

Lecture Note of Design Theories of Ship and Offshore Plant

# Design Theories of Ship and Offshore Plant

## Part I. Ship Design

### Ch. 3 Hull Form Design

Fall 2016

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## Ch. 3 Hull Form Design

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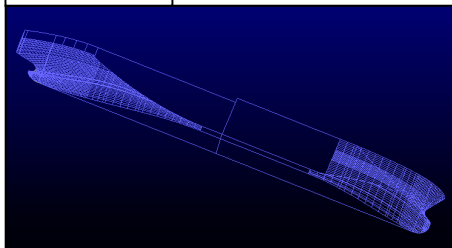
## 3.1 Generation of a Hull Form

## What is a "Hull form"?

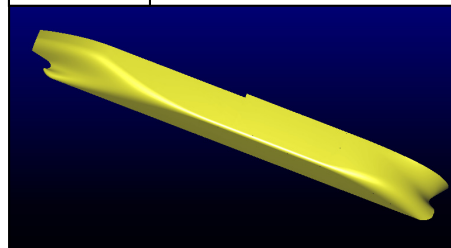
- ☑ **Hull form**
  - **Outer shape of the hull** that is streamlined in order to satisfy requirements of a ship owner such as a deadweight, ship speed, and so on
  - Like a skin of human
- ☑ **Hull form design**
  - Design task that designs the hull form

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

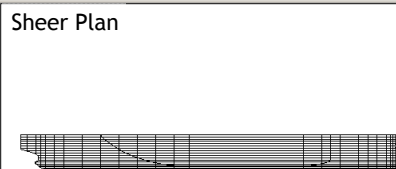
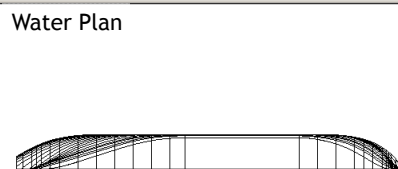
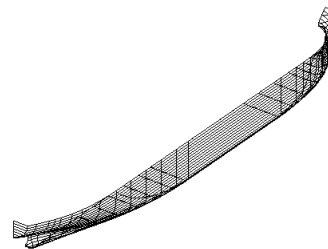
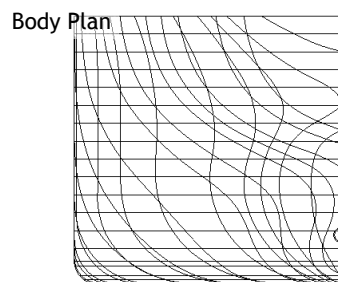
Wireframe model



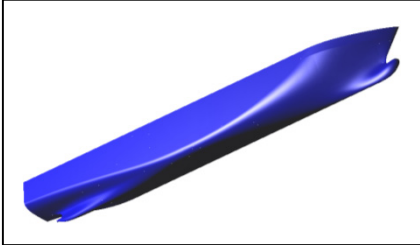
Surface model



## Lines




## 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

- An 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.**

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## Procedure of Car Exterior Design


Idea Sketch & Rendering


→


Tape Drawing

→

Clay Modeling






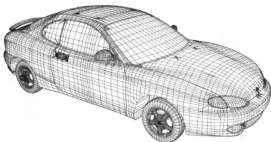



Digital Modeling (Reverse Engineering)

←

Measuring







Hull Form Design

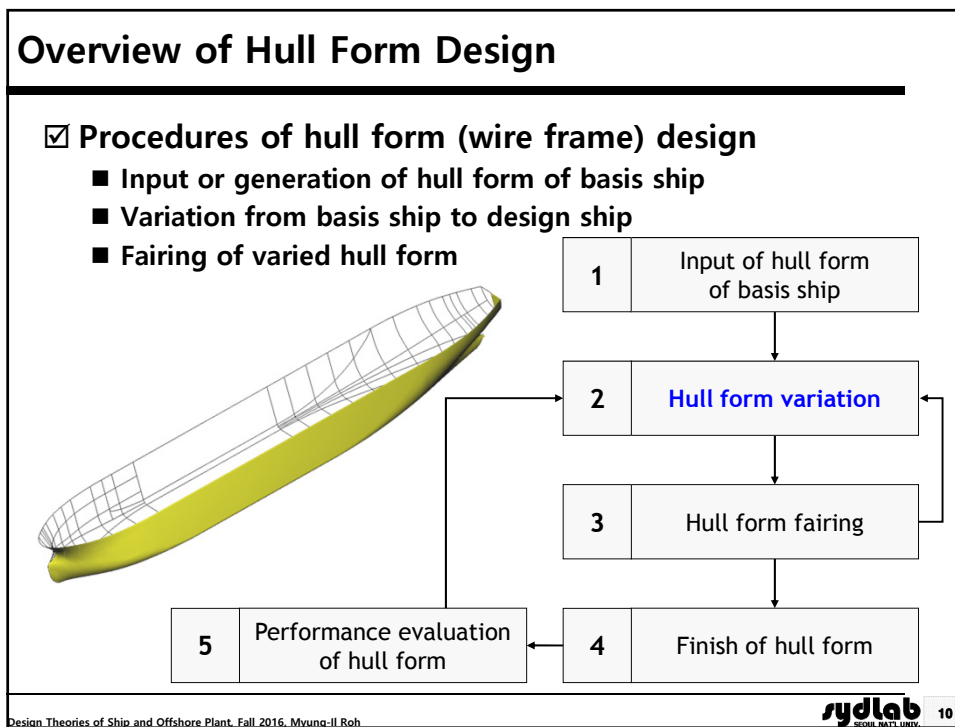
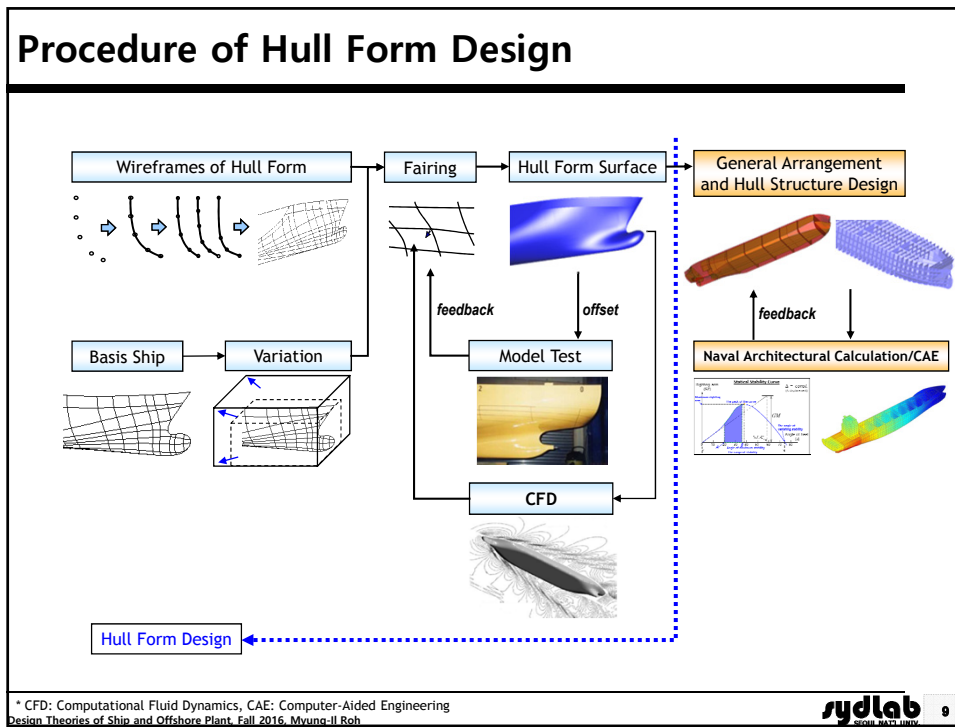
Stylist

↑

↓

Engineer

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## Coordinates for Hull Form Representation

Fore body

“Right-hand Coordinates”

Coordinates for Hull Form

Aft body

y-z plane

x-y plane

x-z plane

\* Some systems use “Left-hand Coordinates” are used.

