **Categorization of Hull Form Methods**

- **Dimensional variation method**
  - **Change of principal dimensions (L_{BP}, B, D, T)**
  - **Change of hull form parameters (e.g, transom height, shaft center height, bossing end radius, maximum deck height, bilge radius, etc.)**

- **C_P variation method**
  - **Change of C_B (actually, displacement) and LCB**
  - **Miscellaneous dimensions (e.g., transom length, bulb length, etc.)**



Procedure of the Hull Form Variation (Overview)



Dimensional Variation
Change of principal dimensions
(*L*, *B*, *D*, *T*)

C_P Variation
Change of C_B and *LCB*

Hydrostatics Calculation
Check of the requirement
for the hull form

No

Yes

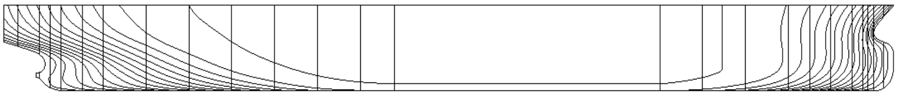
Finish

Dimensional Variation Method

Dimensional Variation Method (1/3)

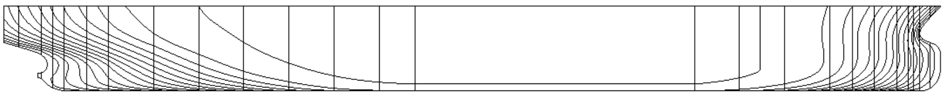
☑ **Change of the Length (L_{BP})**
- **Length ratio between basis ship and design ship: α (= L_{design} / L_{basis})**
- **Multiply x coordinates of all points in each hull form curve by α.**

Basis ship



⬇ Length variation

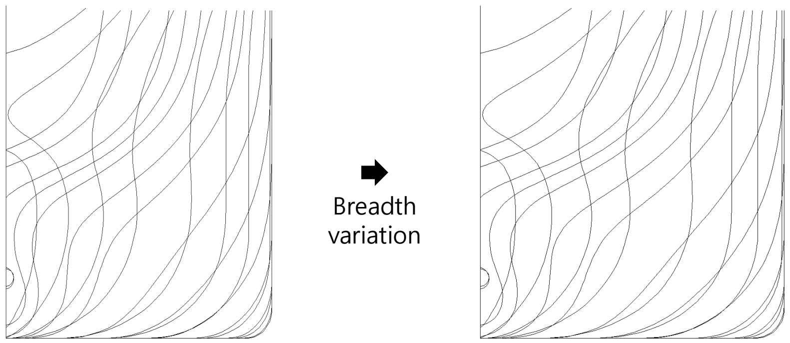
Design ship



Dimensional Variation Method (2/3)

☑ **Change of the Breadth (B)**

- **Breadth ratio between basis ship and design ship: β (= B_{design} / B_{basis})**
- **Multiply y coordinates of all points in each hull form curve by β.**



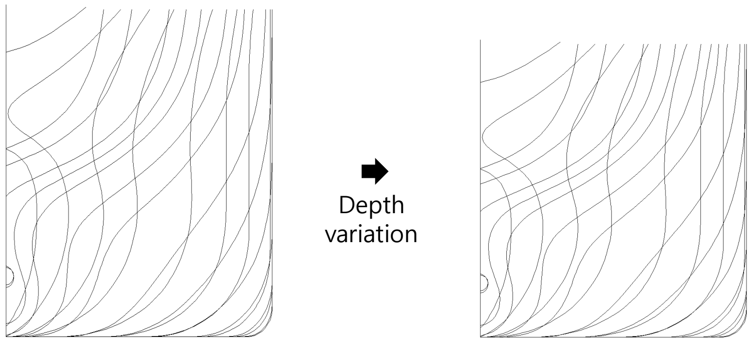
Basis ship

Design ship

Dimensional Variation Method (3/3)

☑ **Change of the Depth (D) or Draft (T)**

- **Depth or Draft ratio between basis ship and design ship: γ (= D_{design} / D_{basis})**
- **Multiply z coordinates of all points in each hull form curve by γ.**

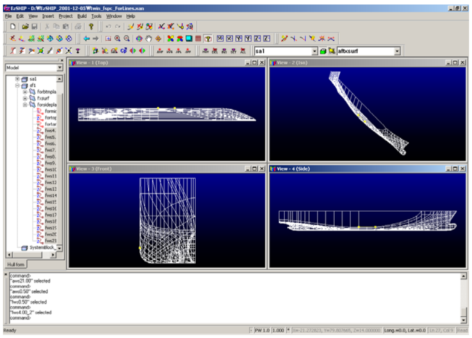


Basis ship

Design ship

Example of a Dimensional Variation Method

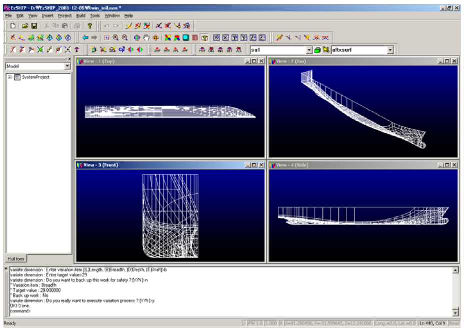
Example of a twin-skeg container ship



```
command>
"aws21.00" selected
command>
"aws0.50" selected
command>
"fws0.50" selected
command>
"fws4.00_2" selected
command>
```

➡ Before Dimensional Variation

L_{BP}: 190m, B: 28.65m, D: 22m, T: 8.5m



```
variate dimension : Enter variation item [(L)Length, (B)Breadth, (D)Depth, (T)Draft]>b
variate dimension : Enter target value>29
variate dimension : Do you want to back up this work for safety ? [Y/N]>n
* Variation item : Breadth
* Target value : 29.000000
* Back up work : No
variate dimension : Do you really want to execute variation process ? [Y/N]>y
OK! Done.
command>
```

After Dimensional Variation ⬅

L_{BP}: 200m, B: 29m, D: 23m, T: 8.6m

C_P Variation Method

C_P Variation Method (1/2)

☑ In shipyard, the hull form of a similar basis ship is chosen and modified to the correct the principal dimensions for a new design ship.
➡ The hull form of the design ship can maintain the hydrostatic/hydrodynamic property of the basis ship.

☑ C_P variation method
In deriving the lines for a new design ship from the similar basis ship, it is usual to correct displacement and LCB (Longitudinal Center of Buoyancy) by adjusting the longitudinal spacing of the transverse sections in order to suit the new CP curve.

- 1-C_P variation method
- Lackenby variation method

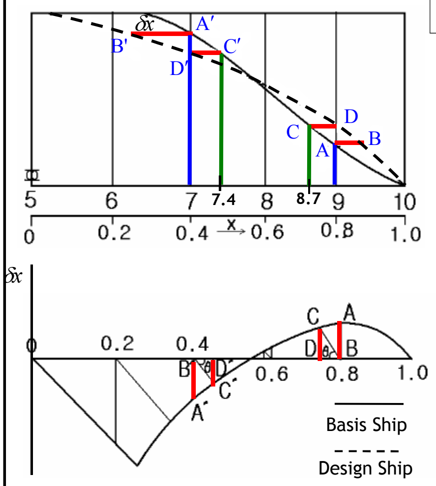
} Correction for displacement

- Swing station method
- Weighted modified swing method

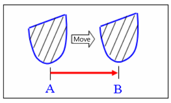
} Correction for LCB

C_P Variation Method (2/2)

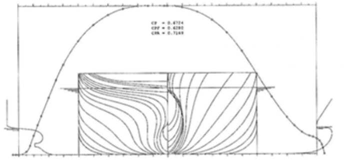
•Adjust the longitudinal spacing of he transverse sections in order to suit the new CP curve.



*The L_{BP} is normalized in terms of two. (from Midship: ±1)



CP Curve
(4,100 TEU Container ship)



① The transverse section of the basis ship located at station 9 (x=0.8)
➡ In the design ship, the transverse section of the basis ship located at station 9 is moved through distance AB.

② The transverse section of the design ship located at station 9 is obtained from that of the basis ship located at station 8.7.

③ The transverse section of the basis ship located at station 7 (x=0.4)
➡ In the design ship, the transverse section of the basis ship located at station 7 is moved through distance A′B′.

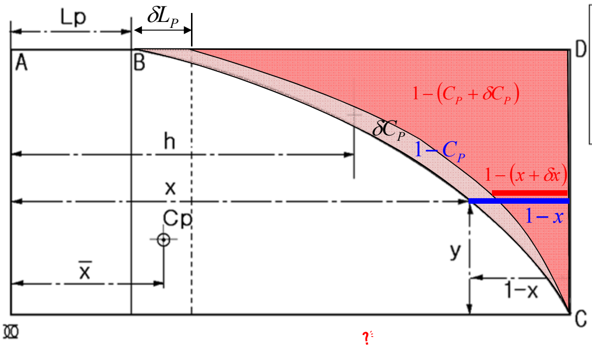
④ The transverse section of the design ship located at station 7 is obtained from that of the basis ship located at station 7.4.

* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 290, 1950.

C_P Variation Method
- "1-C_P" Variation Method (1/5)

Given: **The prismatic coefficients of fore and after bodies the basis ship (** $C_{P_{a,f}}$ **),**
The required changes in the prismatic coefficients of fore and after bodies ($\delta C_{P_{a,f}}$ **)**

Find: $\delta x_{a,f}$



✓ **Assumption:** "The new spacing of the sections from the end of the body is made proportional to the difference between the respective prismatics and unity"

$$1-\left(x_{a,f}+\delta x_{a,f}\right):1-x_{a,f}$$
$$=1-\left(C_{P_{a,f}}+\delta C_{P_{a,f}}\right):1-C_{P_{a,f}}$$

$$\delta x_{a,f}=\frac{\boxed{\delta C_{P_{a,f}}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)$$

: "1-Cp" variation method

How to get the value of $\delta C_{P_{a,f}}$?

$$C_P=\frac{\nabla}{L\cdot A_M}=\frac{Area_{\text{Under curve}}}{Area_{\text{Bounding box}}}=\frac{C_B}{C_M}$$

δC_P: The required change in prismatic coefficient of the half-body

x : The fractional distance of any transverse section from midship

δx: The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient

h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

L_P : The fractional parallel middle of the half-body

δL_P: The consequent change in parallel middle body

$\bar{x}$: The fractional distance from midship of the centroid of the half-body

y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

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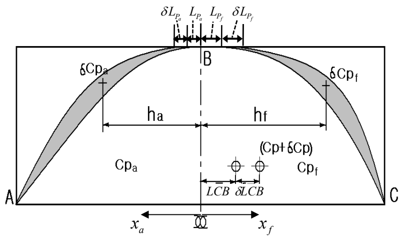
C_P Variation Method
- "1-C_P" Variation Method (2/5)



The + sign indicates movement away from midship (x_a, x_f).

$$C_P=\frac{\nabla}{L\cdot A_M}=\frac{Area_{\text{Under curve}}}{Area_{\text{Bounding box}}}=\frac{C_B}{C_M}$$

δC_P: The required change in prismatic coefficient of the half-body

x : The fractional distance of any transverse section from midship

δx: The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient

h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

✓ "1-Cp" Variation method

$$\delta x_{a,f}=\frac{\boxed{\delta C_{P_{a,f}}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)$$

How to get the value of $\delta C_{P_{f,a}}$?

Method 1. Using the following formula

Given: C_P, δC_P, $\boxed{h_{a,f}}$, $\boxed{LCB}$, δLCB

Find: $\delta C_{P_{a,f}}$

$$\delta C_{P_f}=\frac{2\left[\delta C_P\left(h_a+LCB\right)+\delta LCB\left(C_P+\delta C_P\right)\right]}{h_f+h_a}$$

$$\delta C_{P_a}=\frac{2\left[\delta C_P\left(h_f-LCB\right)-\delta LCB\left(C_P+\delta C_P\right)\right]}{h_f+h_a}$$

The sign of LCB and δLCB are positive for forward of midship and negative for aft of midship.

❖ The derivation of the above formula can refer to the above reference.

$\bar{x}$: The fractional distance from midship of the centroid of the half-body

LCB: The distance of the LCB in the basis ship from midship expressed as a fraction of the half-length

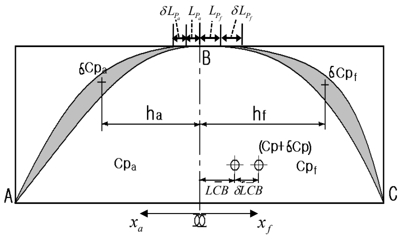
δLCB: The required fractional shift of the LCB in the derived form

---

* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 290, 1950.

C_P Variation Method - "1-C_P" Variation Method (3/5)

Formula for Calculating $h_{f,a}$



The + sign indicates movement away from midship (x_a, x_f).

$$\delta C_{P_f} = \frac{2\left[\delta C_P\left(\boxed{h_a} + \overline{LCB}\right) + \delta\overline{LCB}\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

$$\delta C_{P_a} = \frac{2\left[\delta C_P\left(\boxed{h_f} - \overline{LCB}\right) - \delta\overline{LCB}\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

How to obtain $h_{f,a}$?

✓ Calculation of $h_{f,a}$

Given: $C_{P_{a,f}}$, $\overline{x}_{a,f}$

Find: $h_{a,f}$

$$h_{a,f} = \frac{C_{P_{a,f}}\left(1-2\overline{x}_{a,f}\right))}{1-C_{P_{a,f}}} + \cancel{\frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left[1-2C_{P_{a,f}}\left(1-\overline{x}_{a,f}\right)\right]}$$

$$\boxed{h_{a,f} \approx \frac{C_{P_{a,f}}\left(1-2\overline{x}_{a,f}\right))}{1-C_{P_{a,f}}}}$$

$$C_P = \frac{\nabla}{L \cdot A_M} = \frac{Area_{\text{Under curve}}}{Area_{\text{Bounding box}}} = \frac{C_B}{C_M}$$

δC_P : The required change in prismatic coefficient of the half-body

x : The fractional distance of any transverse section from midship

δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient

h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

L_P : The fractional parallel middle of the half-body

δL_P : The consequent change in parallel middle body

$\overline{x}$: The fractional distance from midship of the centroid of the half-body

y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 290, 1950.

C_P Variation Method - "1-C_P" Variation Method (4/5)

Formula for Estimating the LCB

- LCB represents the balance of the displacement between fore body and aft body. (So, it determines the distribution of the displacement of a ship)
  - Block coefficient of after body (C_{BA}) has an effect on the maneuverability of a ship (Recommending that C_{BA} is less than 0.76.)
  - Hull form of the fore body usually has effect on the wave resistance.
  - Hull form of the after body usually has effect on the friction resistance and propulsion ability.

⇨ **Ponderous (obese) ship: LCB to be located at fore body**
Slender ship: LCB to be located at midship or aft body

- Formula for the LCB when C_{BA} is less than 0.76

$$C_{PA} = C_P - 0.0215 \cdot LCB$$

- When the C_B of the ship is 0.8~0.85 (Ponderous ship):

$$LCB:\ 3.5\text{~}4.0\%\ \text{(forward)}$$

- Lap/Keller formula

$$LCB[\%L] = 13.33C_B - 9.0$$

When the LCB is estimated, the correction factor obtained from basis ship can be applied.

$$\frac{LCB_{\text{basis, actual}}}{LCB_{\text{basis, estimate}}} = C_{corr.}$$

$$LCB_{\text{design}} = C_{corr.} \cdot LCB_{\text{design,estimate}}$$

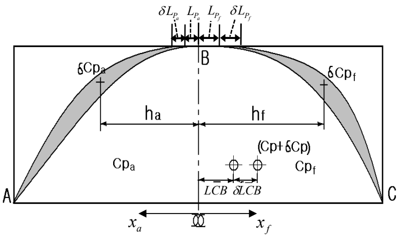
$LCB_{\text{basis,estimate}}$: LCB of the basis ship to be estimated by the formula
$LCB_{\text{basis,actual}}$: Actual LCB of the basis ship
C_{corr}: Correction factor
$LCB_{\text{design,estimate}}$: LCB of the design ship to be estimated by the formula
LCB_{design}: $LCB_{\text{design,estimate}}$ multiplied by correction factor

C_P Variation Method
- "1-C_P" Variation Method (5/5)

✓ "1-C_P"Variation method

$$\delta x_{a,f} = \frac{\delta C_{P_{a,f}}}{1 - C_{P_{a,f}}}(1 - x_{a,f})$$

How to get the value of $\delta C_{P_{a,f}}$?



The + sign indicates movement away from midship (x_a, x_f).

δC_P : The required change in prismatic coefficient of the half-body

x : The fractional distance of any transverse section from midship

δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient

h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

L_P : The fractional parallel middle of the half-body

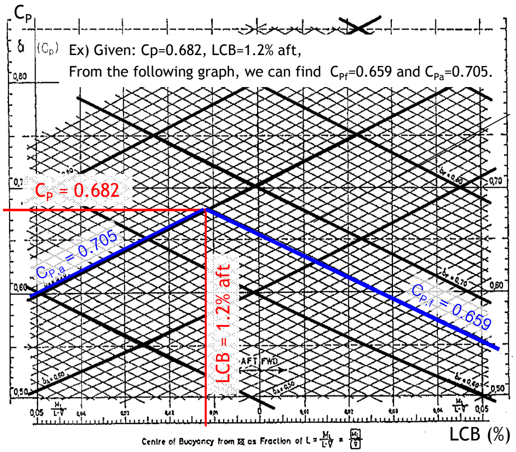
δL_P : The consequent change in parallel middle body

$\bar{x}$: The fractional distance from midship of the centroid of the half-body

y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

Method 2. Using the statistical method

From the "Form Data IV" of Guldhammer,
we can find C_{P_a} and C_{P_f} according to the C_P and LCB.
Similarly, we can find δC_{P_a} and δC_{P_f} according to the $C_P + \delta C_P$ and LCB.



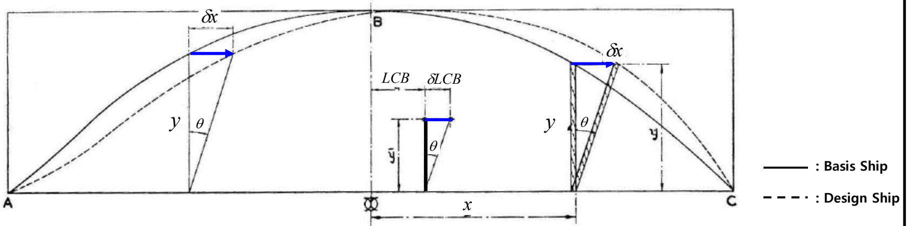
Ex) Given: Cp=0.682, LCB=1.2% aft,
From the following graph, we can find C_{Pf}=0.659 and C_{Pa}=0.705.

C_P Variation Method
- "Swing Station Method"

Swing station method: Changing the LCB position of hull form of a ship by "swinging" the C_P curve

➡ **This method is proposed only to change the LCB, the displacement being maintained constant.**

Each transverse section of the basis ship is "swung" through the same angle θ as shown.



δLCB : the required change in LCB position

$\bar{y}$: the position of the vertical centroid of area above the base (VCB)

$$\bar{y} = \frac{\int_0^T z \cdot A_{wp}(z)dz}{\nabla}$$

➡ $\bar{y}$: It can be obtained from the first moment of the submerged volume of the ship about x axis divided by the displacement (KB, VCB). In this method, this value has to be normalized.