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## 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

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### 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

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

Profile line on center plane ( $y = 0$  plane)

Skeg profile line on skeg

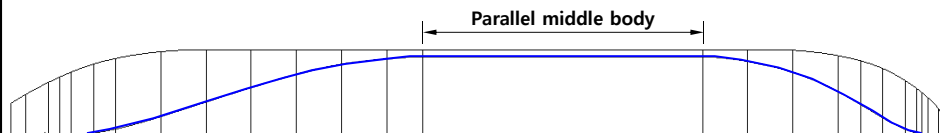
Example of profile line of a twin-skeg container ship

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## Primary Curves for Hull Form Representation - Bottom Tangent Line

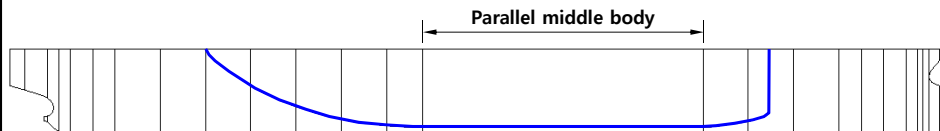
- ☑ Bottom tangent line is an intersection (or tangent) curve between hull form surface and base plane ( $z = 0$  plane)



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.

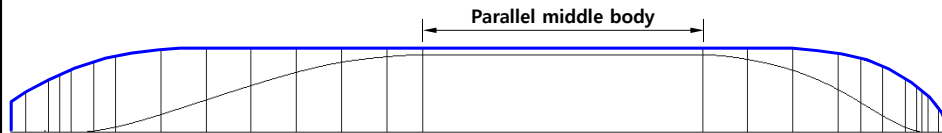


Example of side tangent line of a 320K VLCC



## Primary Curves for Hull Form Representation - Deck Side Line

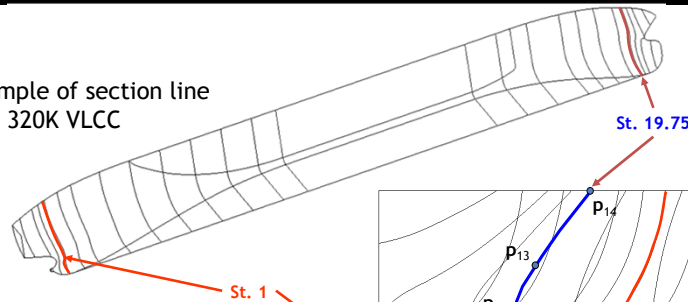
- ☑ Deck side line is a curve representing the side of upper deck
- ☑ Both ends of the curve contact with profile line.



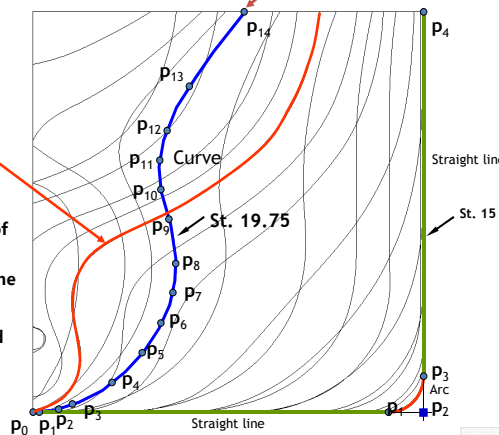
Example of deck side line of a 320K VLCC

## Secondary Curves for Hull Form Representation - Section Line

Example of section line of a 320K VLCC

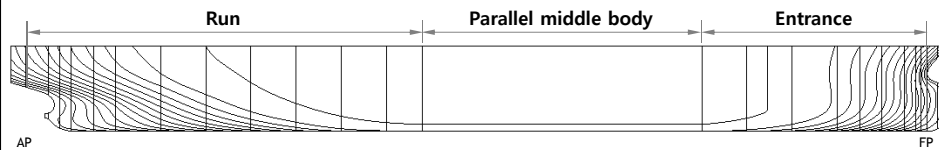


- ☑ Section line is a curve located on a cross (longitudinal) section (y-z plane).
- ☑ Stations are ship hull cross section at a spacing of  $L_{BP}/20$ , station '0' is located at the aft perpendicular, station '20' at the forward perpendicular. Station '10' therefore represents the midship section.
- ☑ 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

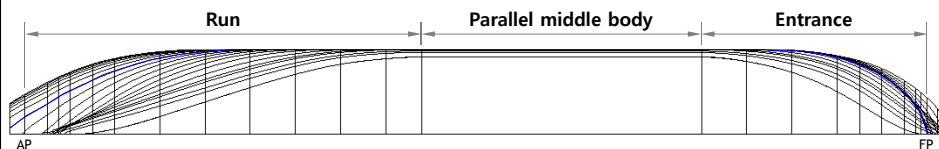
- ☑ Buttock line is a curve located on a profile (lateral) section (x-z plane).
- ☑ Buttock lines make up the **sheer plan** or **buttock plan** of lines.



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.

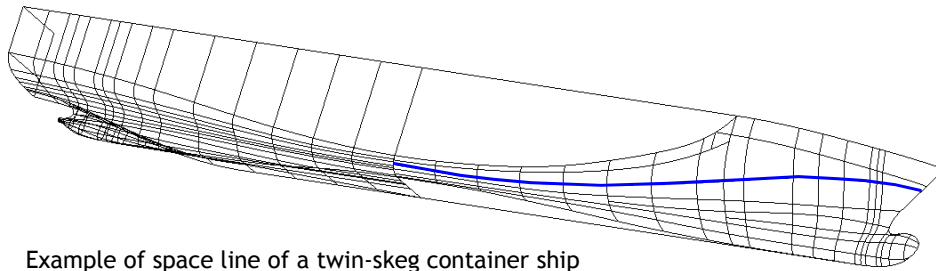


Example of water line of a 320K VLCC

— DLWL (Design Load Water Line)  
↑ Design Draft

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

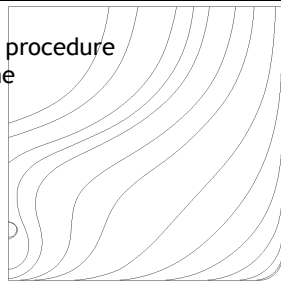
- ☑ Space line is a curve located on a 3D space, as compared with plane curve such as section line, buttock line, water line, etc.
- ☑ For the complicated hull form, space lines are additionally required with plane curves for defining the hull form.



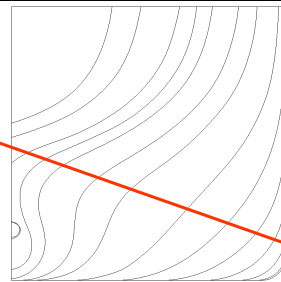
Example of space line of a twin-skeg container ship

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

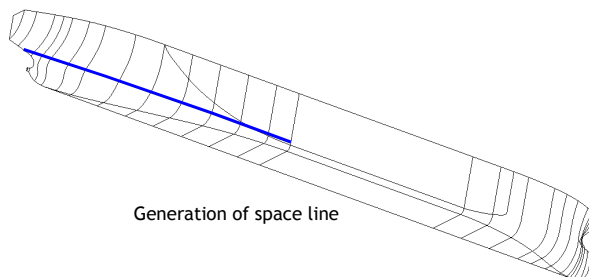
Generation procedure  
of space line



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

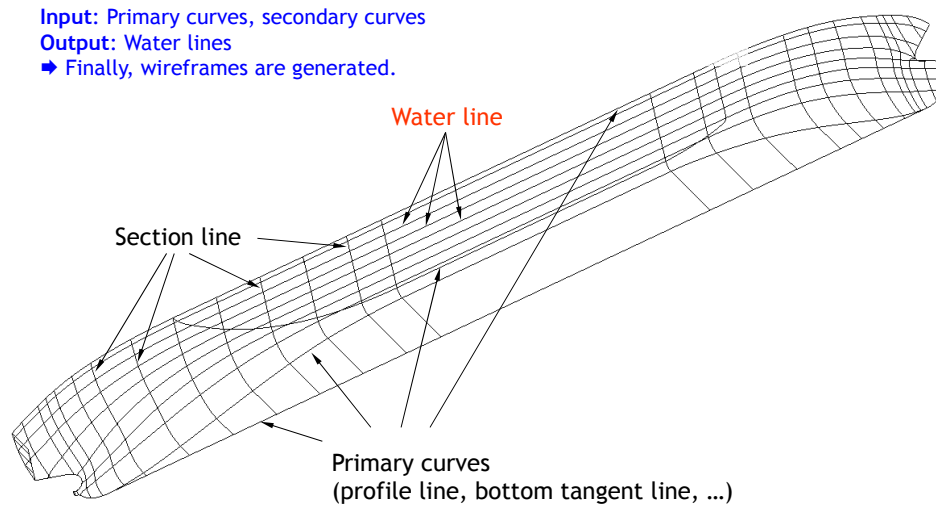
## Wireframes Generation

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)

St. 19.75 St. 19 St. 15

→ Generate a water line by intersection calculation between 'z = a' plane and all primary curves and section lines.

Z = a

Intersection points for generating the water line at 'z = a'

Z

Y

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### 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

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### Generation of Buttock Lines (1/2)

St. 19.75 St. 19 St. 15

→ 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'

Z

Y

y = b

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### 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

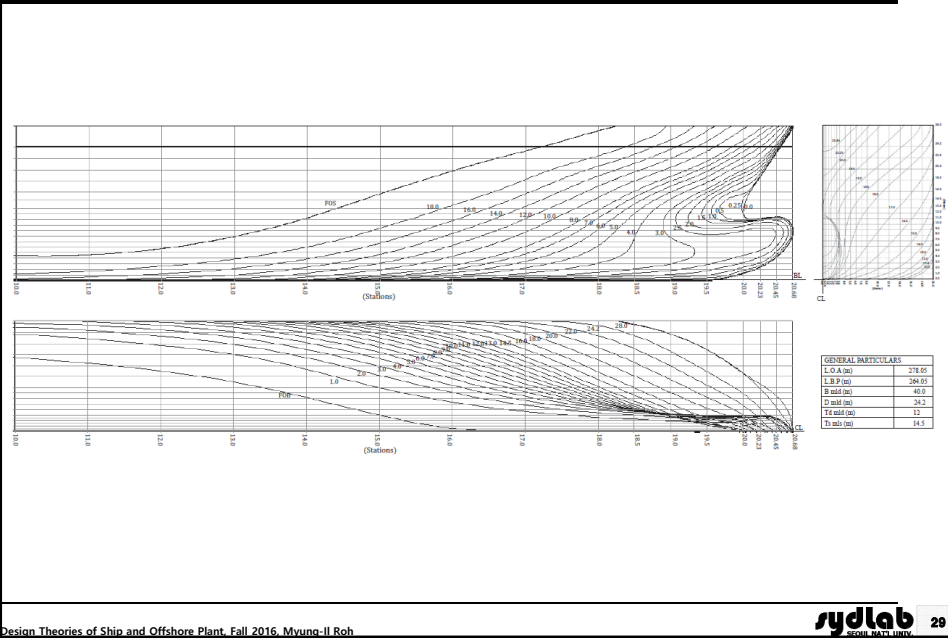
↓ Repeat this for the y position what we want.

Generation of buttock lines

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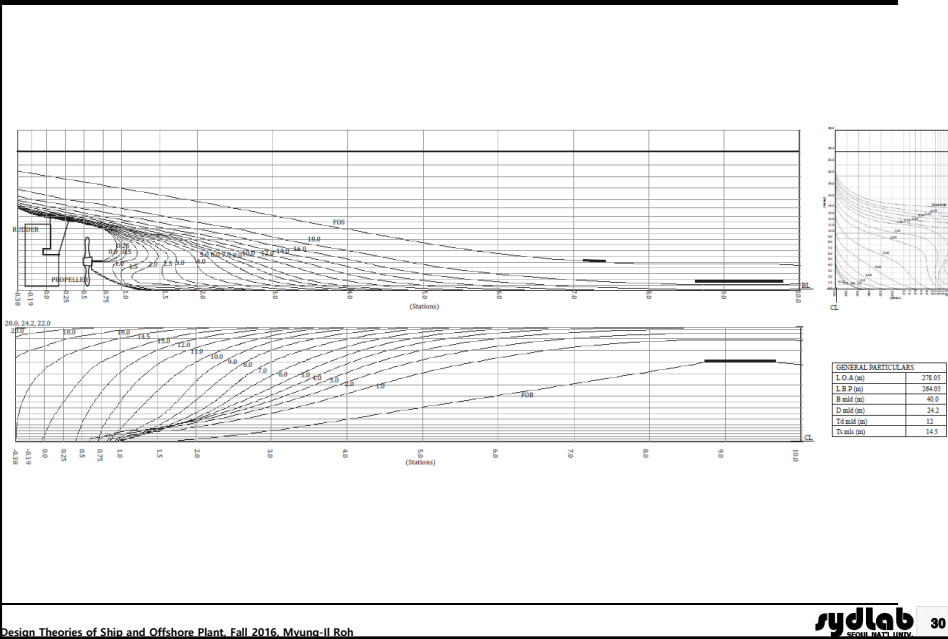
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### Example of Lines of a 6,300TEU Container Ship - Fore Body



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



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

Waterline

→

\* Unit: mm

| Station NO.  | BOTT. CM LINE | HALF BREADTH FROM CENTER LINE |        |        |        |        |        |        |        |        |         |         |         |         |           |         |         |         |         |           |              | Station NO. |
|--------------|---------------|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|-----------|---------|---------|---------|---------|-----------|--------------|-------------|
|              |               | 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 (-0.8) | Half-Breadth  | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | Trans (-0.8) |             |
| -0.19        | AP            | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | AP           |             |
| 0.25         |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         |              |             |
| 0.5          |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         |              |             |
| 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    | 9036    | 13623   | 16033   | 17687     | 19196   | 19906   | 20000   | *       | *         | 1.5          |             |
| 2            |               | 54                            | 2677   | 3365   | 3734   | 3932   | 4029   | 4250   | 5085   | 7269   | 10680   | 13943   | 16441   | 17866   | 18937     | 19811   | 20000   | *       | *       | *         | 2            |             |
| 3            |               | 3025                          | 5958   | 6294   | 7238   | 8182   | 9483   | 11588  | 14600  | 16600  | 17469   | 18517   | 19244   | 19754   | 19990     | 20000   | *       | *       | *       | *         | 3            |             |
| 4            |               | 3974                          | 8451   | 10473  | 12071  | 13627  | 15218  | 16635  | 17938  | 18937  | 19594   | 19941   | 20000   | 20000   | 20000     | *       | *       | *       | *       | *         | 4            |             |
| 5            |               | 4691                          | 12054  | 14349  | 16032  | 17344  | 18359  | 19152  | 19729  | 19996  | 20000   | 20000   | *       | *       | *         | *       | *       | *       | *       | *         | 5            |             |
| 6            |               | 5152                          | 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            |               | 13000                         | 17562  | 18720  | 19408  | 19815  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 9            |             |
| 10           |               | 13517                         | 17469  | 18718  | 19466  | 19926  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 10           |             |
| 11           |               | 12406                         | 16799  | 18906  | 19205  | 19873  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 11           |             |
| 12           |               | 11001                         | 15632  | 17338  | 18464  | 19316  | 19887  | 20000  | 20000  | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 12           |             |
| 13           |               | 9018                          | 14020  | 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   | 7105   | 8420   | 9598   | 10677  | 11684  | 12651  | 13581  | 14471   | 15328   | 16159   | 16935   | 17624     | 18272   | 18877   | 20000   | 20000   | *         | 16           |             |
| 17           |               | 124                           | 3602   | 4865   | 5656   | 6434   | 7181   | 7919   | 8674   | 9438   | 10248   | 11052   | 11859   | 12734   | 13663     | 15032   | 16321   | 17837   | 19014   | 19797     | 17           |             |
| 18           |               | 100                           | 2577   | 3442   | 3967   | 4541   | 4643   | 4952   | 5224   | 5554   | 5931    | 6346    | 6845    | 7479    | 8235      | 9516    | 10921   | 13033   | 15277   | 17449     | 18           |             |
| 18.5         |               | 110                           | 2286   | 2979   | 3414   | 3673   | 3815   | 3895   | 3951   | 4012   | 4115    | 4200    | 4603    | 4959    | 5438      | 6511    | 7872    | 10069   | 12543   | 15057     | 18.5         |             |
| 19           |               | 112                           | 1982   | 2596   | 2988   | 3195   | 3258   | 3215   | 3104   | 2954   | 2804    | 2723    | 2710    | 2780    | 3087      | 3833    | 4987    | 7036    | 9433    | 11867     | 19           |             |
| 19.5         |               | -                             | 1558   | 2160   | 2540   | 2778   | 2891   | 2894   | 2784   | 2660   | 2521    | 1760    | 1385    | 1247    | 1279      | 1685    | 2332    | 4262    | 6237    | 8128      | 19.5         |             |
| 19           |               | -                             | -      | 1195   | 1825   | 2310   | 2652   | 2859   | 2901   | 2788   | 2497    | 2060    | 1301    | -       | 29        | 148     | 603     | 1551    | 2981    | 4700      | 19           |             |
| 20.23        |               | -                             | -      | -      | 1353   | 2045   | 2481   | 2753   | 2893   | 2880   | 2686    | 2125    | 997     | -       | -         | -       | 1590    | 3135    | 5044    | -         | 20.23        |             |
| 20.45        |               | -                             | -      | -      | -      | -      | 1300   | 1910   | 2258   | 2420   | 2400    | 2110    | 1320    | -       | -         | -       | -       | -       | 2344    | -         | 20.45        |             |
| 20.68        |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | 20.68        |             |