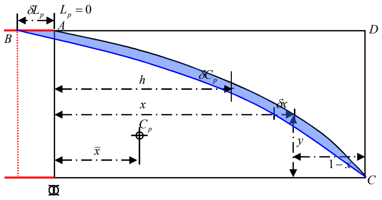
Given: δLCB, $\bar{y}$, $y(x)$
Find: $\delta x_{at\,x}$

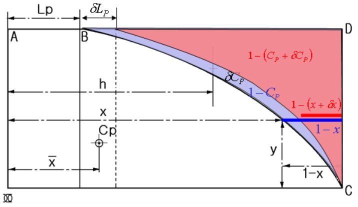
$$\tan\theta = \frac{\delta LCB}{\bar{y}} = \frac{\delta x}{y}$$

$$\boxed{\delta x = \frac{\delta LCB}{\bar{y}} \cdot y}$$

C_P Variation Method
- Disadvantages of "1-C_P" Variation Method

(1) This method cannot be used to reduce the displacement of a ship having no parallel middle body. That is, this method can be applied to a ship having the parallel middle body.





$$\boxed{\delta x_{a,f} = \frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)} \quad \boxed{\delta L_{P_{a,f}} = \frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left(1-L_{P_{a,f}}\right)}$$

$C_P = C_b / C_m$

L_P : the fractional parallel middle of the half-body
x : the fractional distance of any transverse section from midship
$\bar{x}$: the fractional distance from midship of the centroid of the half-body
y : the area of the transverse section at x expressed as a fraction of the maximum ordinate
δC_P : the required change in prismatic coefficient of the half-body
δL_P : the consequent change in parallel middle body
δx : the necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient
h : the fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

(2) There is no control over the extent of the parallel middle body in this method. That is, L_P and C_P cannot be varied independently.

(3) A hull form having no parallel middle body cannot be increased in displacement without the addition of parallel middle body. That is, if C_P changes, the length of parallel middle body changes.

(4) For a given change in C_P curve, the longitudinal distribution of the displacement cannot be arbitrarily controlled by a designer.

C_P Variation Method
- "Lackenby" Method (General Case) (1/3)

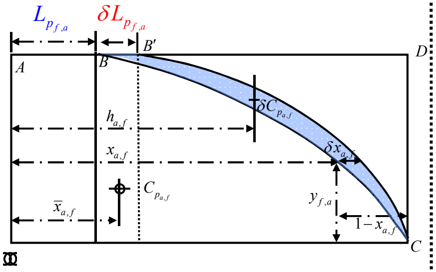
* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 294, 308, 1950.

"1-Cp" Variation Method

$$\boxed{\delta x_{a,f} = \frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)}$$

Given: $C_{P_{a,f}}, \delta C_{P_{a,f}}, L_{P_{a,f}}, \delta L_{P_{a,f}}, \bar{x}_{a,f}, x_{a,f}$

Find: $\delta x_{a,f}$



$$C_P = \frac{\nabla}{L \cdot A_M} = \frac{Area_{\text{Under curve}}}{Area_{\text{Bounding box}}} = \frac{C_B}{C_M}$$

δC_P : The required change in prismatic coefficient of the half-body
x : The fractional distance of any transverse section from midship
δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient
h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P
L_P : The fractional parallel middle of the half-body

<General Case>

Basis Form: Any extent of parallel middle body

Derived From: Any required change in prismatic coefficient and extent of parallel middle body

①
$$\delta x_{a,f} = (1-x_{a,f})\left\{\frac{\delta L_{p_{a,f}}}{1-\ L_{p_{a,f}}} + \frac{x_{a,f} - L_{p_{a,f}}}{A_{a,f}}[\delta C_{P_{a,f}} - \delta L_{p_{a,\text{f}}}\frac{(1-C_{P_{a,f}})}{(1-\ L_{p_{a,f}})}]\right\}$$

$$,(A_{a,f} = C_{P_{a,f}}(1-2\bar{x}_{a,f}) - L_{p_{a,f}}(1-C_{P_{a,f}}))$$

➡ In this formula, the change in the parallel middle body ($\delta L_{pa,f}$) is included.

<Advantages of "Lackenby method">

(1) The parallel middle body ($L_{pf,a}$) can be controlled.

(2) Because δx is proportional to $x(1\text{-}x)$, this method can be applied to the any case of the simple variation.

(3) The required adjustments to the prismatic coefficients of fore and after bodies to give any desired change in LCB position and total prismatic coefficient can be determined.

δL_P : The consequent change in parallel middle body
$\bar{x}$: The fractional distance from midship of the centroid of the half-body
y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 294, 306, 308, 309, 1950.

C_P Variation Method
- "Lackenby" Method (General Case) (2/3)

① "Lackenby" method <General Case>

Given: $C_{P_{a,f}}, \delta C_{P_{a,f}}, L_{P_{a,f}}, \delta L_{P_{a,f}}, \bar{x}_{a,f}, x_{a,f}$

Find: $\delta x_{a,f}$

$$\delta x_{a,f} = (1-x_{a,f})\left\{\frac{\delta L_{p_{a,f}}}{1-L_{p_{a,f}}} + \frac{x_{a,f}-L_{p_{a,f}}}{A_{a,f}}\left[\delta C_{P_{a,f}} - \delta L_{p_{a,f}}\frac{(1-C_{P_{a,f}})}{(1-L_{p_{a,f}})}\right]\right\}$$

$$,(A_{a,f} = C_{P_{a,f}}(1-2\bar{x}_{a,f}) - L_{p_{a,f}}(1-C_{P_{a,f}}))$$

② Calculation of $\delta C_{P_{f,a}}$

Given: $C_P,\ \delta C_P, h_{a,f}, LCB,\ \delta LCB$

Find: $\delta C_{P_{a,f}}$

$$\delta C_{P_f} = \frac{2\left[\delta C_P\left(h_a + LCB\right) + \delta LCB\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

$$\delta C_{P_a} = \frac{2\left[\delta C_P\left(h_f - LCB\right) - \delta LCB\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

③ Calculation of $h_{a,f}$

Given: $C_{p_{a,f}}, \delta C_{p_{a,f}}, L_{p_{a,f}}, \delta L_{p_{a,f}}, \bar{x}_{a,f}, k_{a,f}$

Find: $h_{a,f}$

$$h_{a,f} = C_{p_{a,f}} \cdot \left(\frac{B_{a,f}}{C_{p_{a,f}}}\left[1 - \frac{\delta L_{p_{a,f}} \cdot (1-C_{p_{a,f}})}{\delta C_{p_{a,f}} \cdot (1-L_{p_{a,f}})}\right] + \frac{\delta L_{p_{a,f}} \cdot (1-2\bar{x}_{a,f})}{\delta C_{p_{a,f}} \cdot (1-L_{p_{a,f}})}\right)$$

$$(A_{f,a} = C_{P_{f,a}}(1-2\bar{x}_{f,a}) - L_{p_{f,a}}(1-C_{P_{f,a}})), \left(B_{f,a} = \frac{C_{p_{f,a}} \cdot \left[2\bar{x}_{f,a} - 3k_{f,a}{}^2 - L_{p_{f,a}} \cdot (1-2\bar{x}_{f,a})\right]}{A_{f,a}}\right)$$

To obtain $h_{a,f}$, $\delta C_{P_{a,f}}$ have to be given!

Substituting equation ③ into equation ② and rearranging for $\delta C_{P_{a,f}}$,

Given: $C_P,\ \delta C_P, L_{p_{a,f}}, \delta L_{P_{a,f}}, LCB,\ \delta LCB, k_{a,f}$

Find: $\delta C_{P_{a,f}}$

$$\delta C_{p_f} = \frac{2\left[\delta C_p \cdot (B_a + LCB) + \delta LCB \cdot (C_P + \delta C_P)\right] + C_f \cdot \delta L_{p_f} - C_a \cdot \delta L_{p_a}}{B_f + B_a}$$

$$\delta C_{p_a} = \frac{2\left[\delta C_p \cdot (B_f - LCB) - \delta LCB \cdot (C_P + \delta C_P)\right] - C_f \cdot \delta L_{P_f} + C_a \cdot \delta L_{p_a}}{B_f + B_a}$$

$$(A_{a,f} = C_{P_{a,f}}(1-2\bar{x}_{a,f}) - L_{p_{a,f}}(1-C_{P_{a,f}}))$$

$$\left(B_{a,f} = \frac{C_{p_{a,f}} \cdot \left[2\bar{x}_{a,f} - 3k_{a,f}{}^2 - L_{p_{a,f}} \cdot (1-2\bar{x}_{a,f})\right]}{A_{a,f}}\right)\left(C_{a,f} = \frac{B_{a,f}(1-C_{P_{a,f}}) - C_{P_{a,f}}(1-2\bar{x}_{a,f})}{1-L_{p_{a,f}}}\right)$$

δC_P : The required change in prismatic coefficient of the half-body
x : The fractional distance of any transverse section from midship
δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient
h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P
L_P : The fractional parallel middle of the half-body

δL_P : The consequent change in parallel middle body
$\bar{x}$: The fractional distance from midship of the centroid of the half-body
y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

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* Reference: Lackenby, On The Systematic Geometrical Variation of Ship Forms, RINA , p. 294, 306, 308, 309, 1950.

C_P Variation Method
- "Lackenby" Method (General Case) (3/3)

① "Lackenby" method <General Case>

Given: $C_{P_{a,f}}, \delta C_{P_{a,f}}, L_{P_{a,f}}, \delta L_{P_{a,f}}, \bar{x}_{a,f}, x_{a,f}$

Find: $\delta x_{a,f}$

$$\delta x_{a,f} = (1-x_{a,f})\left\{\frac{\delta L_{p_{a,f}}}{1-L_{p_{a,f}}} + \frac{x_{a,f}-L_{p_{a,f}}}{A_{a,f}}\left[\delta C_{P_{a,f}} - \delta L_{p_{a,f}}\frac{(1-C_{P_{a,f}})}{(1-L_{p_{a,f}})}\right]\right\}$$

$$,(A_{a,f} = C_{P_{a,f}}(1-2\bar{x}_{a,f}) - L_{p_{a,f}}(1-C_{P_{a,f}}))$$

② Calculation of $\delta C_{P_{f,a}}$

Given: $C_P,\ \delta C_P, h_{a,f}, LCB,\ \delta LCB$

Find: $\delta C_{P_{a,f}}$

$$\delta C_{P_f} = \frac{2\left[\delta C_P\left(h_a + LCB\right) + \delta LCB\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

$$\delta C_{P_a} = \frac{2\left[\delta C_P\left(h_f - LCB\right) - \delta LCB\left(C_P + \delta C_P\right)\right]}{h_f + h_a}$$

③ Calculation of $h_{a,f}$

Given: $C_{p_{a,f}}, \delta C_{p_{a,f}}, L_{p_{a,f}}, \delta L_{p_{a,f}}, \bar{x}_{a,f}, k_{a,f}$

Find: $h_{a,f}$

$$h_{a,f} = C_{p_{a,f}} \cdot \left(\frac{B_{a,f}}{C_{p_{a,f}}}\left[1 - \frac{\delta L_{p_{a,f}} \cdot (1-C_{p_{a,f}})}{\delta C_{p_{a,f}} \cdot (1-L_{p_{a,f}})}\right] + \frac{\delta L_{p_{a,f}} \cdot (1-2\bar{x}_{a,f})}{\delta C_{p_{a,f}} \cdot (1-L_{p_{a,f}})}\right)$$

$$(A_{f,a} = C_{P_{f,a}}(1-2\bar{x}_{f,a}) - L_{p_{f,a}}(1-C_{P_{f,a}})), \left(B_{f,a} = \frac{C_{p_{f,a}} \cdot \left[2\bar{x}_{f,a} - 3k_{f,a}{}^2 - L_{p_{f,a}} \cdot (1-2\bar{x}_{f,a})\right]}{A_{f,a}}\right)$$

To obtain $h_{a,f}$, $\delta C_{P_{a,f}}$ have to be given!

Substituting equation ③ into equation ② and rearranging for $\delta C_{P_{a,f}}$,

Given: $C_P,\ \delta C_P, L_{p_{a,f}}, \delta L_{P_{a,f}}, LCB,\ \delta LCB k_{a,f}$

Find: $\delta C_{P_{a,f}}$

$$\delta C_{p_f} = \frac{2\left[\delta C_p \cdot (B_a + LCB) + \delta LCB \cdot (C_P + \delta C_P)\right] + C_f \cdot \delta L_{p_f} - C_a \cdot \delta L_{p_a}}{B_f + B_a}$$

$$\delta C_{p_a} = \frac{2\left[\delta C_p \cdot (B_f - LCB) - \delta LCB \cdot (C_P + \delta C_P)\right] - C_f \cdot \delta L_{P_f} + C_a \cdot \delta L_{p_a}}{B_f + B_a}$$

$$(A_{a,f} = C_{P_{a,f}}(1-2\bar{x}_{a,f}) - L_{p_{a,f}}(1-C_{P_{a,f}}))$$

$$\left(B_{a,f} = \frac{C_{p_{a,f}} \cdot \left[2\bar{x}_{a,f} - 3k_{a,f}{}^2 - L_{p_{a,f}} \cdot (1-2\bar{x}_{a,f})\right]}{A_{a,f}}\right)\left(C_{a,f} = \frac{B_{a,f}(1-C_{P_{a,f}}) - C_{P_{a,f}}(1-2\bar{x}_{a,f})}{1-L_{p_{a,f}}}\right)$$

④ Calculation of $k_{a,f}$

$$k_{a,f} = \frac{I_{a,f}}{S_{a,f}}$$

$k_{a,f}$: The lever of the second moment (i.e., radius of gyration) about midship expressed as a fraction of the length of the half-body
$I_{a,f}$: The second moment about midship expressed as a fraction of the length of the half-body
$S_{a,f}$: The area of the half-body

δC_P : The required change in prismatic coefficient of the half-body
x : The fractional distance of any transverse section from midship
δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient
h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P
L_P : The fractional parallel middle of the half-body

C_P Variation method
- Relation between "1-C_P" Variation Method and "Lackenby" Method

"1-C_P" variation method

Given: $C_{P_{a,f}}$, $\delta C_{P_{a,f}}$

Find: $\delta x_{a,f}$

$$\boxed{\delta x_{a,f}=\frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)}$$

The change in parallel middle body by "1-C_P" variation method

Given: $C_{P_{a,f}}$, $\delta C_{P_{a,f}}$, $L_{P_{a,f}}$

Find: $\delta L_{P_{a,f}}$

$$\boxed{\delta L_{P_{f,a}}=\frac{\delta C_{P_{f,a}}}{1-C_{P_{f,a}}}\left(1-L_{P_{f,a}}\right)}$$

➡ The consequent change in parallel middle body (**$\delta L_{pa,f}$**) is calculated by "1-C_P" variation method.

"Lackenby" method <General Case>

Given: $C_{P_{a,f}}$, $\delta C_{P_{a,f}}$, $L_{P_{a,f}}$, $\delta L_{P_{a,f}}$, $\bar{x}_{a,f}$

Find: $\delta x_{a,f}$

$$\delta x_{f,a}=(1-x_{f,a})\left\{\frac{\delta L_{P_{a,f}}}{1-L_{P_{a,f}}}+\frac{x_{f,a}-L_{P_{a,f}}}{A_{f,a}}\left[\delta C_{P_{f,a}}-\delta L_{P_{a,f}}\frac{(1-C_{P_{f,a}})}{(1-L_{P_{f,a}})}\right]\right\}$$

$$,(A_{a,f}=C_{P_{a,f}}(1-2\bar{x}_{a,f})-L_{P_{a,f}}(1-C_{P_{a,f}}))$$

➡ The change in the parallel middle body (**$\delta L_{pa,f}$**) can be controlled.

(Substituting into the Lackenby method)

$$\delta x_{f,a}=(1-x_{f,a})\left\{\frac{\delta L_{P_{f,a}}}{1-L_{P_{f,a}}}+\frac{x_{f,a}-L_{P_{f,a}}}{A_{f,a}}\left[\delta C_{P_{f,a}}-\delta L_{P_{f,a}}\frac{(1-C_{P_{f,a}})}{(1-L_{P_{f,a}})}\right]\right\}$$

$$\delta x_{a,f}=(1-x_{a,f})\left\{\frac{\left\{\frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\cancel{(1-L_{P_{a,f}})}\right\}}{\cancel{1-L_{P_{a,f}}}}+\frac{x_{a,f}-L_{P_{a,f}}}{A_{a,f}}\left[\delta C_{P_{a,f}}-\left\{\frac{\delta C_{P_{a,f}}}{\cancel{1-C_{P_{a,f}}}}\cancel{(1-L_{P_{a,f}})}\right\}\frac{\cancel{(1-C_{P_{a,f}})}}{\cancel{(1-L_{P_{a,f}})}}\right]\right\}$$

$$\boxed{\therefore\ \delta x_{a,f}=\frac{\delta C_{P_{a,f}}}{1-C_{P_{a,f}}}\left(1-x_{a,f}\right)}$$

➡ This result is equal to the result of "1-C_P" variation method.

➡ That is, "1-C_P" variation method is a special case of Lackenby method.