Stations

↓

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### Relationship Between Lines and Offsets Table (1/2)

Generation of offsets table from the lines

Offsets table

| Station NO.  | BOTT. CM LINE | HALF BREADTH FROM CENTER LINE |        |        |        |        |        |        |        |        |         |         |         |         |           |         |         |         |         |           |              | Station NO. |
|--------------|---------------|-------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|-----------|---------|---------|---------|---------|-----------|--------------|-------------|
|              |               | 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 (-0.8) | Half-Breadth  | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | Trans (-0.8) |             |
| -0.19        | AP            | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | AP           |             |
| 0.25         |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         |              |             |
| 0.5          |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         |              |             |
| 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    | 9036    | 13623   | 16033   | 17687     | 19196   | 19906   | 20000   | *       | *         | 1.5          |             |
| 2            |               | 54                            | 2677   | 3365   | 3734   | 3932   | 4029   | 4250   | 5085   | 7269   | 10680   | 13943   | 16441   | 17866   | 18937     | 19811   | 20000   | *       | *       | *         | 2            |             |
| 3            |               | 3025                          | 5958   | 6294   | 7238   | 8182   | 9483   | 11588  | 14600  | 16600  | 17469   | 18517   | 19244   | 19754   | 19990     | 20000   | *       | *       | *       | *         | 3            |             |
| 4            |               | 3974                          | 8451   | 10473  | 12071  | 13627  | 15218  | 16635  | 17938  | 18937  | 19594   | 19941   | 20000   | 20000   | 20000     | *       | *       | *       | *       | *         | 4            |             |
| 5            |               | 4691                          | 12054  | 14349  | 16032  | 17344  | 18359  | 19152  | 19729  | 19996  | 20000   | 20000   | *       | *       | *         | *       | *       | *       | *       | *         | 5            |             |
| 6            |               | 5152                          | 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            |               | 13000                         | 17562  | 18720  | 19408  | 19815  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 9            |             |
| 10           |               | 13517                         | 17469  | 18718  | 19466  | 19926  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 10           |             |
| 11           |               | 12406                         | 16799  | 18906  | 19205  | 19873  | 20000  | *      | *      | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 11           |             |
| 12           |               | 11001                         | 15632  | 17338  | 18464  | 19316  | 19887  | 20000  | 20000  | *      | *       | *       | *       | *       | *         | *       | *       | *       | *       | *         | 12           |             |
| 13           |               | 9018                          | 14020  | 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   | 7105   | 8420   | 9598   | 10677  | 11684  | 12651  | 13581  | 14471   | 15328   | 16159   | 16935   | 17624     | 18272   | 18877   | 20000   | 20000   | *         | 16           |             |
| 17           |               | 124                           | 3602   | 4865   | 5656   | 6434   | 7181   | 7919   | 8674   | 9438   | 10248   | 11052   | 11859   | 12734   | 13663     | 15032   | 16321   | 17837   | 19014   | 19797     | 17           |             |
| 18           |               | 100                           | 2577   | 3442   | 3967   | 4541   | 4643   | 4952   | 5224   | 5554   | 5931    | 6346    | 6845    | 7479    | 8235      | 9516    | 10921   | 13033   | 15277   | 17449     | 18           |             |
| 18.5         |               | 110                           | 2286   | 2979   | 3414   | 3673   | 3815   | 3895   | 3951   | 4012   | 4115    | 4200    | 4603    | 4959    | 5438      | 6511    | 7872    | 10069   | 12543   | 15057     | 18.5         |             |
| 19           |               | 112                           | 1982   | 2596   | 2988   | 3195   | 3258   | 3215   | 3104   | 2954   | 2804    | 2723    | 2710    | 2780    | 3087      | 3833    | 4987    | 7036    | 9433    | 11867     | 19           |             |
| 19.5         |               | -                             | 1558   | 2160   | 2540   | 2778   | 2891   | 2894   | 2784   | 2660   | 2521    | 1760    | 1385    | 1247    | 1279      | 1685    | 2332    | 4262    | 6237    | 8128      | 19.5         |             |
| 19           |               | -                             | -      | 1195   | 1825   | 2310   | 2652   | 2859   | 2901   | 2788   | 2497    | 2060    | 1301    | -       | 29        | 148     | 603     | 1551    | 2981    | 4700      | 19           |             |
| 20.23        |               | -                             | -      | -      | 1353   | 2045   | 2481   | 2753   | 2893   | 2880   | 2686    | 2125    | 997     | -       | -         | -       | 1590    | 3135    | 5044    | -         | 20.23        |             |
| 20.45        |               | -                             | -      | -      | -      | -      | 1300   | 1910   | 2258   | 2420   | 2400    | 2110    | 1320    | -       | -         | -       | -       | -       | 2344    | -         | 20.45        |             |
| 20.68        |               | -                             | -      | -      | -      | -      | -      | -      | -      | -      | -       | -       | -       | -       | -         | -       | -       | -       | -       | -         | 20.68        |             |

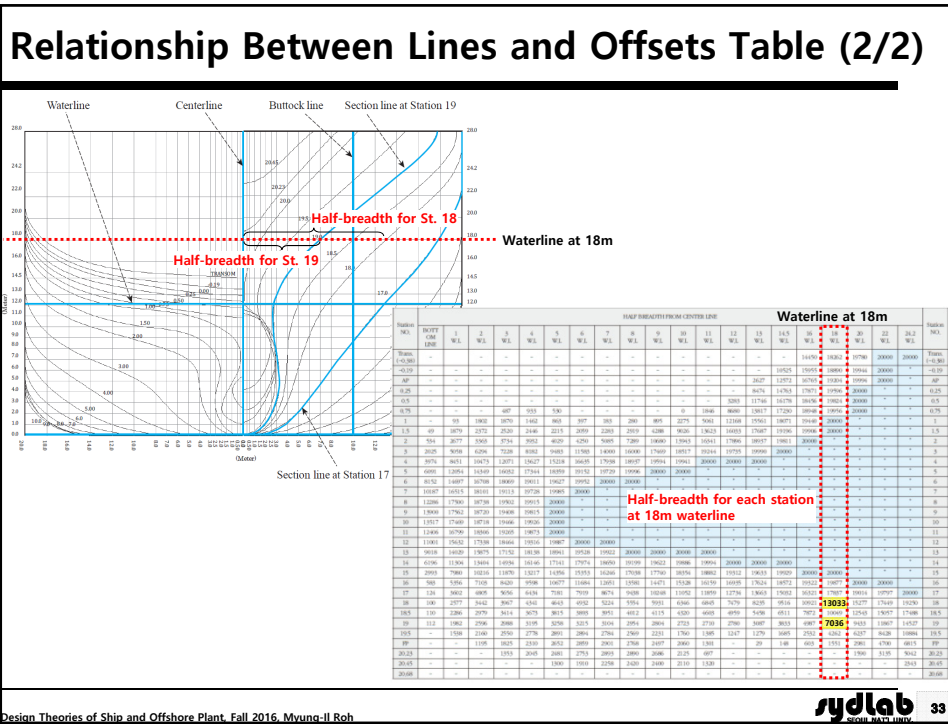
Stations

↓

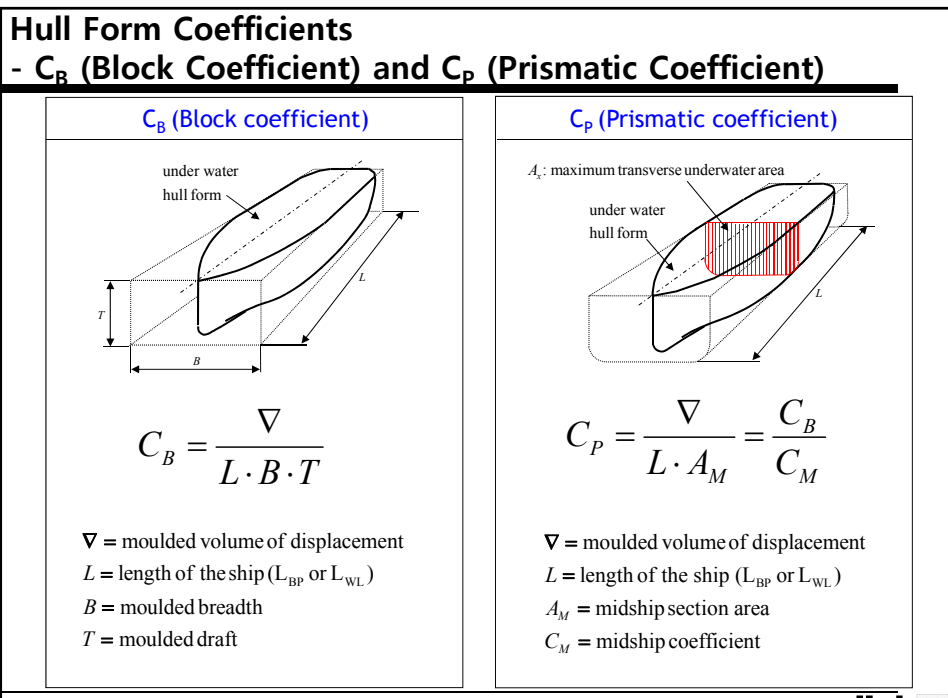
32

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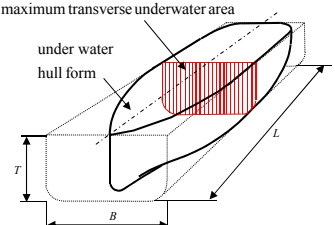
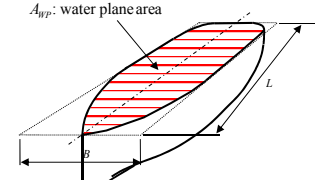
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### Hull Form Coefficients

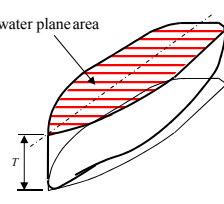
-  $C_M$  (Midship Section Coefficient) and  $C_{WP}$  (Water Plane Area Coefficient)

| $C_M$ (Midship Section Coefficient)  | $C_{WP}$ (Water Plane Area Coefficient)  |
|--|--|
|  <p style="text-align: center;"><math>C_M = \frac{A_M}{B \cdot T}</math></p> <p><math>A_M</math> = midship section area<br/> <math>B</math> = moulded breadth<br/> <math>T</math> = moulded draft</p> |  <p style="text-align: center;"><math>C_{WP} = \frac{A_{WP}}{L \cdot B}</math></p> <p><math>A_{WP}</math> = water plane area<br/> <math>L</math> = length of the ship (LWL or LBP)<br/> <math>B</math> = moulded breadth</p> |

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### Hull Form Coefficients

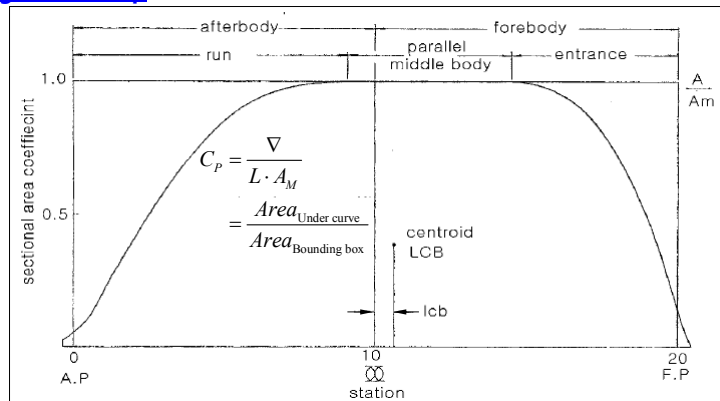
-  $C_{VP}$  (Vertical Prismatic Coefficient)

| $C_{VP}$ (Vertical Prismatic Coefficient)  |
|--|
|  <p style="text-align: center;"><math>C_{VP} = \frac{\nabla}{T \cdot A_{WP}}</math></p> <p><math>\nabla</math> = moulded volume of displacement<br/> <math>A_{WP}</math> = water plane area<br/> <math>T</math> = moulded draft</p> |

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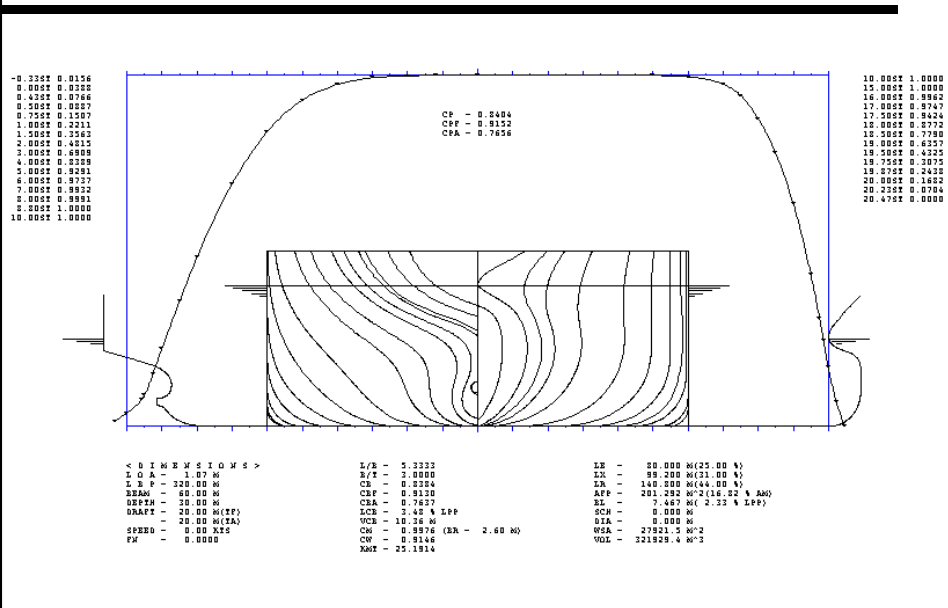
## C<sub>p</sub> Curve (Sectional Area Curve)

- C<sub>p</sub> 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<sub>p</sub>-curve and LCB (Longitudinal Center of Buoyancy)

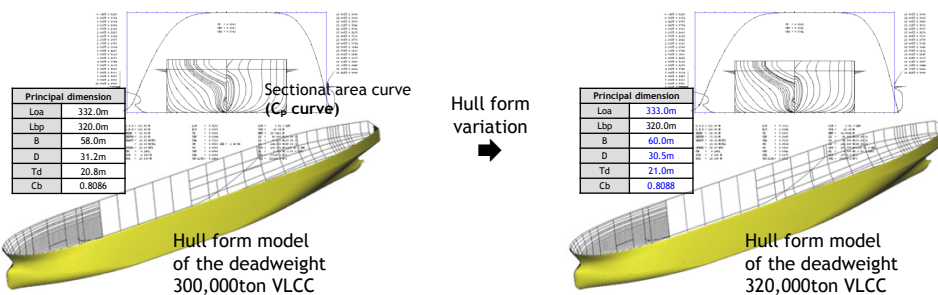
## Example of C<sub>p</sub> Curve of a 320K VLCC



## 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



## Hull Form Variation (2/2)

### ☑ Categorization of Hull Form Variation Methods

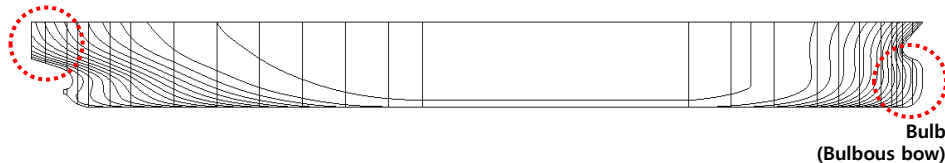
#### ■ Dimensional variation method

- 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.)

Transom

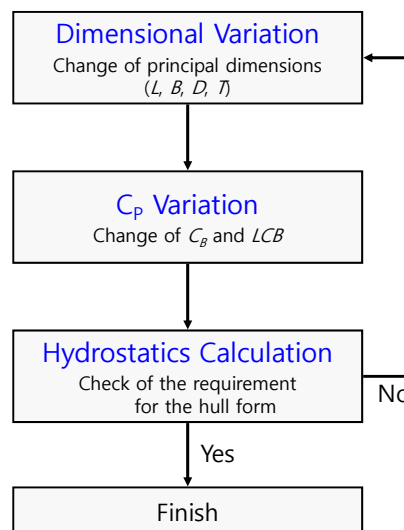


Bulb  
(Bulbous bow)

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## Procedure of the Hull Form Variation (Overview)



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## Dimensional Variation Method

### Dimensional Variation Method (1/3)

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

Basis ship



↓ Length variation

Design ship

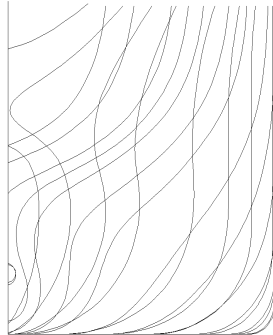


## Dimensional Variation Method (2/3)

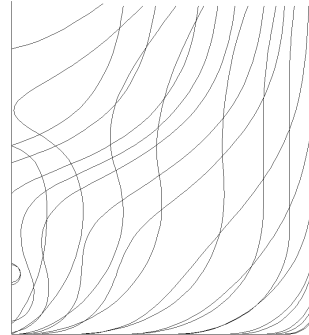
### ☑ Change of the Breadth (B)