δC_P : The required change in prismatic coefficient of the half-body

x : The fractional distance of any transverse section from midship

δx : The necessary longitudinal shift of the section at x to produce the required change in prismatic coefficient

h : The fractional distance from midship of the centroid of the added "sliver" of area represented by δC_P

L_P : The fractional parallel middle of the half-body

δL_P :

$\bar{x}$: The fractional distance from midship of the centroid of the half-body

y : The area of the transverse section at x expressed as a fraction of the maximum ordinate

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Example of a C_P Variation Method

Example of a twin-skeg container ship

```
-0.63ST 0.0000
-0.00ST 0.0267
 0.41ST 0.0044
 0.50ST 0.0811
 0.74ST 0.1312
 1.00ST 0.2019
 1.50ST 0.3275
 1.72ST 0.3773
 2.00ST 0.4370
 2.50ST 0.5337
 3.00ST 0.6202
 4.00ST 0.7621
 5.00ST 0.8586
 6.00ST 0.9296
 7.00ST 0.9758
 8.00ST 0.9969
 9.00ST 1.0000
10.00ST 0.9994
11.00ST 0.9903
12.00ST 0.9682
13.00ST 0.9259
14.00ST 0.8550
15.00ST 0.7463
16.00ST 0.6011
16.58ST 0.5032
17.00ST 0.4290
18.00ST 0.2544
18.50ST 0.1788
19.00ST 0.1217
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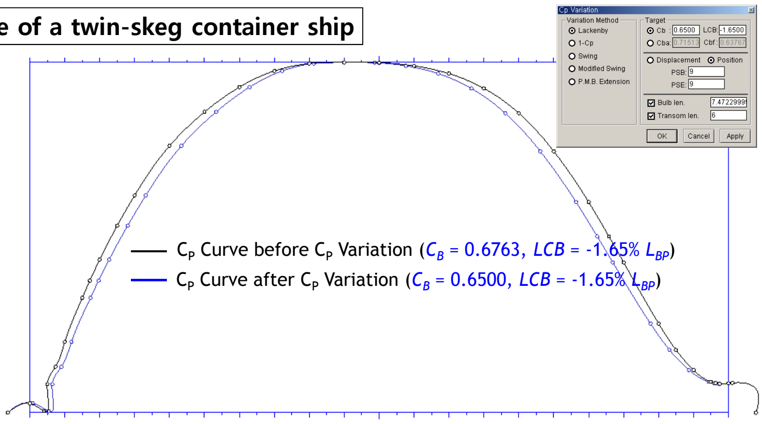

Variation Method
- ● Lackenby
- ○ 1-Cp
- ○ Swing
- ○ Modified Swing
- ○ P.M.B. Extension

Target
- ● Cb : 0.6500 LCB: -1.6500
- ○ Cba: 0.71513 Cbf : 0.63767
- ○ Displacement ● Position
- PSB: 9
- PSE: 9
- ☑ Bulb len. 7.4722999
- ☑ Transom len. 6

```
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 0.54ST 0.0044
 0.64ST 0.0811
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 1.97ST 0.3773
 2.27ST 0.4370
 2.80ST 0.5337
 3.32ST 0.6202
 4.34ST 0.7621
 5.33ST 0.8586
 6.29ST 0.9296
 7.22ST 0.9758
 8.13ST 0.9969
 9.00ST 1.0000
 9.87ST 0.9994
10.00ST 0.9988
10.77ST 0.9903
11.69ST 0.9682
12.64ST 0.9259
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16.69ST 0.4290
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18.32ST 0.1788
18.87ST 0.1217
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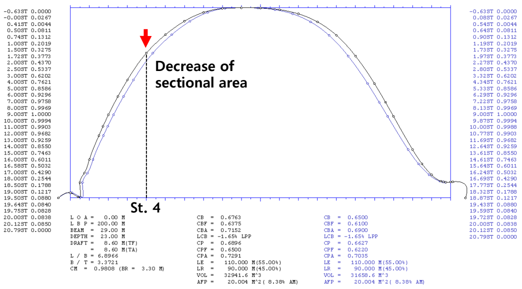
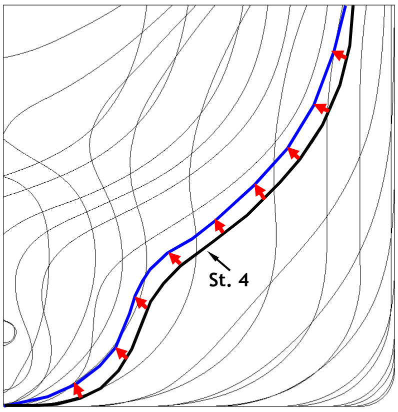
19.59ST 0.0840
19.72ST 0.0828
20.00ST 0.0838
20.12ST 0.0850
20.79ST 0.0000
```

```
L O A =   0.00 M                  CB  =  0.6763                    CB  =  0.6500
L B P = 200.00 M                  CBF =  0.6375                    CBF =  0.6100
BEAM  =  29.00 M                  CBA =  0.7152                    CBA =  0.6900
DEPTH =  23.00 M                  LCB = -1.65% LPP                 LCB = -1.65% LPP
DRAFT =   8.60 M(TF)              CP  =  0.6896                    CP  =  0.6627
      =   8.60 M(TA)              CPF =  0.6500                    CPF =  0.6220
L / B = 6.8966                    CPA =  0.7291                    CPA =  0.7035
B / T = 3.3721                    LE  =   110.000 M(55.00%)        LE  =   110.000 M(55.00%)
CM  =  0.9808 (BR =  3.30 M)      LR  =    90.000 M(45.00%)        LR  =    90.000 M(45.00%)
                                  VOL =   32941.6 M^3              VOL =   31658.6 M^3
                                  AFP =    20.004 M^2( 8.38% AM)   AFP =    20.004 M^2( 8.38% AM)
```

Design of a Body Plan by Using the Changed C_P Curve





Procedure of the Hull Form Variation (Detailed)

1. When C_P and LCB are obtained, calculate or estimate the C_P at fore and after bodies.
2. By using the "1-C_P variation method" or "Lackenby method", correct the difference in C_B (C_P) between the basis ship and design ship.
3. By using the "Swing station method", correct the difference in LCB between the basis ship and design ship.
4. By correcting the local part of C_P curve, determine the C_P curve of design ship.
5. Modification of a body plan
6. Modification of a water plan
7. Modification of a sheer plan
8. Fairing

3.3 Hull Form Fairing

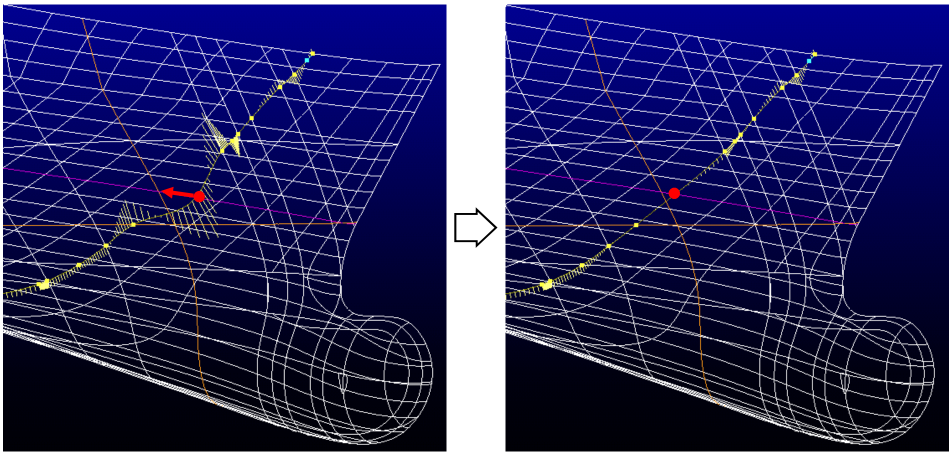
Hull Form Fairing

- ☑ Design task for obtaining a hull form of high quality after hull form variation
- ☑ A kind of touch-up process for the hull form
- ☑ Quality check by using C_P curve

Example of Hull Form Fairing (1/3)

Example of a twin-skeg container ship

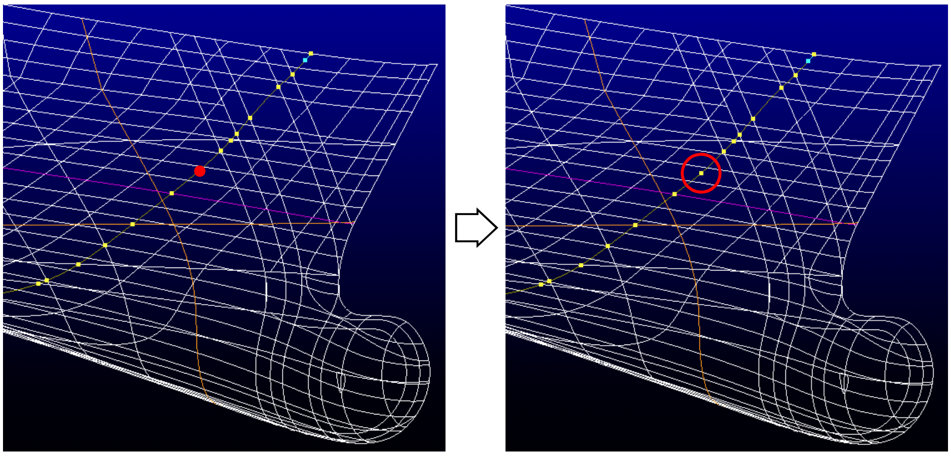
Moving an existing point



Example of Hull Form Fairing (2/3)

Example of a twin-skeg container ship

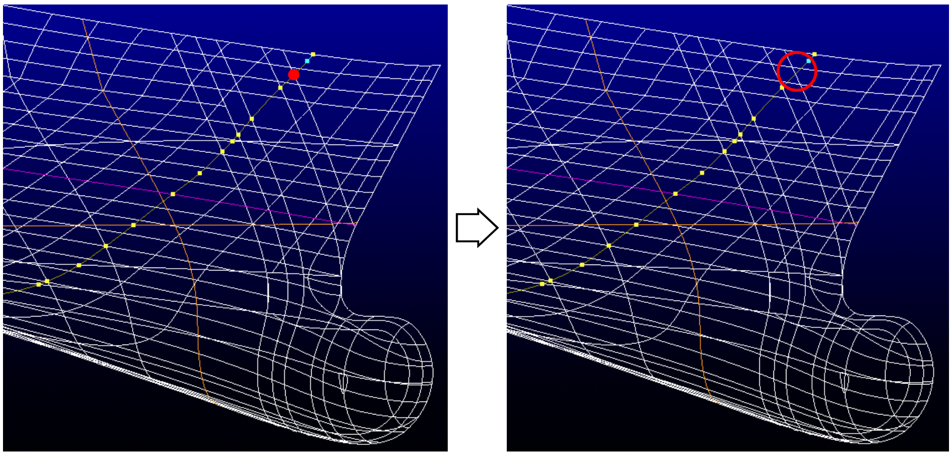
Inserting a new point



Example of Hull Form Fairing (3/3)

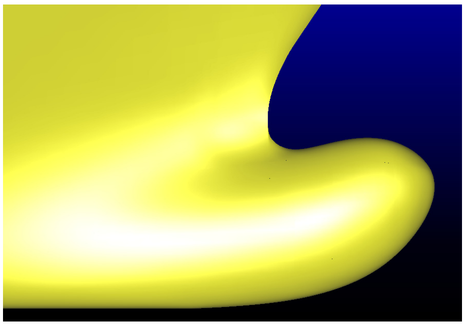
Example of a twin-skeg container ship

Deleting an existing point

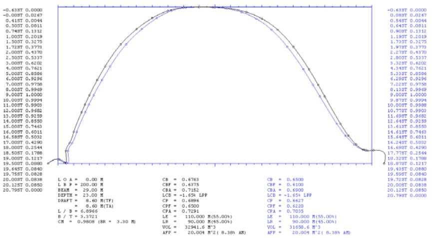


Example of Hull Form of High Quality

Example of a single skeg container ship



Fore body



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 2.50ST 0.5337
 3.00ST 0.6202
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 6.00ST 0.9296
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16.58ST 0.5032
17.00ST 0.4290
18.00ST 0.2544
18.50ST 0.1788
19.00ST 0.1217
19.50ST 0.0880
19.64ST 0.0840
19.75ST 0.0828
20.00ST 0.0838
20.12ST 0.0850
20.79ST 0.0000

L O A =   0.00 M          CB  =  0.6763              CB  =  0.6500
L B P = 200.00 M          CBF =  0.6375              CBF =  0.6100
BEAM  =  29.00 M          CBA =  0.7152              CBA =  0.6900
DEPTH =  23.00 M          LCB = -1.65% LPP           LCB = -1.65% LPP
DRAFT =   8.60 M(TF)      CP  =  0.6896              CP  =  0.6627
      =   8.60 M(TA)      CPF =  0.6500              CPF =  0.6220
L / B = 6.8966            CPA =  0.7291              CPA =  0.7035
B / T = 3.3721            LE  =   110.000 M(55.00%)  LE  =   110.000 M(55.00%)
CM  =  0.9808 (BR =  3.30 M)  LR  =    90.000 M(45.00%)  LR  =    90.000 M(45.00%)
                          VOL =   32941.6 M^3        VOL =   31658.6 M^3
                          AFP =    20.004 M^2( 8.38% AM)  AFP =    20.004 M^2( 8.38% AM)

-0.63ST 0.0000
 0.08ST 0.0267
 0.54ST 0.0044
 0.64ST 0.0811
 0.90ST 0.1312
 1.19ST 0.2019
 1.73ST 0.3275
 1.97ST 0.3773
 2.27ST 0.4370
 2.80ST 0.5337
 3.32ST 0.6202
 4.34ST 0.7621
 5.33ST 0.8586
 6.29ST 0.9296
 7.22ST 0.9758
 8.13ST 0.9969
 9.00ST 1.0000
 9.87ST 0.9994
10.00ST 0.9988
10.77ST 0.9903
11.69ST 0.9682
12.64ST 0.9259
13.61ST 0.8550
14.61ST 0.7463
15.64ST 0.6011
16.24ST 0.5032
16.69ST 0.4290
17.77ST 0.2544
18.32ST 0.1788
18.87ST 0.1217
19.43ST 0.0880
19.59ST 0.0840
19.72ST 0.0828
20.00ST 0.0838
20.12ST 0.0850
20.79ST 0.0000
```
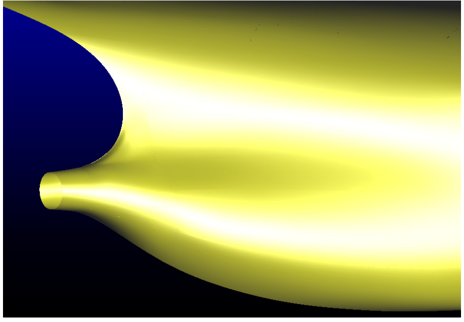
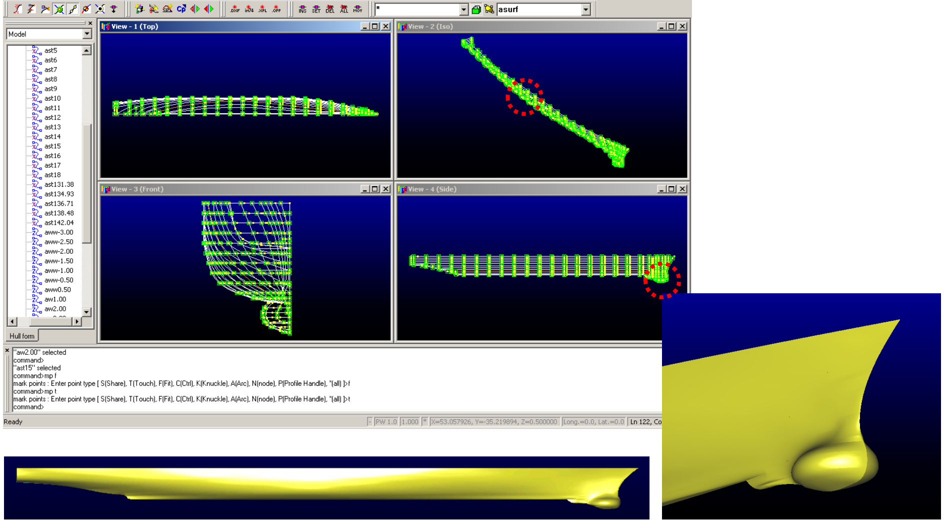

after body



Example of Hull Form of Low Quality (1/2)

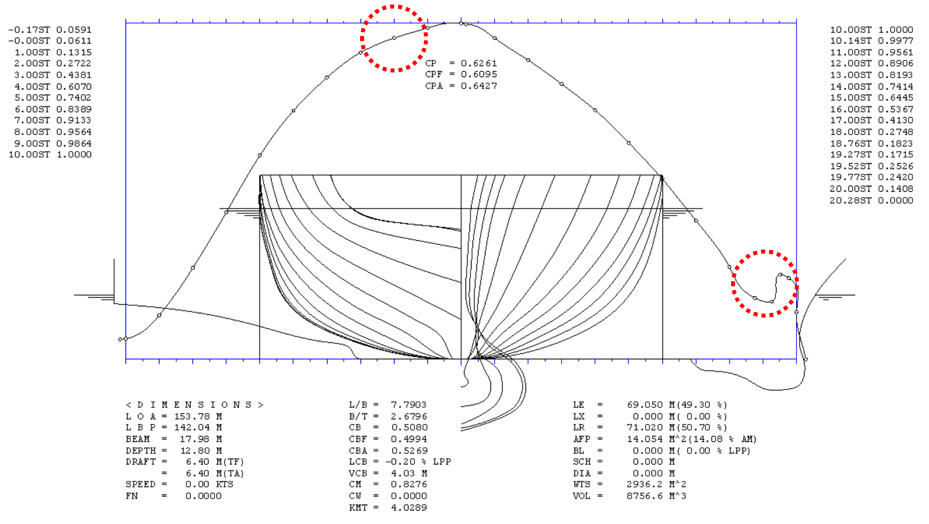
Example of a missile destroyer (DDG-51)



```
"aw2.00" selected
command>
"ast15" selected
command>mp f
mark points : Enter point type [ S(Share), T(Touch), F(Fit), C(Ctrl), K(Knuckle), A(Arc), N(node), P(Profile Handle), *(all) ]>f
command>mp t
mark points : Enter point type [ S(Share), T(Touch), F(Fit), C(Ctrl), K(Knuckle), A(Arc), N(node), P(Profile Handle), *(all) ]>t
command>
Ready    - PW 1.0  1.000  *  X=53.057926, Y=-35.219894, Z=0.500000  Long.=0.0, Lat.=0.0  Ln 122, Co
```

Example of Hull Form of Low Quality (2/2)

Example of a missile destroyer (DDG-51)



```
-0.17ST 0.0591
-0.00ST 0.0611
 1.00ST 0.1315
 2.00ST 0.2722
 3.00ST 0.4381
 4.00ST 0.6070
 5.00ST 0.7402
 6.00ST 0.8389
 7.00ST 0.9133
 8.00ST 0.9564
 9.00ST 0.9864
10.00ST 1.0000
```

```
CP  = 0.6261
CPF = 0.6095
CPA = 0.6427
```

```
10.00ST 1.0000
10.14ST 0.9977
11.00ST 0.9561
12.00ST 0.8906
13.00ST 0.8193
14.00ST 0.7414
15.00ST 0.6445
16.00ST 0.5367
17.00ST 0.4130
18.00ST 0.2748
18.76ST 0.1823
19.27ST 0.1715
19.52ST 0.2526
19.77ST 0.2420
20.00ST 0.1408
20.28ST 0.0000
```

```
< D I M E N S I O N S >         L/B =  7.7903            LE  =   69.050 M(49.30 %)
L O A = 153.78 M                B/T =  2.6796            LX  =    0.000 M( 0.00 %)
L B P = 142.04 M                CB  =  0.5080            LR  =   71.020 M(50.70 %)
BEAM  =  17.98 M                CBF =  0.4994            AFP =   14.054 M^2(14.08 % AM)
DEPTH =  12.80 M                CBA =  0.5269            BL  =    0.000 M( 0.00 % LPP)
DRAFT =   6.40 M(TF)            LCB = -0.20 % LPP        SCH =    0.000 M
      =   6.40 M(TA)            VCB =  4.03 M            DIA =    0.000 M
SPEED =   0.00 KTS              CM  =  0.8276            WTS =   2936.2 M^2
FN    =   0.0000                CW  =  0.0000            VOL =   8756.6 M^3
                                KMT =  4.0289
```

3.4 Performance Evaluation of a Hull Form

Performance Evaluation of a Hull Form

☑ **Stability**
- Hull form coefficients
- Hydrostatic tables and hydrostatic curves

☑ **Resistance**
- Traditional and standard series methods
- Regression based methods (Statistical methods)
- Direct model test
- Computational Fluid Dynamics (CFD)

☑ **Maneuverability**
- Dependent on couple effect between hull form and rudder

Stability Performance

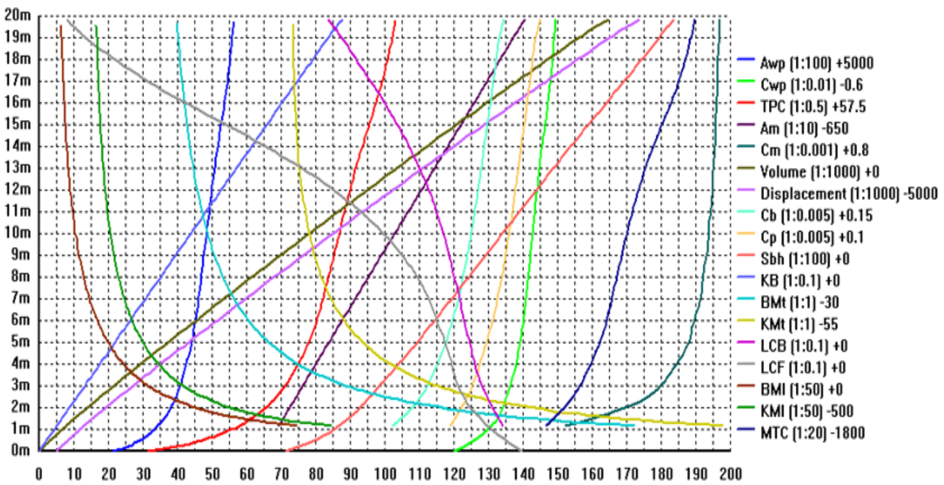
Hydrostatic Values

☑ $\text{Draft}_{\text{Mld}}$, $\text{Draft}_{\text{Scant}}$: Draft from base line, moulded / scantling (m)
☑ $\text{Volume}_{\text{Mld}}(\nabla)$, $\text{Volume}_{\text{Ext}}$: Displacement volume, moulded / extreme (m^3)
☑ $\text{Displacement}_{\text{Mld}}(\Delta)$, $\text{Displacement}_{\text{Ext}}$: Displacement, moulded / extreme (ton)
☑ LCB: Longitudinal center of buoyancy from midship (Sign: - Aft / + Forward)
☑ LCF: Longitudinal center of floatation from midship (Sign: - Aft / + Forward)
☑ VCB: Vertical center of buoyancy above base line (m)
☑ TCB: Transverse center of buoyancy from center line (m)
☑ KM_T: Transverse metacenter height above base line (m)
☑ KM_L: Longitudinal metacenter height above base line (m)
☑ MTC: Moment to change trim one centimeter (ton-m)
☑ TPC: Increase in $\text{Displacement}_{\text{Mld}}$ (ton) per one centimeter immersion
☑ WSA: Wetted surface area (m^2)
☑ C_B: Block coefficient
☑ C_{WP}: Water plane area coefficient
☑ C_M: Midship section area coefficient
☑ C_P: Prismatic coefficient
☑ Trim: Trim(= after draft – forward draft) (m)

Hydrostatic Curve

☑ **Hydrostatic curve: Curve for representing hydrostatic values**

Example of Hydrostatic Curve



Generation of Hydrostatic Tables and Hydrostatic Curves

Given: Offsets table, Formulas for calculating hydrostatic values
Find: Hydrostatic tables as function of draft, Hydrostatic curves

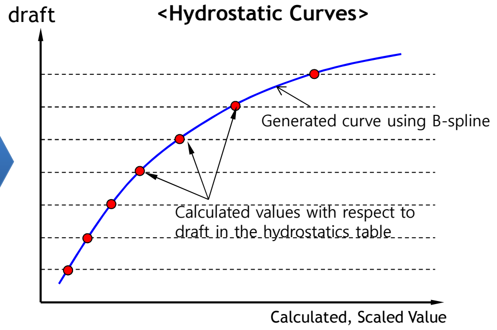
✓ **Calculation of hydrostatic values as function of draft**

<Hydrostatic Tables>

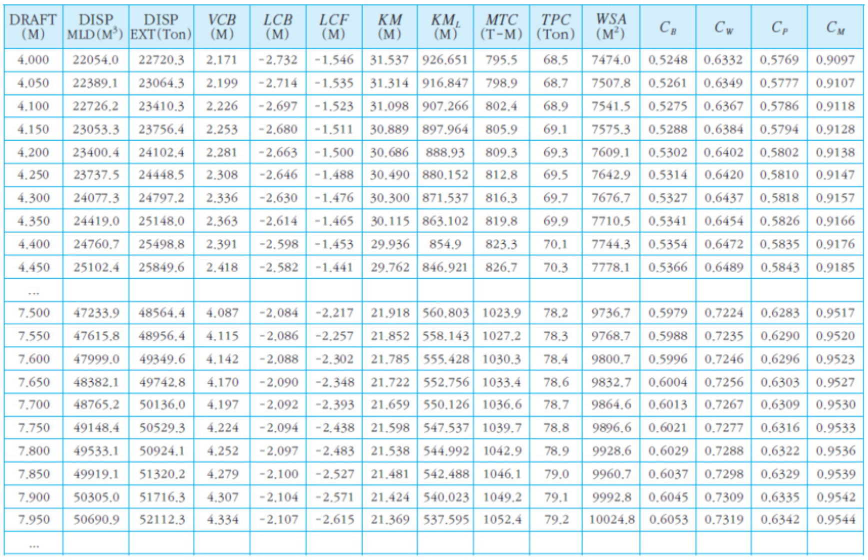
Draft [m]

	Δ	LCB	TCB	KB	KM_T	…
0	…	…	…	…	…	…
1	…	…	…	…	…	…
2	…	…	…	…	…	…
3	…	…	…	…	…	…
4	…	…	…	…	…	…
5	…	…	…	…	…	…
…	…	…	…	…	…	…

<Hydrostatic Curves>

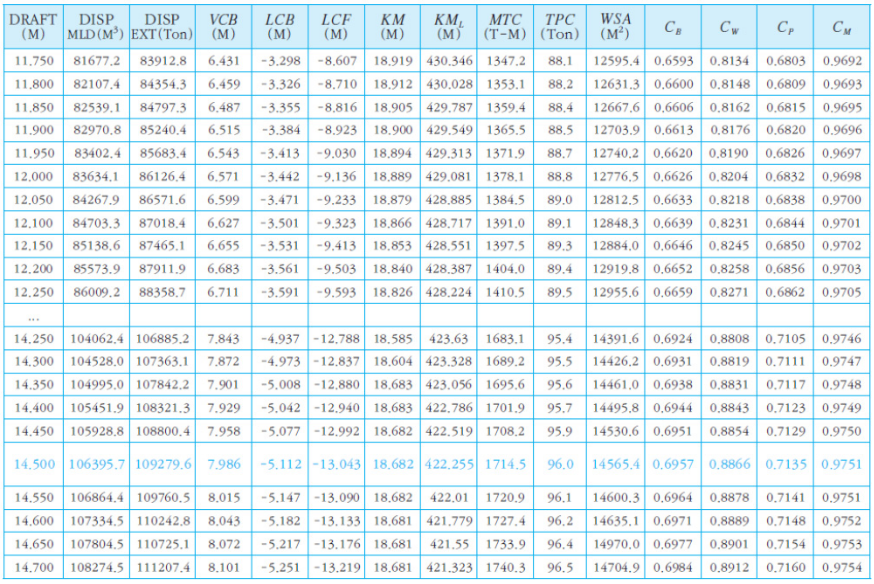


Example of Hydrostatic Tables of a 6,300TEU Container Ship (1/2)



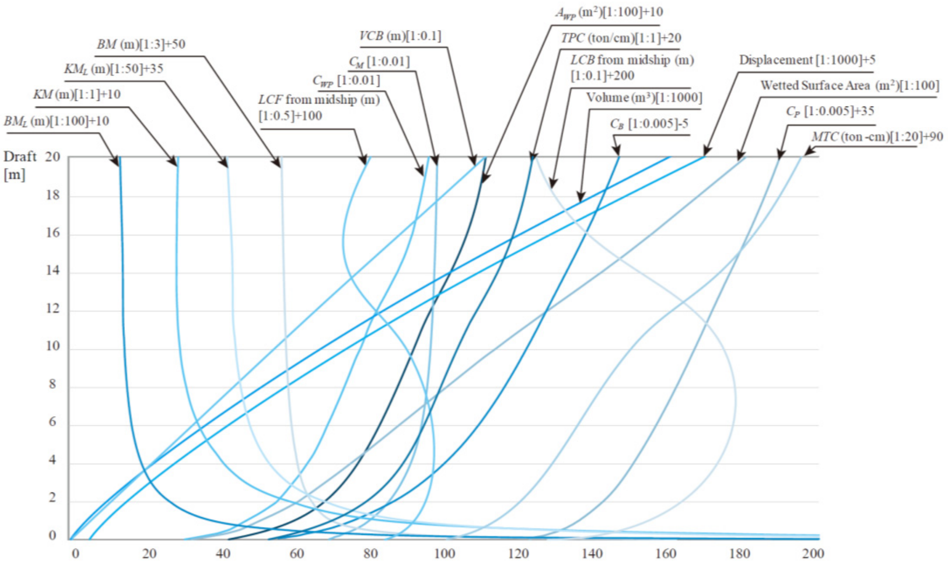
DRAFT (M)	DISP MLD(M^3)	DISP EXT(Ton)	VCB (M)	LCB (M)	LCF (M)	KM (M)	KM_L (M)	MTC (T-M)	TPC (Ton)	WSA (M^2)	C_B	C_W	C_P	C_M
4.000	22054.0	22720.3	2.171	-2.732	-1.546	31.537	926.651	795.5	68.5	7474.0	0.5248	0.6332	0.5769	0.9097
4.050	22389.1	23064.3	2.199	-2.714	-1.535	31.314	916.847	798.9	68.7	7507.8	0.5261	0.6349	0.5777	0.9107
4.100	22726.2	23410.3	2.226	-2.697	-1.523	31.098	907.266	802.4	68.9	7541.5	0.5275	0.6367	0.5786	0.9118
4.150	23053.3	23756.4	2.253	-2.680	-1.511	30.889	897.964	805.9	69.1	7575.3	0.5288	0.6384	0.5794	0.9128
4.200	23400.4	24102.4	2.281	-2.663	-1.500	30.686	888.93	809.3	69.3	7609.1	0.5302	0.6402	0.5802	0.9138
4.250	23737.5	24448.5	2.308	-2.646	-1.488	30.490	880.152	812.8	69.5	7642.9	0.5314	0.6420	0.5810	0.9147
4.300	24077.3	24797.2	2.336	-2.630	-1.476	30.300	871.537	816.3	69.7	7676.7	0.5327	0.6437	0.5818	0.9157
4.350	24419.0	25148.0	2.363	-2.614	-1.465	30.115	863.102	819.8	69.9	7710.5	0.5341	0.6454	0.5826	0.9166
4.400	24760.7	25498.8	2.391	-2.598	-1.453	29.936	854.9	823.3	70.1	7744.3	0.5354	0.6472	0.5835	0.9176
4.450	25102.4	25849.6	2.418	-2.582	-1.441	29.762	846.921	826.7	70.3	7778.1	0.5366	0.6489	0.5843	0.9185
...														
7.500	47233.9	48564.4	4.087	-2.084	-2.217	21.918	560.803	1023.9	78.2	9736.7	0.5979	0.7224	0.6283	0.9517
7.550	47615.8	48956.4	4.115	-2.086	-2.257	21.852	558.143	1027.2	78.3	9768.7	0.5988	0.7235	0.6290	0.9520
7.600	47999.0	49349.6	4.142	-2.088	-2.302	21.785	555.428	1030.3	78.4	9800.7	0.5996	0.7246	0.6296	0.9523
7.650	48382.1	49742.8	4.170	-2.090	-2.348	21.722	552.756	1033.4	78.6	9832.7	0.6004	0.7256	0.6303	0.9527
7.700	48765.2	50136.0	4.197	-2.092	-2.393	21.659	550.126	1036.6	78.7	9864.6	0.6013	0.7267	0.6309	0.9530
7.750	49148.4	50529.3	4.224	-2.094	-2.438	21.598	547.537	1039.7	78.8	9896.6	0.6021	0.7277	0.6316	0.9533
7.800	49533.1	50924.1	4.252	-2.097	-2.483	21.538	544.992	1042.9	78.9	9928.6	0.6029	0.7288	0.6322	0.9536
7.850	49919.1	51320.2	4.279	-2.100	-2.527	21.481	542.488	1046.1	79.0	9960.7	0.6037	0.7298	0.6329	0.9539
7.900	50305.0	51716.3	4.307	-2.104	-2.571	21.424	540.023	1049.2	79.1	9992.8	0.6045	0.7309	0.6335	0.9542
7.950	50690.9	52112.3	4.334	-2.107	-2.615	21.369	537.595	1052.4	79.2	10024.8	0.6053	0.7319	0.6342	0.9544
...														

Example of Hydrostatic Tables of a 6,300TEU Container Ship (2/2)



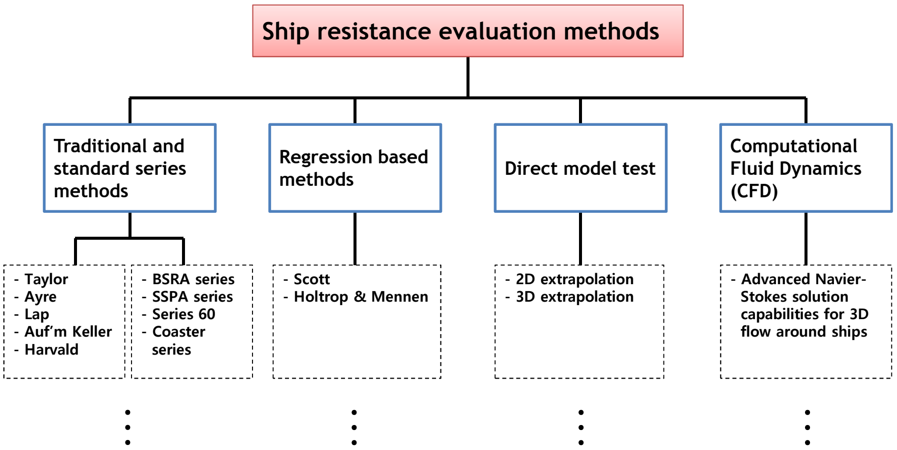
DRAFT (M)	DISP MLD(M^3)	DISP EXT(Ton)	VCB (M)	LCB (M)	LCF (M)	KM (M)	KM_L (M)	MTC (T-M)	TPC (Ton)	WSA (M^2)	C_B	C_W	C_P	C_M
11.750	81677.2	83912.8	6.431	-3.298	-8.607	18.919	430.346	1347.2	88.1	12595.4	0.6593	0.8134	0.6803	0.9692
11.800	82107.4	84354.3	6.459	-3.326	-8.710	18.912	430.028	1353.1	88.2	12631.3	0.6600	0.8148	0.6809	0.9693
11.850	82539.1	84797.3	6.487	-3.355	-8.816	18.905	429.787	1359.4	88.4	12667.6	0.6606	0.8162	0.6815	0.9695
11.900	82970.8	85240.4	6.515	-3.384	-8.923	18.900	429.549	1365.5	88.5	12703.9	0.6613	0.8176	0.6820	0.9696
11.950	83402.4	85683.4	6.543	-3.413	-9.030	18.894	429.313	1371.9	88.7	12740.2	0.6620	0.8190	0.6826	0.9697
12.000	83634.1	86126.4	6.571	-3.442	-9.136	18.889	429.081	1378.1	88.8	12776.5	0.6626	0.8204	0.6832	0.9698
12.050	84267.9	86571.6	6.599	-3.471	-9.233	18.879	428.885	1384.5	89.0	12812.5	0.6633	0.8218	0.6838	0.9700
12.100	84703.3	87018.4	6.627	-3.501	-9.323	18.866	428.717	1391.0	89.1	12848.3	0.6639	0.8231	0.6844	0.9701
12.150	85138.6	87465.1	6.655	-3.531	-9.413	18.853	428.551	1397.5	89.3	12884.0	0.6646	0.8245	0.6850	0.9702
12.200	85573.9	87911.9	6.683	-3.561	-9.503	18.840	428.387	1404.0	89.4	12919.8	0.6652	0.8258	0.6856	0.9703
12.250	86009.2	88358.7	6.711	-3.591	-9.593	18.826	428.224	1410.5	89.5	12955.6	0.6659	0.8271	0.6862	0.9705
...														
14.250	104062.4	106885.2	7.843	-4.937	-12.788	18.585	423.63	1683.1	95.4	14391.6	0.6924	0.8808	0.7105	0.9746
14.300	104528.0	107363.1	7.872	-4.973	-12.837	18.604	423.328	1689.2	95.5	14426.2	0.6931	0.8819	0.7111	0.9747
14.350	104995.0	107842.2	7.901	-5.008	-12.880	18.683	423.056	1695.6	95.6	14461.0	0.6938	0.8831	0.7117	0.9748
14.400	105451.9	108321.3	7.929	-5.042	-12.940	18.683	422.786	1701.9	95.7	14495.8	0.6944	0.8843	0.7123	0.9749
14.450	105928.8	108800.4	7.958	-5.077	-12.992	18.682	422.519	1708.2	95.9	14530.6	0.6951	0.8854	0.7129	0.9750
14.500	106395.7	109279.6	7.986	-5.112	-13.043	18.682	422.255	1714.5	96.0	14565.4	0.6957	0.8866	0.7135	0.9751
14.550	106864.4	109760.5	8.015	-5.147	-13.090	18.682	422.01	1720.9	96.1	14600.3	0.6964	0.8878	0.7141	0.9751
14.600	107334.5	110242.8	8.043	-5.182	-13.133	18.681	421.779	1727.4	96.2	14635.1	0.6971	0.8889	0.7148	0.9752
14.650	107804.5	110725.1	8.072	-5.217	-13.176	18.681	421.55	1733.9	96.4	14970.0	0.6977	0.8901	0.7154	0.9753
14.700	108274.5	111207.4	8.101	-5.251	-13.219	18.681	421.323	1740.3	96.5	14704.9	0.6984	0.8912	0.7160	0.9754

Example of Hydrostatic Curves of a 6,300TEU Container Ship



Resistance Performance

Types of Ship Resistance Evaluation Methods



Ship resistance evaluation methods

Traditional and standard series methods
- Taylor
- Ayre
- Lap
- Auf'm Keller
- Harvald

- BSRA series
- SSPA series
- Series 60
- Coaster series

Regression based methods
- Scott
- Holtrop & Mennen

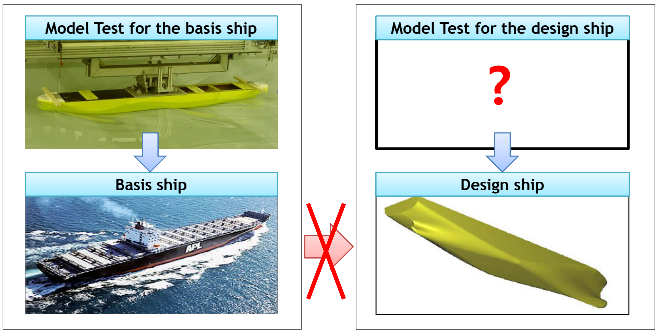
Direct model test
- 2D extrapolation
- 3D extrapolation

Computational Fluid Dynamics (CFD)
- Advanced Navier-Stokes solution capabilities for 3D flow around ships

⋮

* John Carlton, Marine Propellers and Propulsion, 3rd Edition, Elsevier, 2012

Resistance estimation by Holtrop-Mennen's Method
- Reason why a statistical method is presented at the initial design stage of a ship (1/2)



As the resistance of a full-scale ship cannot be measured directly, our knowledge about the resistance of ships comes from model tests.

However, at the initial design stage of a ship, the model for the design ship is not provided. Furthermore, the design ship and the basis ship are not preserved geometrical similarity.