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

Basis ship



Design ship



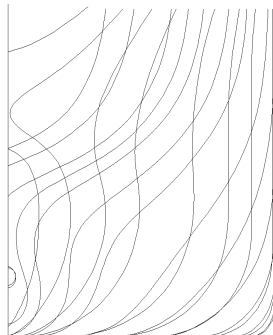
➔  
Breadth  
variation

## Dimensional Variation Method (3/3)

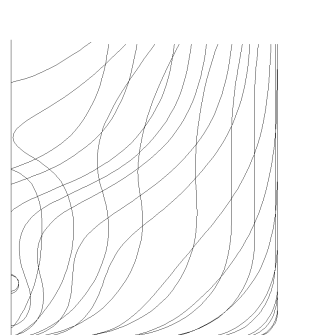
### ☑ Change of the Depth (D) or Draft (T)

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

Basis ship



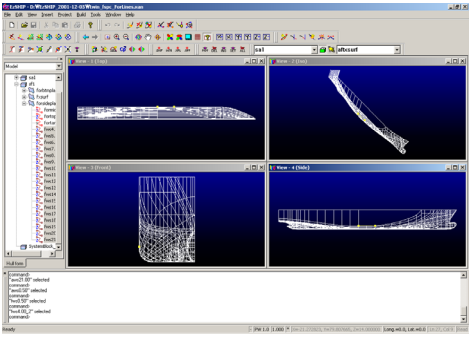
Design ship



➔  
Depth  
variation

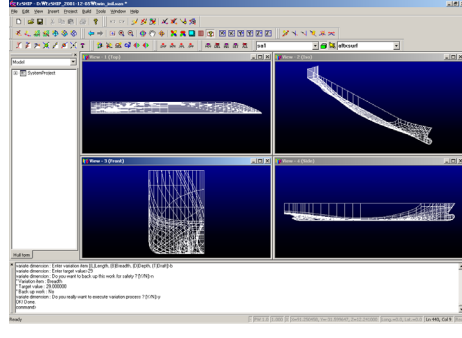
## Example of a Dimensional Variation Method

**Example of a twin-skeg container ship**




➔ Before Dimensional Variation  
 $L_{BP}: 190m, B: 28.65m, D: 22m, T: 8.5m$

← After Dimensional Variation  
 $L_{BP}: 200m, B: 29m, D: 23m, T: 8.6m$




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## C<sub>p</sub> Variation Method

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## C<sub>p</sub> Variation Method (1/2)

- ☑ In shipyard, the hull form of a similar basis ship is chosen and modified to 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<sub>p</sub> 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 C<sub>p</sub> curve.**

  - 1-C<sub>p</sub> variation method } Correction for displacement
  - Lackenby variation method } Correction for displacement
  - Swing station method } Correction for LCB
  - Weighted modified swing method } Correction for LCB

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## C<sub>p</sub> Variation Method (2/2)

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

\*The L<sub>BP</sub> 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.

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### C<sub>p</sub> Variation Method

#### - "1-C<sub>p</sub>" Variation Method (1/5)

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

**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"

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

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

: "1-C<sub>p</sub>" variation method

$C_p = \frac{\nabla}{L \cdot A_M} = \frac{\text{Area}_{\text{Under curve}}}{\text{Area}_{\text{Bounding box}}} = \frac{C_B}{C_M}$

$\delta C_p$ : The required change in prismatic coefficient of the half-body

$x$ : The fractional distance of any transverse section from midship

$\delta x$ : 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  $\delta C_p$

$L_p$ : The fractional parallel middle of the half-body

$\delta L_p$ : 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

### C<sub>p</sub> Variation Method

#### - "1-C<sub>p</sub>" Variation Method (2/5)

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

✓ "1-C<sub>p</sub>" 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  $\delta C_{p_{a,f}}$ ?

**Method 1. Using the following formula**

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

**Find:**  $\delta C_{p_{a,f}}$

$$\delta C_{p_f} = \frac{2[\delta C_p(h_a + LCB) + \delta LCB(C_p + \delta C_p)]}{h_f + h_a}$$

$$\delta C_{p_a} = \frac{2[\delta C_p(h_f - LCB) - \delta LCB(C_p + \delta C_p)]}{h_f + h_a}$$

The sign of LCB and  $\delta LCB$  are positive for forward of midship and negative for aft of midship.

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

$C_p = \frac{\nabla}{L \cdot A_M} = \frac{\text{Area}_{\text{Under curve}}}{\text{Area}_{\text{Bounding box}}} = \frac{C_B}{C_M}$

$\delta C_p$ : The required change in prismatic coefficient of the half-body

$x$ : The fractional distance of any transverse section from midship

$\delta x$ : 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  $\delta C_p$

$\bar{x}$ : 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

$\delta LCB$ : The required fractional shift of the LCB in the derived form

## C<sub>p</sub> Variation Method

### - "1-C<sub>p</sub>" Variation Method (3/5)

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#### Formula for Calculating h<sub>f,a</sub>

The + sign indicates movement away from midship (x<sub>a</sub>, x<sub>f</sub>).

$$C_p = \frac{\nabla}{L \cdot A_M} = \frac{\text{Area}_{\text{Under curve}}}{\text{Area}_{\text{Bounding box}}} = \frac{C_B}{C_M}$$

$\delta C_p$ : The required change in prismatic coefficient of the half-body  
 $x$ : The fractional distance of any transverse section from midship  
 $\delta x$ : 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  $\delta C_p$   
 $L_p$ : The fractional parallel middle of the half-body

$$\delta C_{p_f} = \frac{2[\delta C_p(h_a + LCB) + \delta LCB(C_p + \delta C_p)]}{h_f + h_a}$$

$$\delta C_{p_a} = \frac{2[\delta C_p(h_f - LCB) - \delta LCB(C_p + \delta C_p)]}{h_f + h_a}$$

How to obtain h<sub>f,a</sub>?

✓ Calculation of h<sub>f,a</sub>

Given: C<sub>p,a,f</sub>, x̄<sub>a,f</sub>

Find: h<sub>a,f</sub>

$$h_{a,f} = \frac{C_{p,a,f}(1 - 2\bar{x}_{a,f})}{1 - C_{p,a,f}} + \frac{\delta C_{p,a,f}}{1 - C_{p,a,f}} [1 - 2C_{p,a,f}(1 - \bar{x}_{a,f})]$$

$$h_{a,f} \approx \frac{C_{p,a,f}(1 - 2\bar{x}_{a,f})}{1 - C_{p,a,f}}$$

$\delta L_p$ : 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. 290, 1950.

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## C<sub>p</sub> Variation Method

### - "1-C<sub>p</sub>" Variation Method (4/5)

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#### 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<sub>BA</sub>) has an effect on the maneuverability of a ship (Recommending that C<sub>BA</sub> 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<sub>BA</sub> is less than 0.76
$$C_{pA} = C_p - 0.0215 \cdot LCB$$
- When the C<sub>B</sub> of the ship is 0.8-0.85 (Ponderous ship):
$$LCB : 3.5-4.0\% \text{ (forward)}$$
- 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.

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

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

LCB<sub>basis, estimate</sub>: LCB of the basis ship to be estimated by the formula  
 LCB<sub>basis, actual</sub>: Actual LCB of the basis ship  
 C<sub>corr.</sub>: Correction factor  
 LCB<sub>design, estimate</sub>: LCB of the design ship to be estimated by the formula  
 LCB<sub>design</sub>: LCB<sub>design, estimate</sub> multiplied by correction factor

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### C<sub>p</sub> Variation Method

#### - "1-C<sub>p</sub>" Variation Method (5/5)

**The + sign indicates movement away from midship (x<sub>a</sub>, x<sub>f</sub>).**

$\delta C_p$ : The required change in prismatic coefficient of the half-body

$x$ : The fractional distance of any transverse section from midship

$\delta x$ : 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  $\delta C_p$

$L_p$ : The fractional parallel middle of the half-body

$\delta L_p$ : 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

✓ "1-C<sub>p</sub>" 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  $\delta C_{p_{a,f}}$ ?

---

#### 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  $\delta C_{p_a}$  and  $\delta C_{p_f}$  according to the  $C_p + \delta C_p$  and LCB.

Ex) Given:  $C_p=0.682$ ,  $LCB=1.2\%$  aft,  
From the following graph, we can find  $C_{p_a}=0.659$  and  $C_{p_f}=0.705$ .

Centre of Buoyancy from Mid as Fraction of L =  $\frac{LCB}{L}$

### C<sub>p</sub> Variation Method

#### - "Swing Station Method"

**Swing station method: Changing the LCB position of hull form of a ship by "swinging" the C<sub>p</sub> 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  $\theta$  as shown.

$\delta LCB$ : the required change in LCB position

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

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

➔  $\bar{y}$ : 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:**  $\delta LCB, \bar{y}, y(x)$

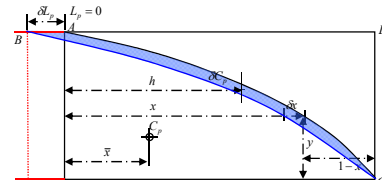
**Find:**  $\delta x_{atx}$

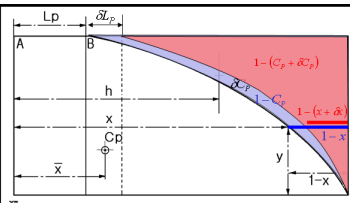
$$\tan \theta = \frac{\delta LCB}{\bar{y}} = \frac{\delta x}{y}$$

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

### C<sub>p</sub> Variation Method - Disadvantages of "1-C<sub>p</sub>" 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.





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

$$\delta L_{p_{a,f}} = \frac{\delta C_{p_{a,f}}}{1 - C_{p_{a,f}}} (1 - L_{p_{a,f}})$$


$C_p = C_p / C_m$   
 $L_p$ : 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  
 $\delta C_p$ : the required change in prismatic coefficient of the half-body  
 $\delta L_p$ : the consequent change in parallel middle body  
 $\delta x$ : 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  $\delta C_p$

(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.

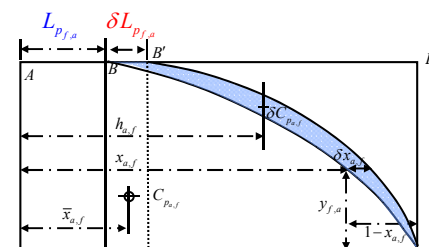
Design Theories of Ship and Offshore Plant, Fall 2016, Myung-II Roh


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### C<sub>p</sub> Variation Method - "Lackenby" Method (General Case) (1/3)

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



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

**"1-C<sub>p</sub>" Variation Method**

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

**<General Case>**  
**Basis Form:** Any extent of parallel middle body  
**Derived From:** Any required change in prismatic coefficient and extent of parallel middle body

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

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

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

**<Advantages of "Lackenby method">**

- (1) The parallel middle body ( $L_{p_{a,f}}$ ) can be controlled.
- (2) Because  $\delta x$  is proportional to  $x(1-x)$ , 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.

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

$\delta C_p$ : The required change in prismatic coefficient of the half-body  
 $x$ : The fractional distance of any transverse section from midship  
 $\delta x$ : 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  $\delta C_p$   
 $L_p$ : The fractional parallel middle of the half-body

$\delta L_p$ : 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<sub>p</sub> 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:**  $\delta x_{a,f}$

$$\delta x_{a,f} = (1-x_{a,f}) \left\{ \frac{\delta L_{p_{a,f}} \cdot x_{a,f} - L_{p_{a,f}} \cdot \delta C_{p_{a,f}}}{1-L_{p_{a,f}}} - \delta L_{p_{a,f}} \frac{(1-C_{p_{a,f}})}{(1-L_{p_{a,f}})} \right\}$$

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

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:**  $h_{a,f}$

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

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

**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:**  $\delta C_{p_{a,f}}$

$$\delta C_{p_j} = \frac{2[\delta C_p \cdot (B_a + LCB) + \delta LCB \cdot (C_p + \delta C_p)] + C_j \cdot \delta L_{p_j} - C_a \cdot \delta L_{p_a}}{B_j + B_a}$$

$$\delta C_{p_a} = \frac{2[\delta C_p \cdot (B_j - LCB) - \delta LCB \cdot (C_p + \delta C_p)] - C_j \cdot \delta L_{p_j} + C_a \cdot \delta L_{p_a}}{B_j + B_a}$$

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

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

$\delta C_p$ : The required change in prismatic coefficient of the half-body  
 $x$ : The fractional distance of any transverse section from midship  
 $\delta x$ : 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 "silver" of area represented by  $\delta C_p$   
 $L_p$ : The fractional parallel middle of the half-body

$\delta L_p$ : 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<sub>p</sub> 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:**  $\delta x_{a,f}$

$$\delta x_{a,f} = (1-x_{a,f}) \left\{ \frac{\delta L_{p_{a,f}} \cdot x_{a,f} - L_{p_{a,f}} \cdot \delta C_{p_{a,f}}}{1-L_{p_{a,f}}} - \delta L_{p_{a,f}} \frac{(1-C_{p_{a,f}})}{(1-L_{p_{a,f}})} \right\}$$

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

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:**  $h_{a,f}$

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

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

**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:**  $\delta C_{p_{a,f}}$

$$\delta C_{p_j} = \frac{2[\delta C_p \cdot (B_a + LCB) + \delta LCB \cdot (C_p + \delta C_p)] + C_j \cdot \delta L_{p_j} - C_a \cdot \delta L_{p_a}}{B_j + B_a}$$

$$\delta C_{p_a} = \frac{2[\delta C_p \cdot (B_j - LCB) - \delta LCB \cdot (C_p + \delta C_p)] - C_j \cdot \delta L_{p_j} + C_a \cdot \delta L_{p_a}}{B_j + B_a}$$

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

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

$\delta C_p$ : The required change in prismatic coefficient of the half-body  
 $x$ : The fractional distance of any transverse section from midship  
 $\delta x$ : 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 "silver" of area represented by  $\delta C_p$   
 $L_p$ : The fractional parallel middle of the half-body

④ Calculation of  $k_{a,f}$ : The lever of the second moment (i.e. radius of gyration) about midship expressed as a fraction of the length of the half-body

$$k_{a,f} = \frac{I_{a,f}}{S_{a,f}} \quad I_{a,f}: \text{The second moment about midship expressed as a fraction of the length of the half-body}$$

$$S_{a,f}: \text{The area of the half-body}$$

### C<sub>p</sub> Variation method

#### - Relation between "1-C<sub>p</sub>" Variation Method and "Lackenby" Method

**"1-C<sub>p</sub>" variation method**  
 Given: C<sub>p<sub>a,f</sub></sub>, δC<sub>p<sub>a,f</sub></sub>  
 Find: δx<sub>a,f</sub>

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

↓

**The change in parallel middle body by "1-C<sub>p</sub>" variation method**  
 Given: C<sub>p<sub>a,f</sub></sub>, δC<sub>p<sub>a,f</sub></sub>, L<sub>p<sub>a,f</sub></sub>  
 Find: δL<sub>p<sub>a,f</sub></sub>

$$\delta L_{p_{a,f}} = \frac{\delta C_{p_{a,f}}}{1 - C_{p_{a,f}}} (1 - L_{p_{a,f}})$$

→ The consequent change in parallel middle body (δL<sub>p<sub>a,f</sub></sub>) is calculated by "1-C<sub>p</sub>" variation method.

**"Lackenby" method <General Case>**  
 Given: C<sub>p<sub>a,f</sub></sub>, δC<sub>p<sub>a,f</sub></sub>, L<sub>p<sub>a,f</sub></sub>, δL<sub>p<sub>a,f</sub></sub>, x̄<sub>a,f</sub>  
 Find: δx<sub>a,f</sub>

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

(A<sub>f,a</sub> = C<sub>p<sub>a,f</sub></sub> (1 - 2x̄<sub>a,f</sub>) - L<sub>p<sub>a,f</sub></sub> (1 - C<sub>p<sub>a,f</sub></sub>))

→ The change in the parallel middle body (δL<sub>p<sub>a,f</sub></sub>) can be controlled.