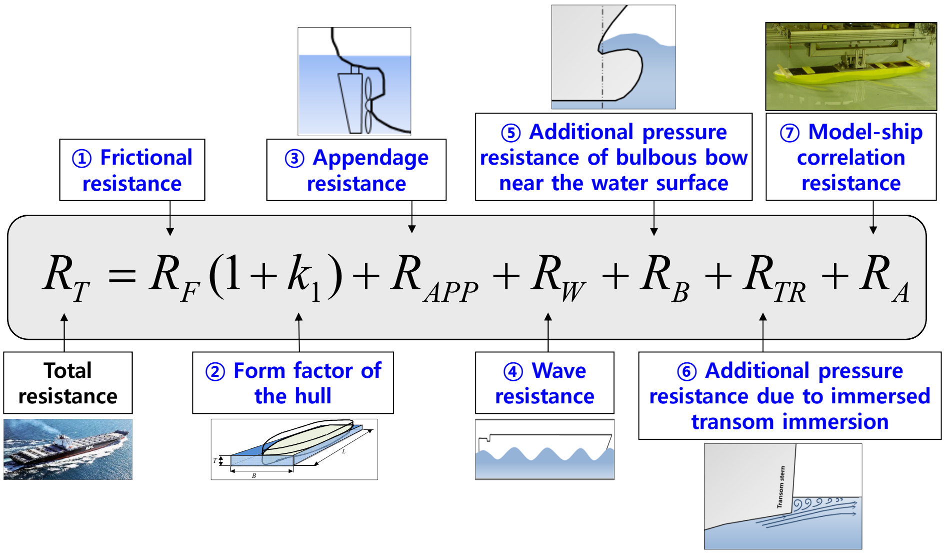
Resistance estimation by Holtrop-Mennen's Method
- Reason why a statistical method is presented at the initial design stage of a ship (2/2)

Therefore, a statistical method was presented for the determination of the required propulsive power in the initial design stage.
This method was developed through a regression analysis of random model experiments and full-scale data.

Many naval architects use the method, generally in the form presented in 1984 and find it gives acceptable results although it has to said that a number of the formula seem very complicated and the physics behind them are not at all clear (a not infrequent corollary of regression analysis).

* Holtrop and Mennen's method, which was originally presented in the *Journal of International Shipbuilding Progress*, Vol. 25 (Oct. 1978), revised in Vol. 29 (July 1982) and again in N.S.M.B. Publication 769 (1984) and in a paper presented to SMSSH'88 (October 1988), meets all criteria with formulae derived by regression analysis from the considerable data bank of the Netherlands Ship Model Basin being provided for every variable.

Formula Proposed by Holtrop & Mennen



① Frictional resistance

③ Appendage resistance

⑤ Additional pressure resistance of bulbous bow near the water surface

⑦ Model-ship correlation resistance

$$R_T = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

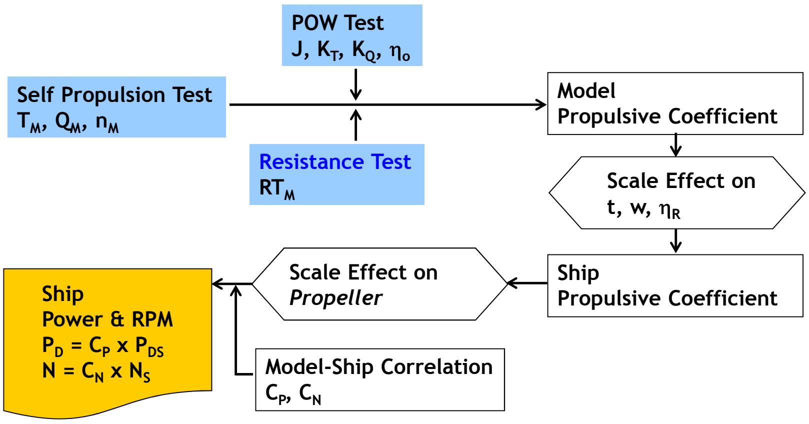
Total resistance

② Form factor of the hull

④ Wave resistance

⑥ Additional pressure resistance due to immersed transom immersion

Model Test in the Towing Tank



POW Test
J, K_T, K_Q, η_o

Self Propulsion Test
T_M, Q_M, n_M

Resistance Test
RT_M

Model
Propulsive Coefficient

Scale Effect on
t, w, η_R

Ship
Propulsive Coefficient

Scale Effect on
Propeller

Model-Ship Correlation
C_P, C_N

Ship
Power & RPM
$P_D = C_P \times P_{DS}$
$N = C_N \times N_S$

Classifications of Model Test (1/4)

☑ Resistance Test

- The ship model is towed by a carriage and the total longitudinal forces acting on the model are measured at various speeds.
- During these tests the ship model is free to move “vertically” and “in pitch”.
- The tests are done at one or several displacements or trim angles.
- Given: Ship Speed (V_M)
- Find: Total resistance (R_{TM})

* Reference: MARIN, Stadt Towing Tank

Classifications of Model Test (2/4)

☑ **Self Propulsion Test**

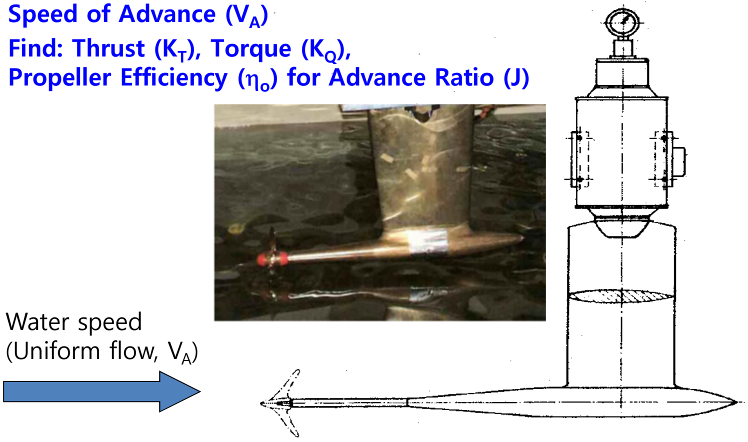
- **The ship model is self propelled and free to move “vertically” and “in pitch”.**
- **The horsepower required to drive the model at various speeds is measured.**
- **Given: Ship Speed (V_M)**
- **Find: Thrust (T_M), Torque (Q_M), Propeller RPM (n_M)**

* Reference: MARIN, Stadt Towing Tank

Classifications of Model Test (3/4)

☑ **Propeller Open Water (POW) Test**

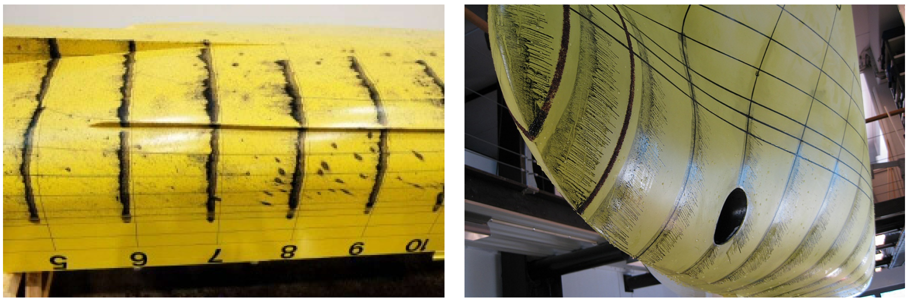
- **This test is carried out under ideal condition in which the propeller does not get disturbed by the hull.**
- **Given: Propeller Dimensions (D_P, P_i, A_E/A_O, z), Propeller RPM (n), Speed of Advance (V_A)**
- **Find: Thrust (K_T), Torque (K_Q), Propeller Efficiency (η_o) for Advance Ratio (J)**



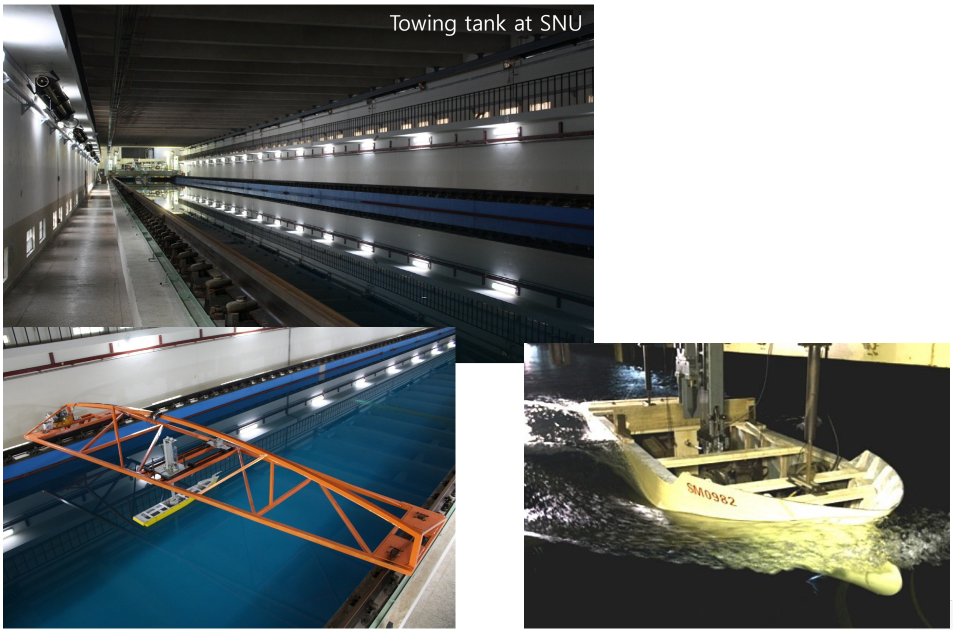
Classifications of Model Test (4/4)

☑ Flow visualization test

- Stripes of a paint are applied to the model which is then towed at a desired Froude scaled speed and propeller rotation rate.
- This leads to the paint streaking along the flow lines at the boundary layer of the model hull.

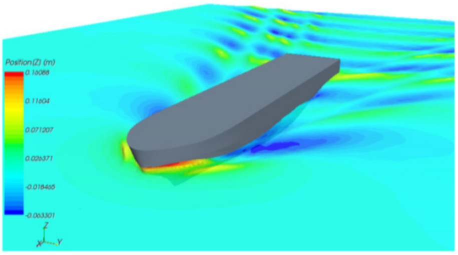


Example of Resistance Test in the Towing Tank

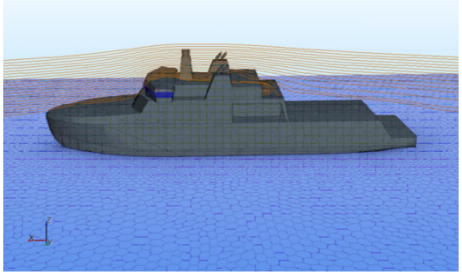


Computational Fluid Dynamics (CFD) (1/3)

- ☑ **A branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows**
- ☑ **Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.**



Resistance test using CFD to optimize hull form

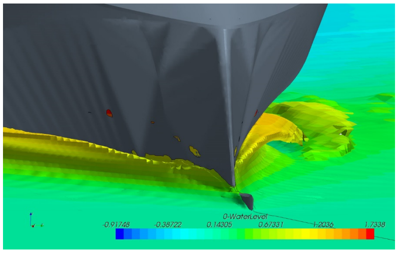


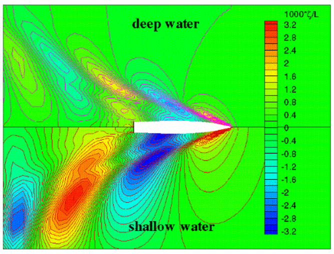
Aerodynamic analysis of turbulence levels over the helicopter flight deck

* Reference: STX Canada, US Marine

Computational Fluid Dynamics (CFD) (2/3)

- ☑ **Procedures for CFD**
  - ■ **Preprocessing**
    - ● **The geometry (physical bounds) of the problem is defined.**
    - ● **The volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or non-uniform.**
    - ● **The physical modeling is defined – for example, the equations of motion + enthalpy + radiation + species conservation**
    - ● **Boundary conditions are defined. This involves specifying the fluid behavior and properties at the boundaries of the problem. For transient problems, the initial conditions are also defined**
  - ■ **Simulation**
    - ● **The simulation is started and the equations are solved iteratively as a steady-state or transient**
  - ■ **Post-processing**
    - ● **Finally a postprocessor is used for the analysis and visualization of the resulting solution.**



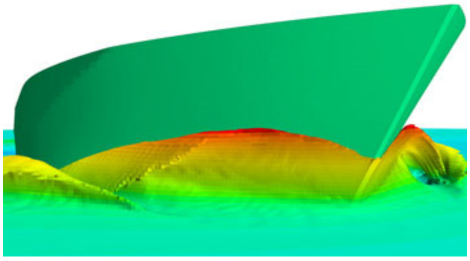


* Reference: Stadt Towing Tank, Ship and Ocean Industries R&D Center in Taiwan

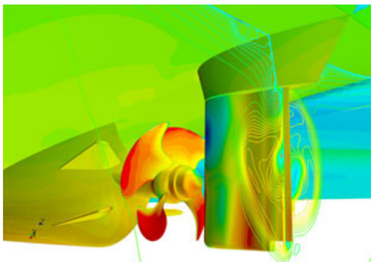
Computational Fluid Dynamics (CFD) (3/3)

☑ **Methodology for CFD**

- **Discretization methods: Finite volume method, Finite element method, Finite difference method, Spectral element method, Boundary element method, High-resolution discretization schemes, etc.**
- **Turbulence models: Reynolds-averaged Navier-Stokes, Large eddy simulation, Detached eddy simulation, Direct numerical simulation, Coherent vortex simulation, Probability density function methods, Vortex method, Vorticity confinement method, Linear eddy model, etc.**
- **Two-phase flow**



Computed breaking bow wave



Computed pressure and axial velocity distributions in stern regions

* Reference: Danish Centre for Maritime Technology

Maneuvering Performance

Maneuverability

☑ Key measures of maneuvering capability
- Turning ability
- Course changing and Yaw checking ability
- Stopping ability
- Straight line stability and course keeping ability

☑ A hydrodynamic derivatives of ship are required to predict numerically its maneuvering capability.

Methods for Estimating Maneuvering Capability

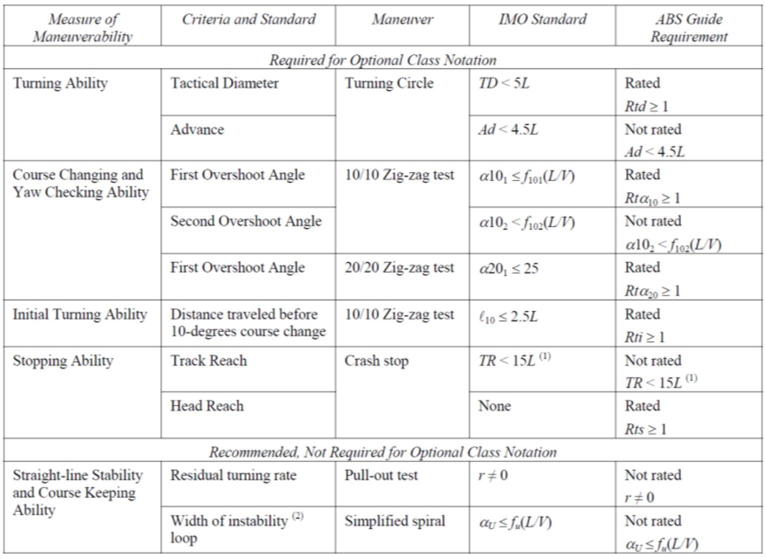
☑ Regression Analysis Results from Similar Ships (Semi-empirical Methods)

☑ Theoretical Prediction Methods

☑ Model Tests (Experiments with Scale Models)
- Straight line test
- Rotating arm test
- Planar Motion Mechanism (PMM) test
- Free running (radio controlled) model test

☑ Full Scale Tests
- Tests of adherence to classification society standard

Standards and Criteria of Maneuverability

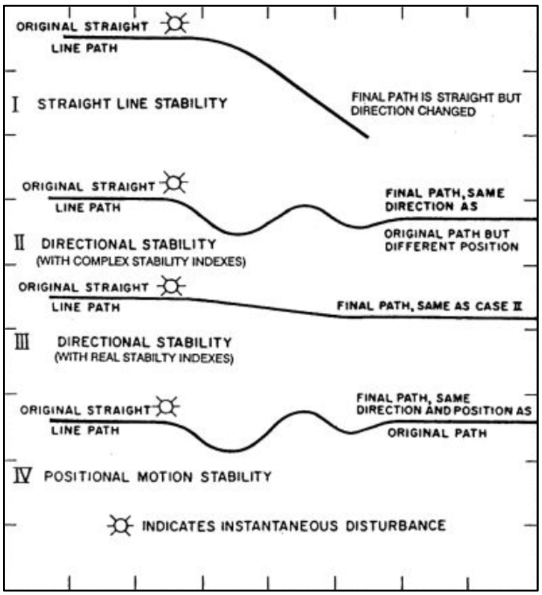


Measure of Maneuverability	*Criteria and Standard*	*Maneuver*	*IMO Standard*	*ABS Guide Requirement*
Required for Optional Class Notation				
Turning Ability	Tactical Diameter	Turning Circle	$TD < 5L$	Rated $Rtd \geq 1$
	Advance		$Ad < 4.5L$	Not rated $Ad < 4.5L$
Course Changing and Yaw Checking Ability	First Overshoot Angle	10/10 Zig-zag test	$\alpha 10_1 \leq f_{101}(L/V)$	Rated $Rt\alpha_{10} \geq 1$
	Second Overshoot Angle		$\alpha 10_2 < f_{102}(L/V)$	Not rated $\alpha 10_2 < f_{102}(L/V)$
	First Overshoot Angle	20/20 Zig-zag test	$\alpha 20_1 \leq 25$	Rated $Rt\alpha_{20} \geq 1$
Initial Turning Ability	Distance traveled before 10-degrees course change	10/10 Zig-zag test	$\ell_{10} \leq 2.5L$	Rated $Rti \geq 1$
Stopping Ability	Track Reach	Crash stop	$TR < 15L$ (1)	Not rated $TR < 15L$ (1)
	Head Reach		None	Rated $Rts \geq 1$
Recommended, Not Required for Optional Class Notation				
Straight-line Stability and Course Keeping Ability	Residual turning rate	Pull-out test	$r \neq 0$	Not rated $r \neq 0$
	Width of instability (2) loop	Simplified spiral	$\alpha_U \leq f_u(L/V)$	Not rated $\alpha_U \leq f_u(L/V)$

Note) 1: For large, low powered vessels, *TR* < 20*L*. 2: Applicable only for path-unstable vessels.

* Reference: ABS, Guide for Vessel Maneuverability, 2006

Types of Straight Line Stability



* Reference: SNAME PNA, Vol. III

Necessity of Hydrodynamic Derivatives in Theoretical Prediction Methods

☑ The hydrodynamic derivatives should be determined to truly measure maneuvering capability.

☑ The velocity derivatives are required to assess stability.

☑ The acceleration derivatives are required to determine the magnitude of the stability indices.

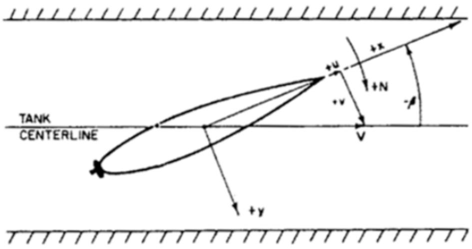
☑ Additionally, the control surface derivatives are needed to compute trajectory of a ship.

Model Tests

☑ Objective: To predict maneuvering capability or to determine hydrodynamic derivatives for the used for theoretical prediction methods

☑ Types of Model Tests
- Straight line test
- Rotating arm test
- Planar Motion Mechanism (PMM) test
- Free running (radio controlled) model test

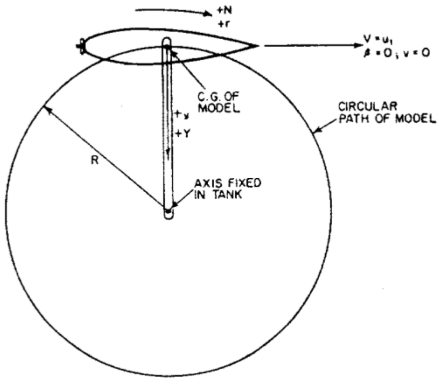
Model Test
- Straight Line Test

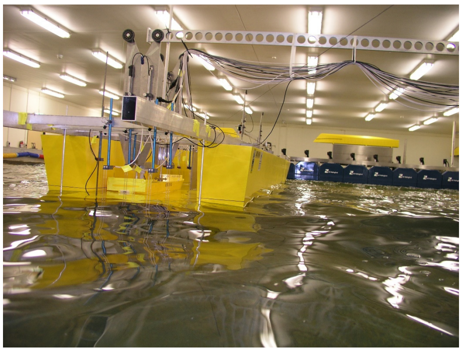


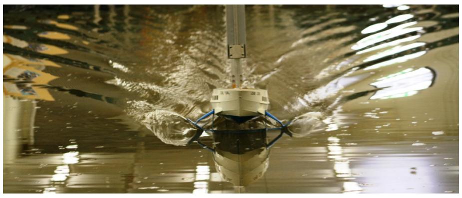
β = Drift angle
V = Velocity along x - axis in global coordinate system
u = velocity along x - axis in ship coordinate system
v = velocity along y - axis in ship coordinate system
$v = -V \sin \beta$

* Reference: MARIN, Stadt Towing Tank

Model Test
- Rotating Arm Test



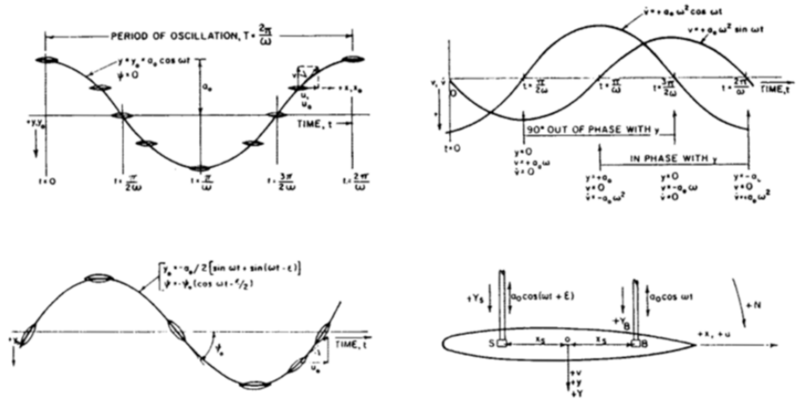


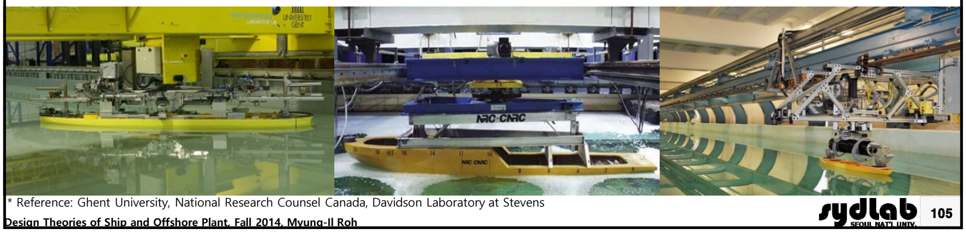


$\beta = 0$
$u = V$
$v = -V \sin \beta = 0$
R = Arm radius
r = angular yaw velocity $= \frac{u}{R} = \frac{d\psi}{dt}$
where, ψ = yaw oscillation

* Reference: Australian Maritime College

Model Test
- Planar Motion Mechanism (PMM) Test





* Reference: Ghent University, National Research Counsel Canada, Davidson Laboratory at Stevens

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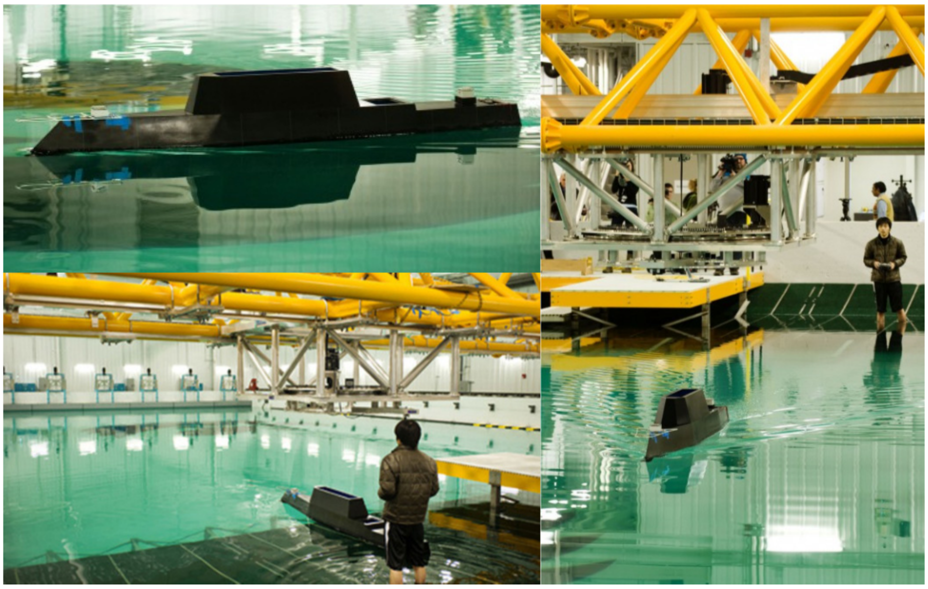
Model Test
- Free Running (Radio Controlled) Model Test



* Reference: University of Iowa

Full Scale Maneuvering Tests

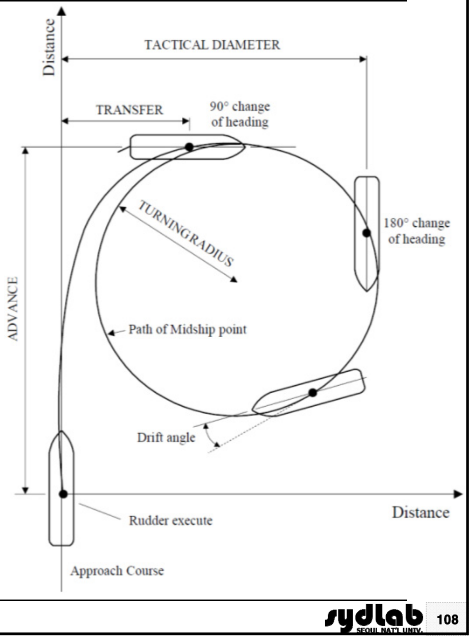
☑ **Standard Tests**
- **Turning circle test**
- **10/10 zig-zag test**
- **20/20 zig-zag test**
- **Crash stop test**

☑ **Non-standard Tests**
- **Pull out test**
- **Simplified spiral test**

Standard Maneuvering Tests - Turning Circle Test

☑ **Measure of the ability to turn the ship using hard over rudder to determine:**
- **Minimum advance at 90° change of heading**
- **Transfer**
- **Tactical diameter: Transfer at 180° change of heading**
- **Speed lost in turn**
- **Max roll angle**
- **Peak & final yaw rate**

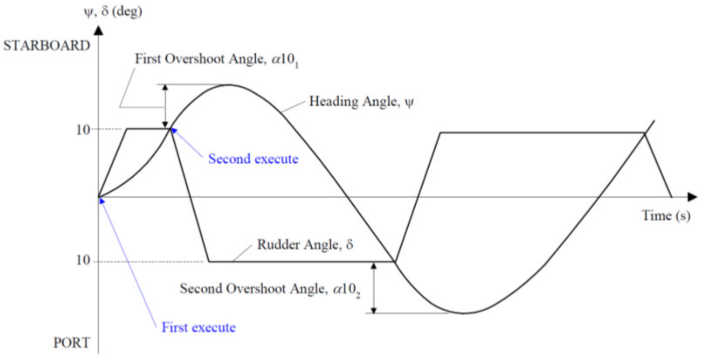
☑ **Performed to both starboard and port**



* Reference: ABS, Guide for Vessel Maneuverability, 2006

Standard Maneuvering Tests
- 10/10 & 20/20 Zig-Zag Tests

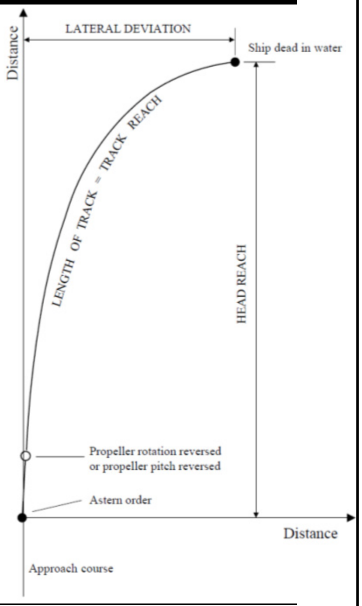
- ☑ **Initial turning**
  - ■ Change of heading response to a moderate helm, measured using: Distance traveled before course change, Time to 2nd execute
- ☑ **Course changing & yaw checking**
  - ■ Measure of the response to counter-rudder applied in a certain state of turning using heading overshoot using 1st and 2nd overshoot angles. Done at 10° & 20°
- ☑ **This test is to be done to both port and starboard.**



* Reference: ABS, Guide for Vessel Maneuverability, 2006

Standard Maneuvering Tests
- Stopping Ability Test

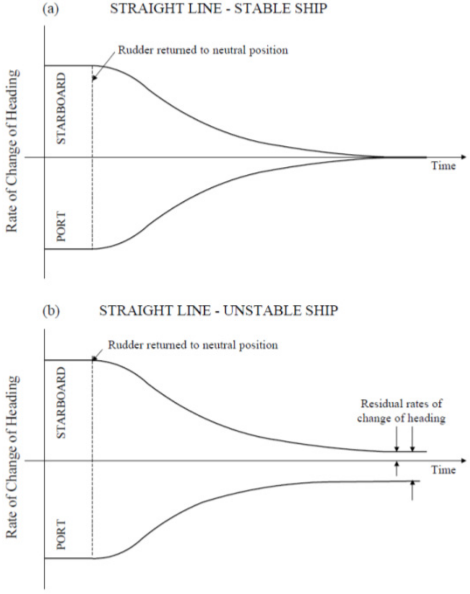
- ☑ **Engine stop and full astern maneuver performed after a steady approach at test speed to measure:**
  - ■ Track reach: Distance along the ship's track that the ship covers from the moment that the "full astern" command is given until ahead speed changes sign
  - ■ Head reach: Distance along the direction of the course at the moment when the "full astern" command was given. The distance is measured from the moment when the "full astern" command is given until the ship is stopped dead in the water.



* Reference: ABS, Guide for Vessel Maneuverability, 2006

Non-standard Maneuvering Tests
- Pull Out Test

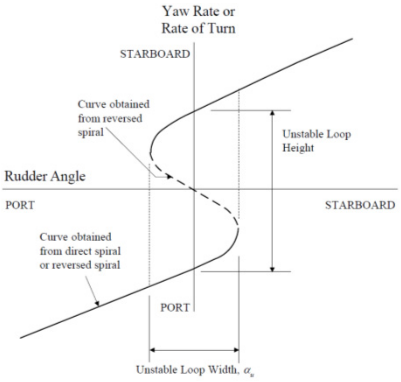
- ☑ **This test allows for the determination of whether a ship is dynamically stable and able to keep the course.**
  - ■ **After the completion of the turning circle test, the rudder is returned to neutral position, (zero for twin screw vessels, may not equal to zero for single screw vessels) and kept there until a steady turning rate is obtained.**
- ☑ **That is, residual turning rate after return to zero rudder used to assess if a ship is straight line stable or not.**



* Reference: ABS, Guide for Vessel Maneuverability, 2006

Non-standard Maneuvering Tests
- Simplified Spiral Test

- ☑ **If the ship is found to be straight-line unstable by the pull-out test, one of spiral tests may also be performed.**
  - ■ **Direct spiral maneuver (Dieudonné Spiral)**
    - ● **It is an orderly sequence of turning circle tests to obtain a steady turning rate versus rudder angle relation.**
    - ● **The maneuver requires a very long time and therefore is not recommended for sea trial.**
  - ■ **Reverse spiral (Bech Spiral) test**
    - ● **It may provide a more rapid procedure than the direct spiral test in developing the spiral curve and enables obtaining the dashed or unstable portion of the yaw rate versus rudder angle relationship.**
    - ● **In the reverse spiral test, the ship is steered to obtain a constant yaw rate, the mean rudder angle required to produce this yaw rate is measured and the yaw rate versus rudder angle plot is created.**
    - ● **Points on the curve of yaw rate versus rudder angle may be taken in any order.**

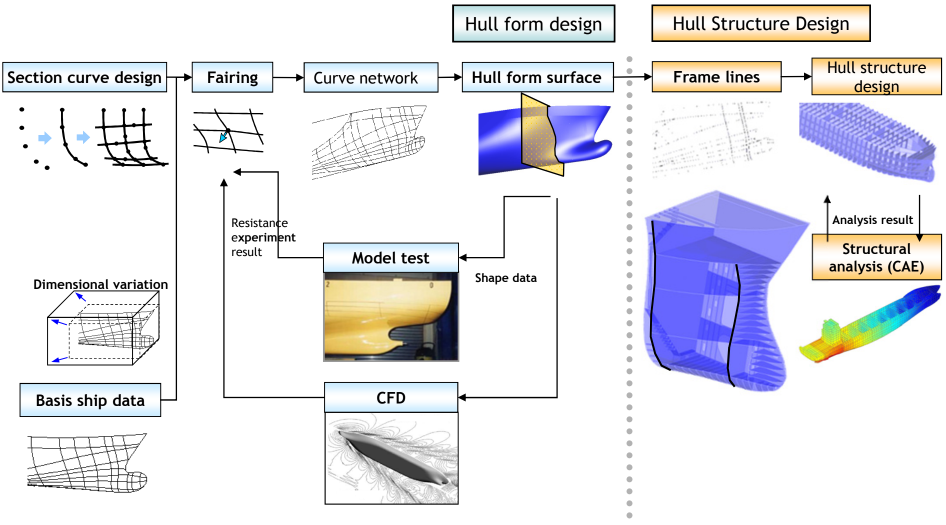


Relation between Rudder Angle and Yaw (Turn) Rate for Straight-line Unstable Ship

* Reference: ABS, Guide for Vessel Maneuverability, 2006

3.5 Generation of Hull Form Surface

Ship Shape ("Hull Form") Design



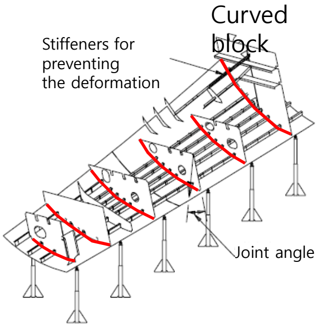
* CFD: Computational Fluid Dynamics, CAE: Computer-Aided Engineering

Needs of the Hull Surface Modeling

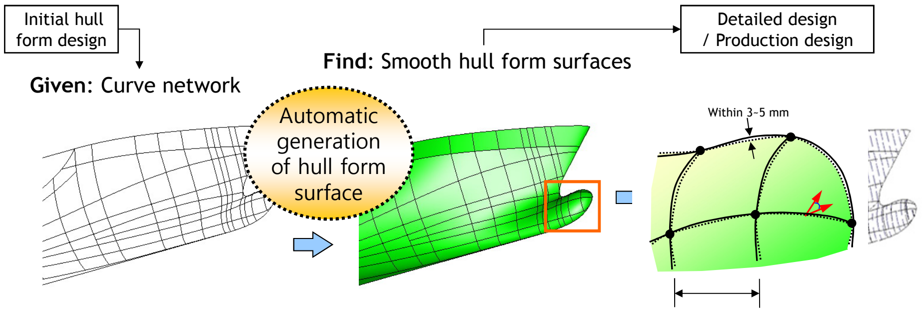
☑ **The important production information such as joint length (welding length), painting area, weight, and CG of the building blocks should be estimated at the initial design stage.**

☑ **For this, we need the hull surface modeling not hull curve modeling.**

☑ **Furthermore, the estimation of the cost and duration of the construction, the jig information for the fixed curved block can be estimated.**



Quality Requirement of a Hull Form Surface



Initial hull form design

Given: Curve network

Find: Smooth hull form surfaces

Detailed design / Production design

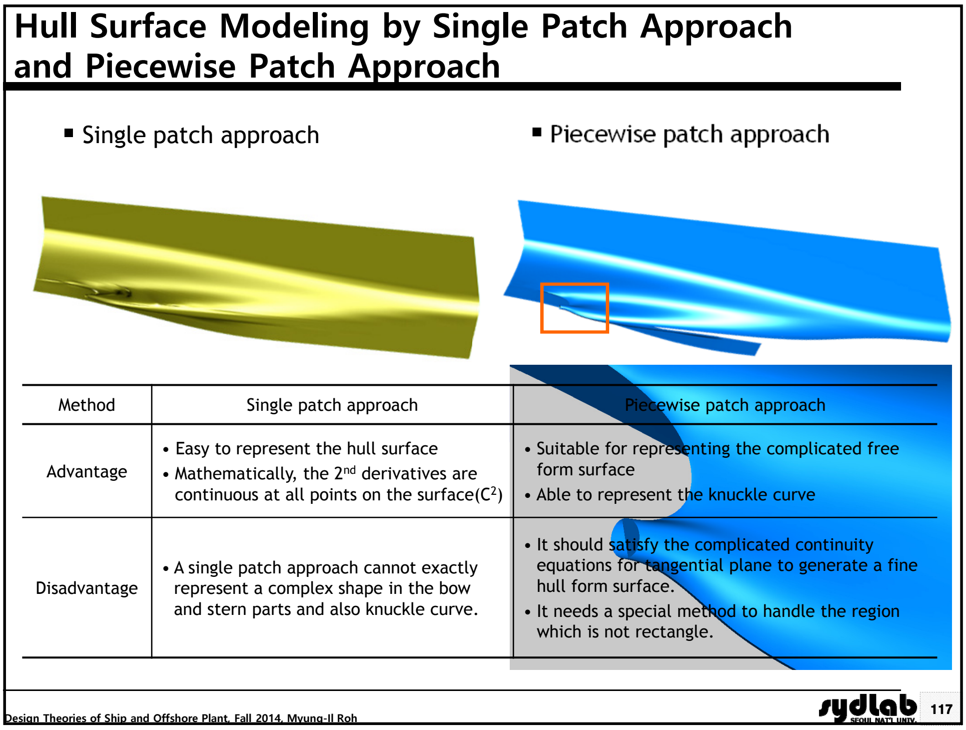
Automatic generation of hull form surface

- Irregular topology
- In the form of non-uniform B-spline curves

Requirements
- In the form of Bicubic B-spline surface patches
- Max. distance error between given curve network and generated surface < tolerance*
- Smoothness: exact or close to G^1**

- Intersection between surfaces and plane
- Validation of the fairness

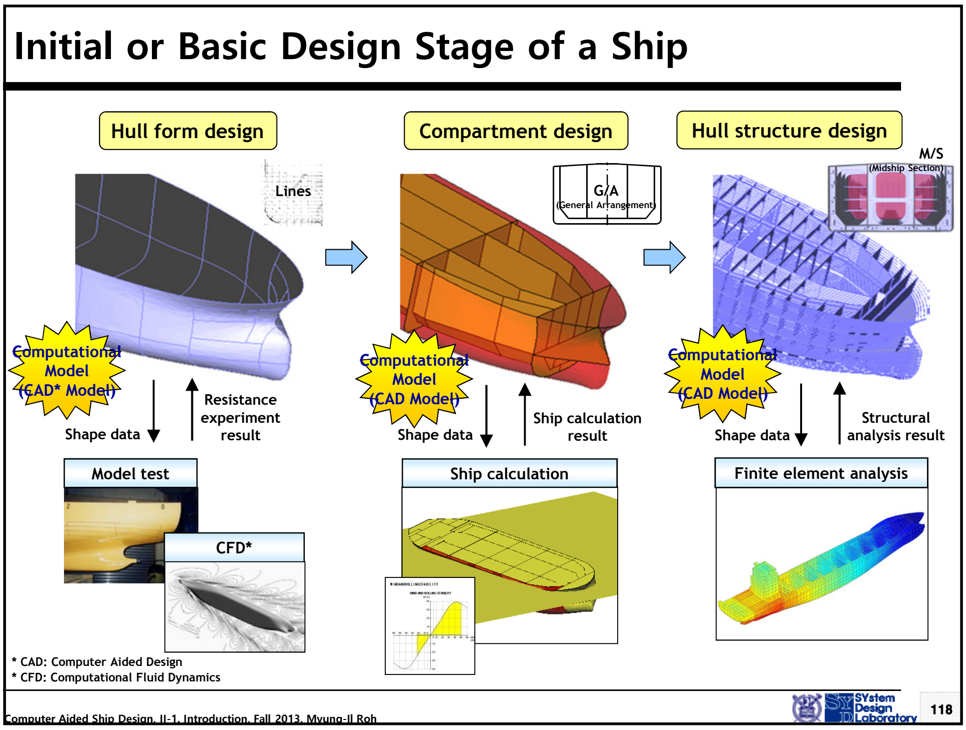
* Acceptable tolerance in shipbuilding industry is about 3~5 mm.
** G^1 means geometric continuity or tangential plane continuity. IntelliShip requires exact G^1 hull form surfaces.



Hull Surface Modeling by Single Patch Approach and Piecewise Patch Approach

- Single patch approach
- Piecewise patch approach

Method	Single patch approach	Piecewise patch approach
Advantage	• Easy to represent the hull surface • Mathematically, the 2nd derivatives are continuous at all points on the surface(C^2)	• Suitable for representing the complicated free form surface • Able to represent the knuckle curve
Disadvantage	• A single patch approach cannot exactly represent a complex shape in the bow and stern parts and also knuckle curve.	• It should satisfy the complicated continuity equations for tangential plane to generate a fine hull form surface. • It needs a special method to handle the region which is not rectangle.



Initial or Basic Design Stage of a Ship

Hull form design

Lines

Computational Model (CAD* Model)

Shape data

Resistance experiment result

Model test

CFD*

Compartment design

G/A (General Arrangement)

Computational Model (CAD Model)

Shape data

Ship calculation result

Ship calculation

Hull structure design

M/S (Midship Section)

Computational Model (CAD Model)

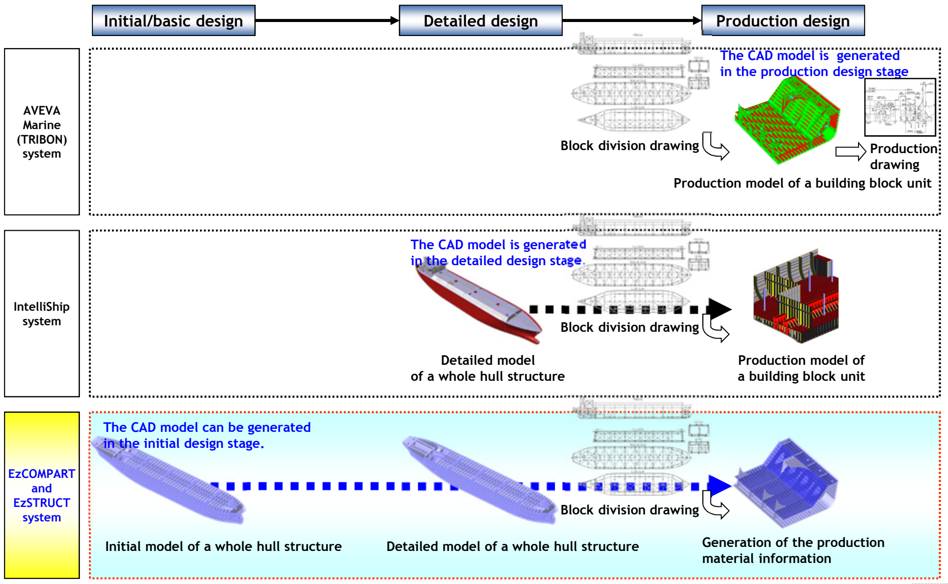
Shape data

Structural analysis result

Finite element analysis

* CAD: Computer Aided Design
* CFD: Computational Fluid Dynamics

Design Stages and CAD Systems for a Ship


Initial/basic design

Detailed design

Production design

AVEVA Marine (TRIBON) system

The CAD model is generated in the production design stage

Block division drawing

Production drawing

Production model of a building block unit

IntelliShip system

The CAD model is generated in the detailed design stage

Block division drawing

Detailed model of a whole hull structure

Production model of a building block unit

EzCOMPART and EzSTRUCT system

The CAD model can be generated in the initial design stage.

Block division drawing

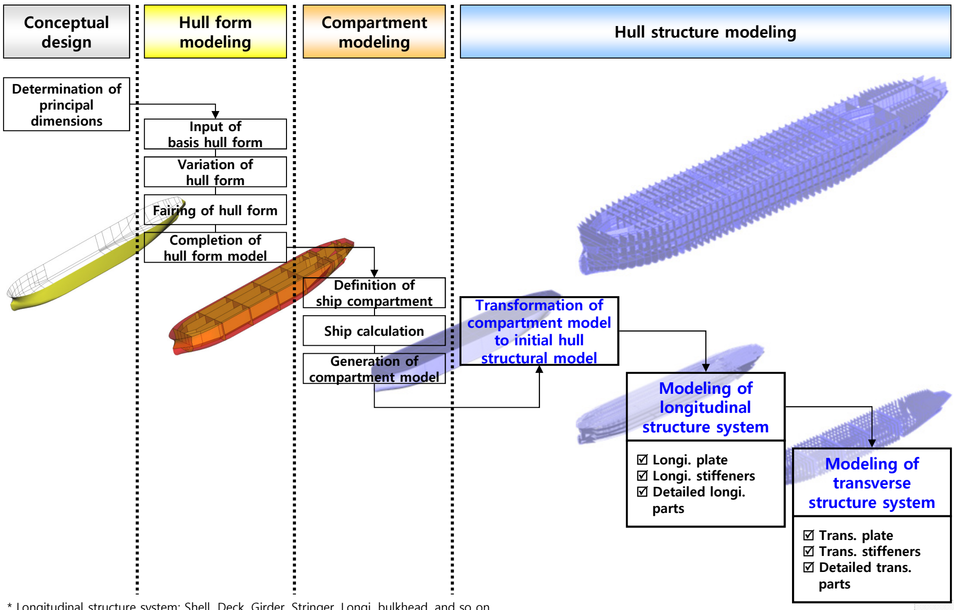
Initial model of a whole hull structure

Detailed model of a whole hull structure

Generation of the production material information

* TRIBON: CAD system (the exclusive use of shipbuilding), developed by Product of TRIBON Solution in Sweden
* IntelliShip: M-CAD systmem(the exclusive use of shipbuilding), co-developed by Intergraph, Samsung Heavy Industries, Odense shipyard in Denmark, and Hitachi Shipyard in Japan

Modeling Stages of the Initial or Basic Design


Conceptual design

Hull form modeling

Compartment modeling

Hull structure modeling

Determination of principal dimensions

Input of basis hull form

Variation of hull form

Fairing of hull form

Completion of hull form model

Definition of ship compartment

Ship calculation

Generation of compartment model

Transformation of compartment model to initial hull structural model

Modeling of longitudinal structure system

- ☑ Longi. plate
- ☑ Longi. stiffeners
- ☑ Detailed longi. parts

Modeling of transverse structure system

- ☑ Trans. plate
- ☑ Trans. stiffeners
- ☑ Detailed trans. parts

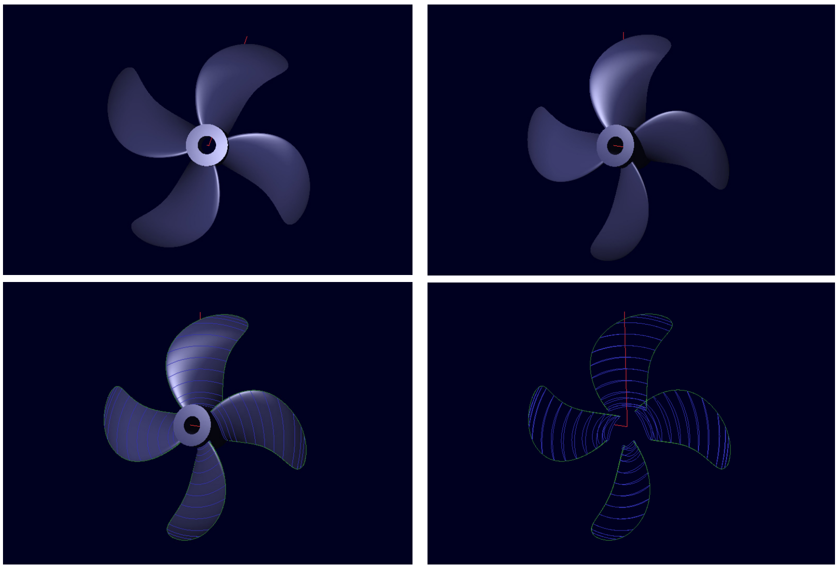
* Longitudinal structure system: Shell, Deck, Girder, Stringer, Longi. bulkhead, and so on
* Transverse structure system: Trans. bulkhead, Web frame, and so on

3.6 Appendage Design

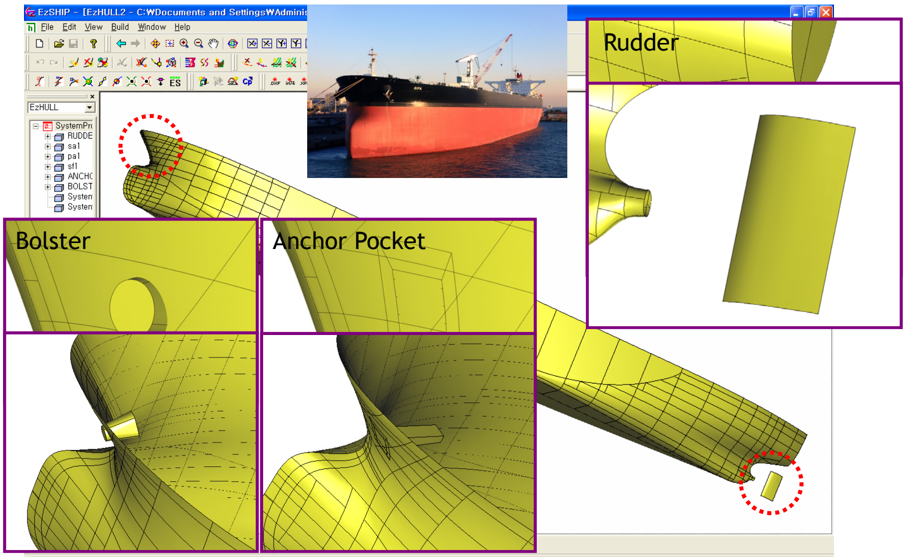
Appendage Design
- Example of a Propeller

- ☑ Ship: 4,900 TEU Container Ship
- ☑ Owner: NYK, Japan
- ☑ Shipyard: HHI (2007.7.20)
- ☑ Diameter: 8.3 m
- ☑ Weight: 83.3 ton
- ☑ No of Blades: 5

Appendage Design
- Propeller



Appendage Design
- Design of Bolster, Anchor Pocket, and Rudder



```
command>f
MSG: Fit done,
command>
```

```
Ready    - PW 1,0 [0, 0, 0, 0/SL:0, 0, 0, 0] 1,000 * X= 209,953880, Y= -32,281970, Z= 0,000000 Long,=0,0, Lat,=0,0  Ln 28, Col 9  Read
```

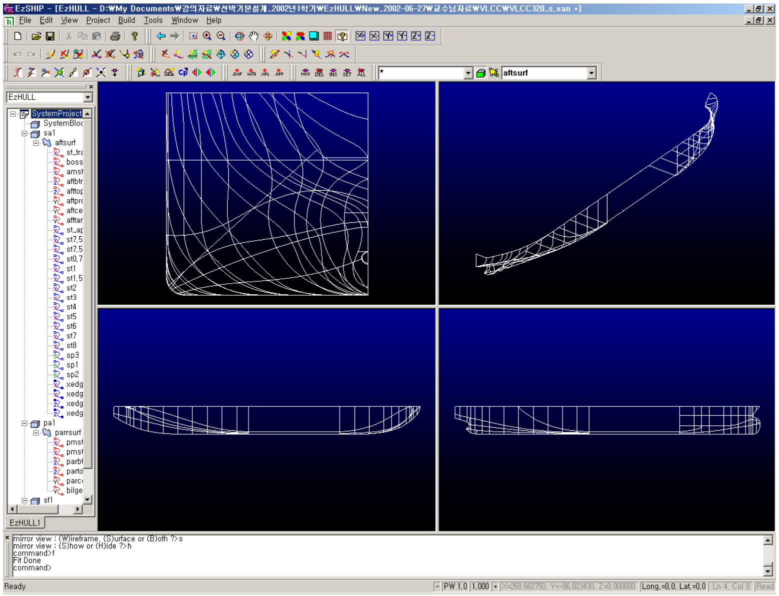
3.7 Examples of Hull Form Design

Hull Form Design of a 320K VLCC

Principal Particulars

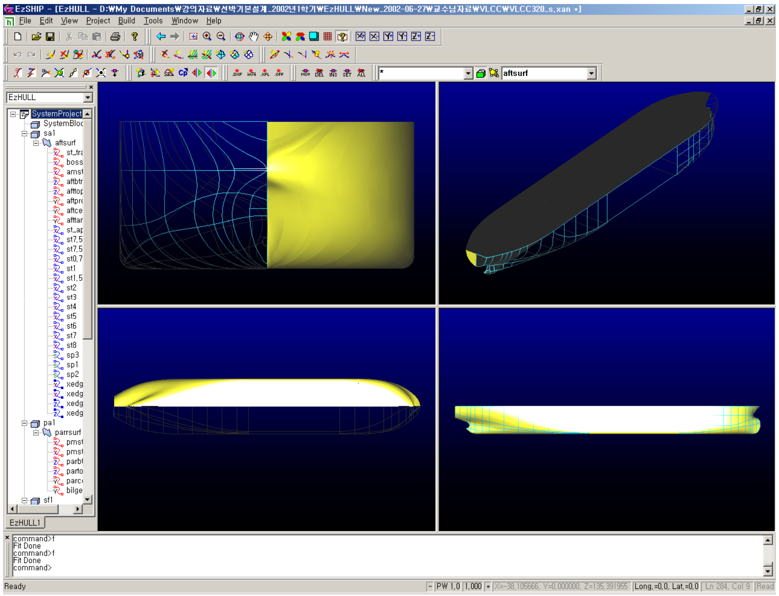
Item		Value	Remark
Principal Dimensions	LOA	332.0 m	
	LBP	320.0 m	
	B	60.0 m	
	D	30.5 m	
	Td / Ts	21.0 / 22.5 m	
Cargo Capacity		320,000 MT	at Ts
Speed		16 knots	at Td
Main Engine	Type	SULZER 7RTA84T-D	
	MCR	39,060 PS x 76.0 rpm	
	NCR	35,150 PS x 73.4 rpm	
Propeller Diameter		10.2 m	

Hull Form Design of a 320K VLCC
- Wireframe Model



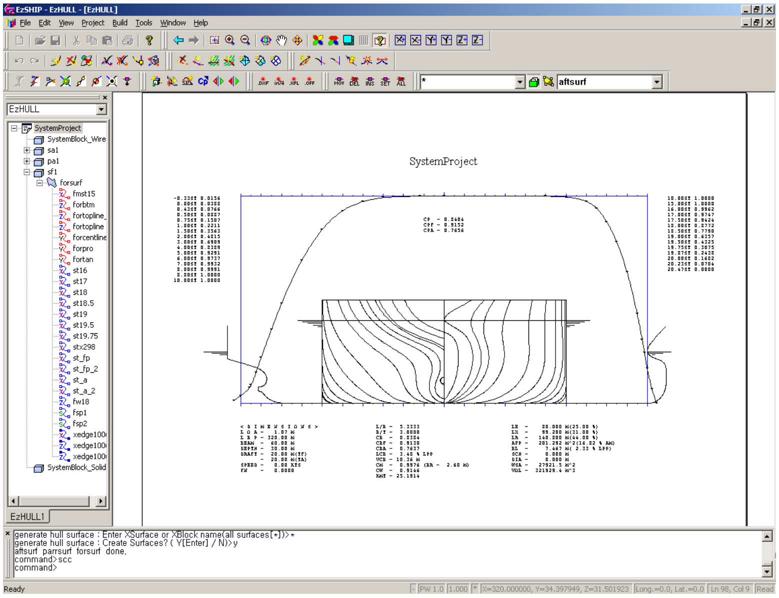
```
mirror view : (W)ireframe, (S)urface or (B)oth ?>s
mirror view : (S)how or (H)ide ?>h
command>f
Fit Done
command>
```

Hull Form Design of a 320K VLCC
- Surface Model



```
command>f
Fit Done
command>f
Fit Done
command>
```

Hull Form Design of a 320K VLCC
- C_P Curve



```
-0.33ST 0.0156
 0.00ST 0.0388
 0.43ST 0.0766
 0.50ST 0.0887
 0.75ST 0.1507
 1.00ST 0.2211
 1.50ST 0.3563
 2.00ST 0.4815
 3.00ST 0.6909
 4.00ST 0.8389
 5.00ST 0.9291
 6.00ST 0.9737
 7.00ST 0.9932
 8.00ST 0.9991
 8.80ST 1.0000
10.00ST 1.0000
```

```
CP  - 0.8404
CPF - 0.9152
CPA - 0.7656
```

```
10.00ST 1.0000
15.00ST 1.0000
16.00ST 0.9962
17.00ST 0.9747
17.50ST 0.9424
18.00ST 0.8772
18.50ST 0.7790
19.00ST 0.6357
19.50ST 0.4325
19.75ST 0.3075
19.87ST 0.2438
20.00ST 0.1682
20.23ST 0.0704
20.47ST 0.0000
```

```
< D I M E N S I O N S >            L/B -  5.3333                       LE   -    80.000 M(25.00 %)
L O A -   1.07 M                   B/T -  3.0000                       LX   -    99.200 M(31.00 %)
L B P - 320.00 M                   CB  -  0.8384                       LR   -   140.800 M(44.00 %)
BEAM  -  60.00 M                   CBF -  0.9130                       AFP  -   201.292 M^2(16.82 % AM)
DEPTH -  30.00 M                   CBA -  0.7637                       BL   -     7.467 M( 2.33 % LPP)
DRAFT -  20.00 M(TF)               LCB -  3.48 % LPP                   SCH  -     0.000 M
      -  20.00 M(TA)               VCB - 10.36 M                       DIA  -     0.000 M
SPEED -   0.00 KTS                 CM  -  0.9976 (BR -  2.60 M)        WSA  -   27921.5 M^2
FN    -   0.0000                   CW  -  0.9146                       VOL  -  321929.4 M^3
                                   KMT - 25.1914
```

```
generate hull surface : Enter XSurface or XBlock name(all surfaces[*])>*
generate hull surface : Create Surfaces? ( Y[Enter] / N)>y
aftsurf  parrsurf  forsurf  done.
command>scc
command>
```

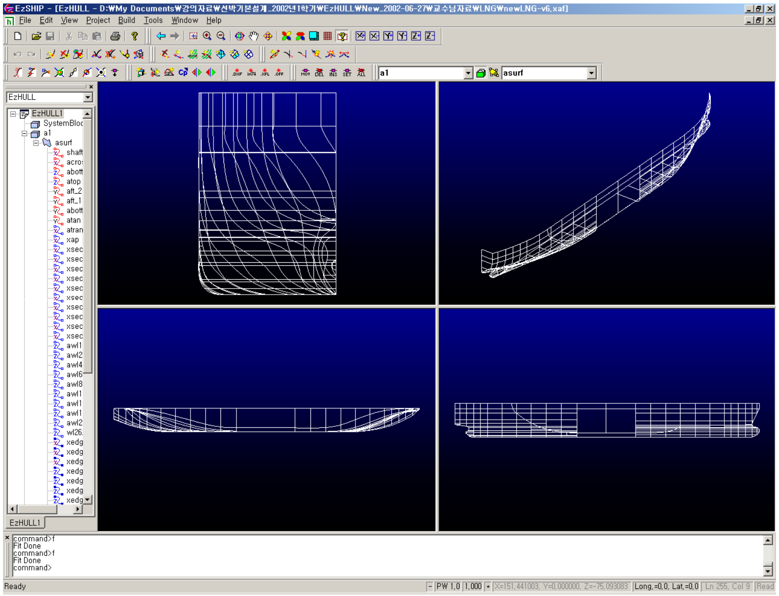
```
Ready    - | PW 1.0 | 1.000 | * | X=320.000000, Y=34.397949, Z=31.501923 | Long.=0.0, Lat.=0.0 | Ln 98, Col 9 | Read
```

Hull Form Design of a 145K CBM LNGC

Principal Particulars

Item		Value	Remark
Principal Dimensions	LOA	282.6 m	
	LBP	271.6 m	
	B	43.4 m	
	D	26.5 m	
	Td / Ts	11.3 / 12.0 m	
Cargo Capacity		145,216 CBM	at Td
Speed		20.2 knots	at Td
Main Engine	Type	Mitsubishi MS 40-2	
	MCR	38,709 PS x 83.0 rpm	
	NCR	34,838 PS x 80.0 rpm	
Propeller Diameter		8.28 m	

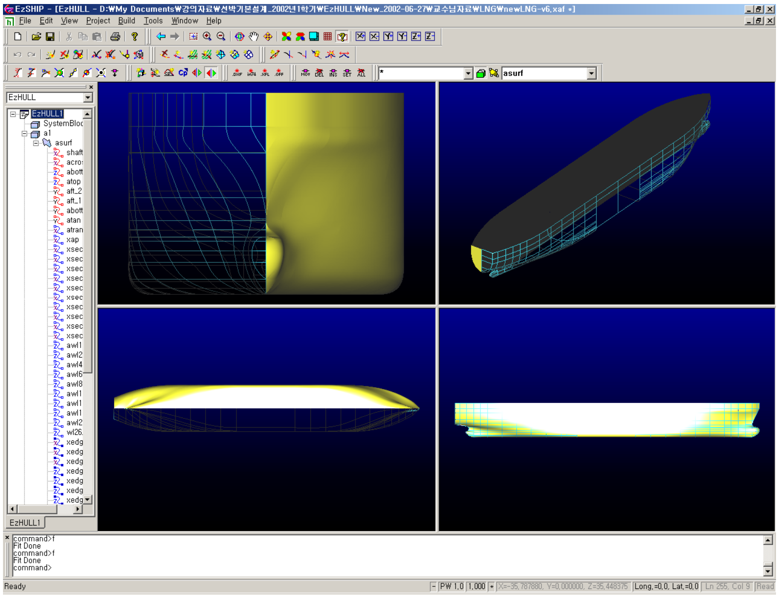
Hull Form Design of a 145K CMB LNGC
- Wireframe Model



EzSHIP - [EzHULL - D:₩My Documents₩강의자료₩선박기본설계_2002년1학기₩EzHULL₩New_2002-06-27₩교수님자료₩LNG₩newLNG-v6.xaf]

```
command>f
Fit Done
command>f
Fit Done
command>
```

Hull Form Design of a 145K CMB LNGC
- Surface Model



EzSHIP - [EzHULL - D:₩My Documents₩강의자료₩선박기본설계_2002년1학기₩EzHULL₩New_2002-06-27₩교수님자료₩LNG₩newLNG-v6.xaf *]

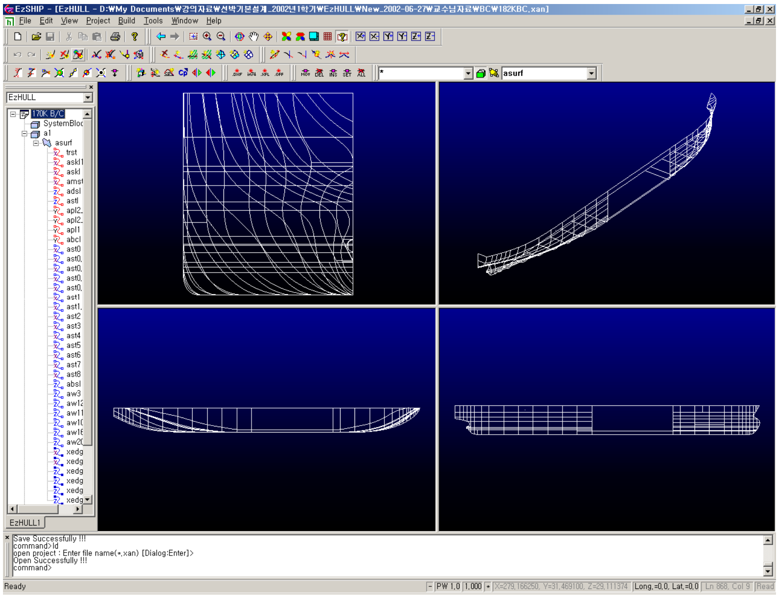
```
command>f
Fit Done
command>f
Fit Done
command>
```

Hull Form Design of a 182K Bulk Carrier

Principal Particulars

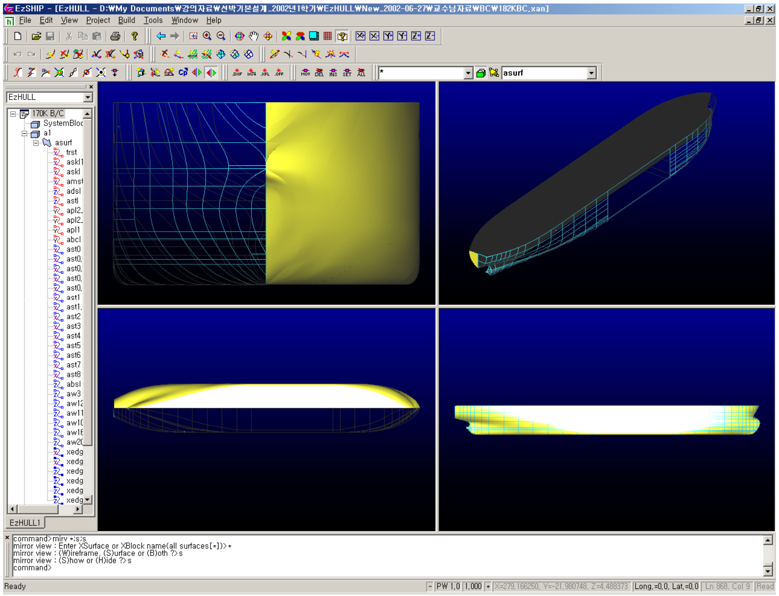
Item		Value	Remark
Principal Dimensions	LOA	292.85 m	
	LBP	282.7 m	
	B	46.7 m	
	D	25.8 m	
	Td / Ts	17.9 / 17.9 m	
Cargo Capacity		182,000 MT	at Td
Speed		14.5 knots	at Td
Main Engine	Type	B&W 7S60MC-C	
	MCR	17,940 BHP x 93.0 rpm	
	NCR	15,249 BHP x 84.5 rpm	
Propeller Diameter		7.91 m	

Hull Form Design of a 182K Bulk Carrier
- Wireframe Model


EzSHIP - [EzHULL - D:₩My Documents₩강의자료₩선박기본설계_2002년1학기₩EzHULL₩New_2002-06-27₩교수님자료₩BC₩182KBC.xan]

```
Save Successfully !!!
command>ld
open project : Enter file name(*.xan) [Dialog:Enter]>
Open Successfully !!!
command>
```

Hull Form Design of a 182K Bulk Carrier - Surface Model



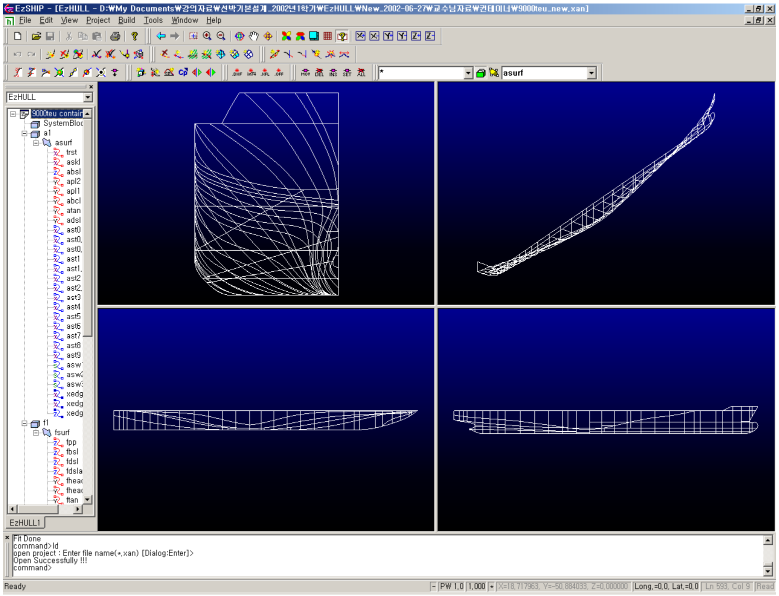
```
command>mirv *;s;s
mirror view : Enter XSurface or XBlock name(all surfaces[*])>*
mirror view : (W)ireframe, (S)urface or (B)oth ?>s
mirror view : (S)how or (H)ide ?>s
command>
```

Hull Form Design of a 9,000 TEU Container Ship

Principal Particulars

Item		Value	Remark
Principal Dimensions	LOA	356.18 m	
	LBP	341.18 m	
	B	45.3 m	
	D	27.0 m	
	Td / Ts	14.0 / 14.0 m	
Cargo Capacity		9,012 TEU	at Td
Speed		25.0 knots	at Td
Main Engine	Type	HSD B&W 12K98MC-C	
	MCR	91,491 PS x 94.0 rpm	
	NCR	77,767 PS x 89.0 rpm	
Propeller Diameter		9.70 m	

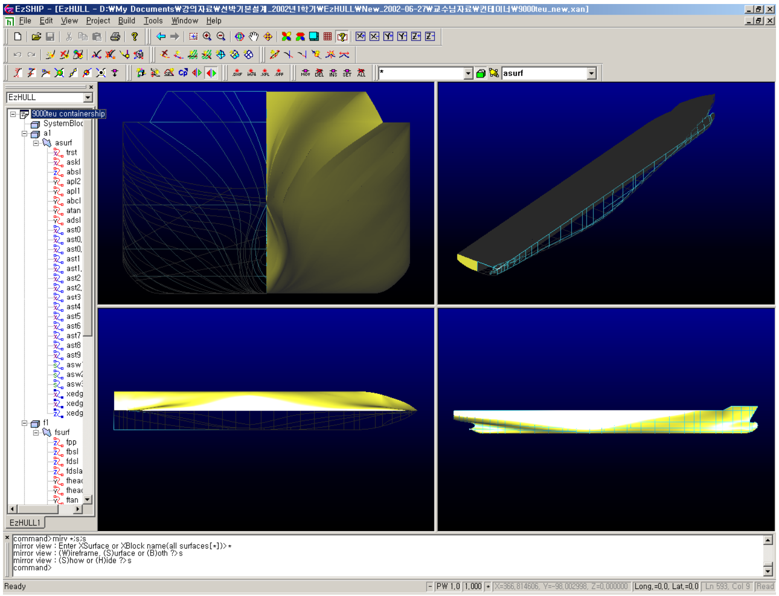
Hull Form Design of a 9,000 TEU Container Ship
- Wireframe Model



```
Fit Done
command>ld
open project : Enter file name(*.xan) [Dialog:Enter]>
Open Successfully !!!
command>
```

```
Ready    PW 1.0 | 1.000 | X=18.717963, Y=-50.884033, Z=0.000000 | Long.=0.0, Lat.=0.0 | Ln 593, Col 9 | Read
```

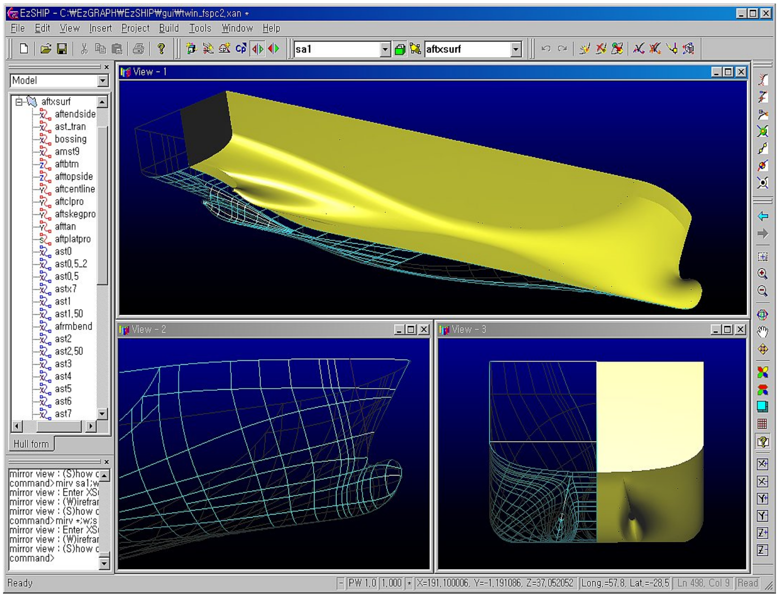
Hull Form Design of a 9,000 TEU Container Ship
- Surface Model



```
command>mirv *;s;s
mirror view : Enter XSurface or XBlock name(all surfaces[*])>*
mirror view : (W)ireframe, (S)urface or (B)oth ?>s
mirror view : (S)how or (H)ide ?>s
command>
```

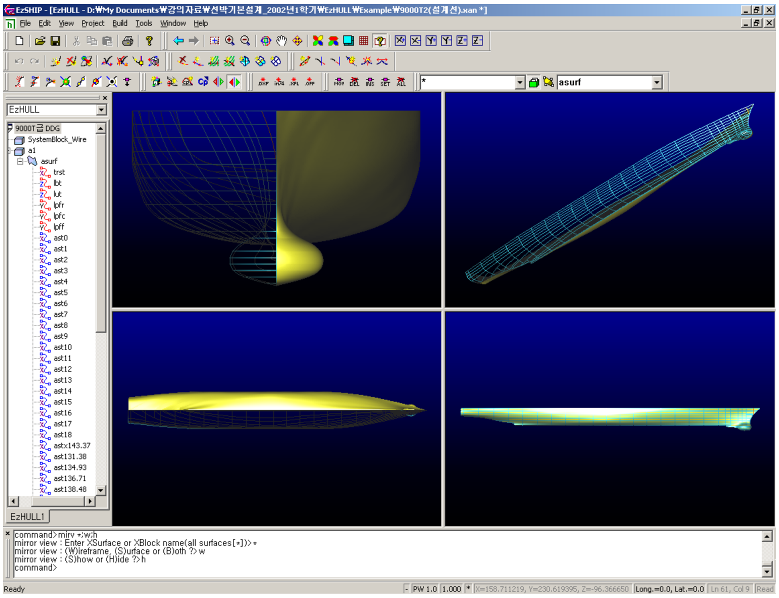
```
Ready    PW 1.0 | 1.000 | X=366.814606, Y=-98.002998, Z=0.000000 | Long.=0.0, Lat.=0.0 | Ln 593, Col 9 | Read
```

Hull Form Design of a Container Ship



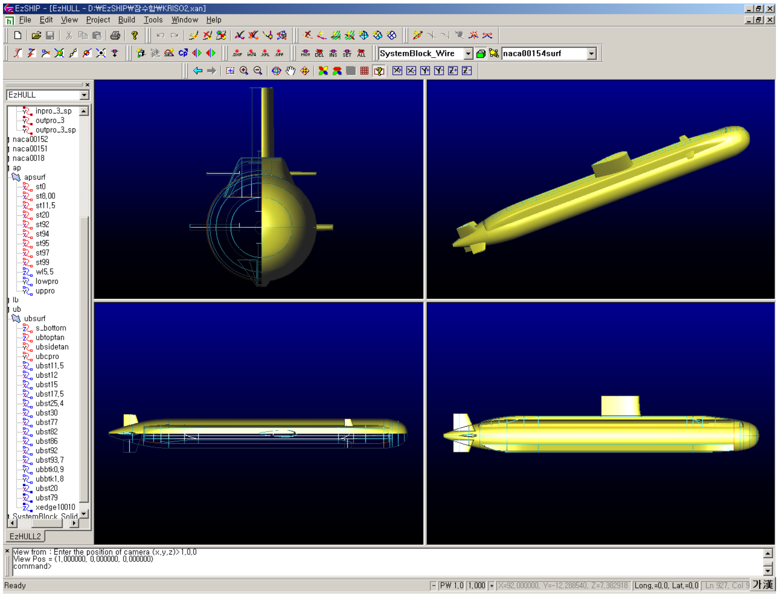
```
mirror view : (S)how c
command>mirv sa1;w
mirror view : Enter XS
mirror view : (W)irefrar
mirror view : (S)how c
command>mirv *;w;s
mirror view : Enter XS
mirror view : (W)irefrar
mirror view : (S)how c
command>
```

Hull Form Design of a Guided Missile Destroyer



```
command>mirv *;w;h
mirror view : Enter XSurface or XBlock name(all surfaces[*])>*
mirror view : (W)ireframe, (S)urface or (B)oth ?>w
mirror view : (S)how or (H)ide ?>h
command>
```

Hull Form Design of a Submarine



```
view from : Enter the position of camera (x,y,z)>1,0,0
View Pos = (1.000000, 0.000000, 0.000000)
command>
```

Hull Form Design of a 100,000 ton Nimitz Class Aircraft Carrier