↓

**(Substituting into the Lackenby method)**

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

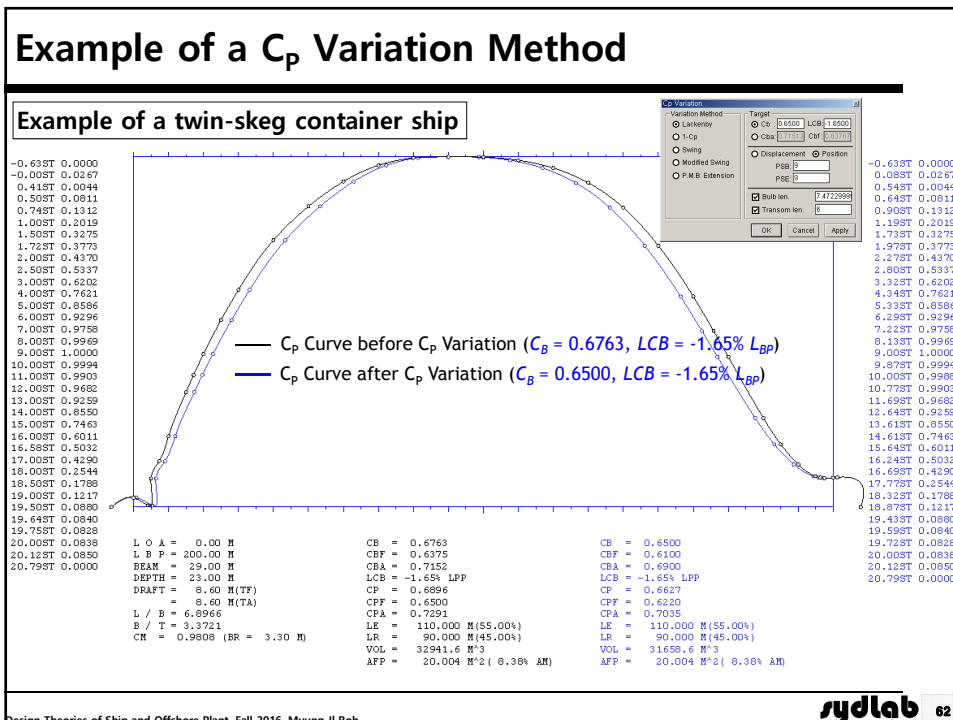
$$\delta x_{a,f} = (1 - x_{a,f}) \left\{ \frac{\delta C_{p_{a,f}} (1 - L_{p_{a,f}})}{1 - C_{p_{a,f}}} + \frac{x_{a,f} - L_{p_{a,f}}}{A_{a,f}} [\delta C_{p_{a,f}} - \frac{\delta C_{p_{a,f}} (1 - C_{p_{a,f}})}{1 - C_{p_{a,f}}}] \right\}$$

∴ δx<sub>a,f</sub> =  $\frac{\delta C_{p_{a,f}}}{1 - C_{p_{a,f}}} (1 - x_{a,f})$

→ This result is equal to the result of "1-C<sub>p</sub>" variation method.  
 → That is, "1-C<sub>p</sub>" variation method is a special case of Lackenby method.

δC<sub>p</sub>: 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 "silver" of area represented by δC<sub>p</sub>  
 L<sub>p</sub>: The fractional parallel middle of the half-body

x̄: 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



## Design of a Body Plan by Using the Changed $C_p$ Curve

St. 4

St. 4

|         |        |        |        |
|---------|--------|--------|--------|
| -0.4397 | 0.0000 | 0.0000 | 0.0000 |
| -0.4007 | 0.0007 | 0.0007 | 0.0007 |
| -0.3617 | 0.0014 | 0.0014 | 0.0014 |
| -0.3227 | 0.0021 | 0.0021 | 0.0021 |
| -0.2837 | 0.0028 | 0.0028 | 0.0028 |
| -0.2447 | 0.0035 | 0.0035 | 0.0035 |
| -0.2057 | 0.0042 | 0.0042 | 0.0042 |
| -0.1667 | 0.0049 | 0.0049 | 0.0049 |
| -0.1277 | 0.0056 | 0.0056 | 0.0056 |
| -0.0887 | 0.0063 | 0.0063 | 0.0063 |
| -0.0497 | 0.0070 | 0.0070 | 0.0070 |
| -0.0107 | 0.0077 | 0.0077 | 0.0077 |
| 0.0283  | 0.0084 | 0.0084 | 0.0084 |
| 0.0673  | 0.0091 | 0.0091 | 0.0091 |
| 0.1063  | 0.0098 | 0.0098 | 0.0098 |
| 0.1453  | 0.0105 | 0.0105 | 0.0105 |
| 0.1843  | 0.0112 | 0.0112 | 0.0112 |
| 0.2233  | 0.0119 | 0.0119 | 0.0119 |
| 0.2623  | 0.0126 | 0.0126 | 0.0126 |
| 0.3013  | 0.0133 | 0.0133 | 0.0133 |
| 0.3403  | 0.0140 | 0.0140 | 0.0140 |
| 0.3793  | 0.0147 | 0.0147 | 0.0147 |
| 0.4183  | 0.0154 | 0.0154 | 0.0154 |
| 0.4573  | 0.0161 | 0.0161 | 0.0161 |
| 0.4963  | 0.0168 | 0.0168 | 0.0168 |
| 0.5353  | 0.0175 | 0.0175 | 0.0175 |
| 0.5743  | 0.0182 | 0.0182 | 0.0182 |
| 0.6133  | 0.0189 | 0.0189 | 0.0189 |
| 0.6523  | 0.0196 | 0.0196 | 0.0196 |
| 0.6913  | 0.0203 | 0.0203 | 0.0203 |
| 0.7303  | 0.0210 | 0.0210 | 0.0210 |
| 0.7693  | 0.0217 | 0.0217 | 0.0217 |
| 0.8083  | 0.0224 | 0.0224 | 0.0224 |
| 0.8473  | 0.0231 | 0.0231 | 0.0231 |
| 0.8863  | 0.0238 | 0.0238 | 0.0238 |
| 0.9253  | 0.0245 | 0.0245 | 0.0245 |
| 0.9643  | 0.0252 | 0.0252 | 0.0252 |
| 1.0033  | 0.0259 | 0.0259 | 0.0259 |
| 1.0423  | 0.0266 | 0.0266 | 0.0266 |
| 1.0813  | 0.0273 | 0.0273 | 0.0273 |
| 1.1203  | 0.0280 | 0.0280 | 0.0280 |
| 1.1593  | 0.0287 | 0.0287 | 0.0287 |
| 1.1983  | 0.0294 | 0.0294 | 0.0294 |
| 1.2373  | 0.0301 | 0.0301 | 0.0301 |
| 1.2763  | 0.0308 | 0.0308 | 0.0308 |
| 1.3153  | 0.0315 | 0.0315 | 0.0315 |
| 1.3543  | 0.0322 | 0.0322 | 0.0322 |
| 1.3933  | 0.0329 | 0.0329 | 0.0329 |
| 1.4323  | 0.0336 | 0.0336 | 0.0336 |
| 1.4713  | 0.0343 | 0.0343 | 0.0343 |
| 1.5103  | 0.0350 | 0.0350 | 0.0350 |
| 1.5493  | 0.0357 | 0.0357 | 0.0357 |
| 1.5883  | 0.0364 | 0.0364 | 0.0364 |
| 1.6273  | 0.0371 | 0.0371 | 0.0371 |
| 1.6663  | 0.0378 | 0.0378 | 0.0378 |
| 1.7053  | 0.0385 | 0.0385 | 0.0385 |
| 1.7443  | 0.0392 | 0.0392 | 0.0392 |
| 1.7833  | 0.0399 | 0.0399 | 0.0399 |
| 1.8223  | 0.0406 | 0.0406 | 0.0406 |
| 1.8613  | 0.0413 | 0.0413 | 0.0413 |
| 1.9003  | 0.0420 | 0.0420 | 0.0420 |
| 1.9393  | 0.0427 | 0.0427 | 0.0427 |
| 1.9783  | 0.0434 | 0.0434 | 0.0434 |
| 2.0173  | 0.0441 | 0.0441 | 0.0441 |
| 2.0563  | 0.0448 | 0.0448 | 0.0448 |
| 2.0953  | 0.0455 | 0.0455 | 0.0455 |
| 2.1343  | 0.0462 | 0.0462 | 0.0462 |
| 2.1733  | 0.0469 | 0.0469 | 0.0469 |
| 2.2123  | 0.0476 | 0.0476 | 0.0476 |
| 2.2513  | 0.0483 | 0.0483 | 0.0483 |
| 2.2903  | 0.0490 | 0.0490 | 0.0490 |
| 2.3293  | 0.0497 | 0.0497 | 0.0497 |
| 2.3683  | 0.0504 | 0.0504 | 0.0504 |
| 2.4073  | 0.0511 | 0.0511 | 0.0511 |
| 2.4463  | 0.0518 | 0.0518 | 0.0518 |
| 2.4853  | 0.0525 | 0.0525 | 0.0525 |
| 2.5243  | 0.0532 | 0.0532 | 0.0532 |
| 2.5633  | 0.0539 | 0.0539 | 0.0539 |
| 2.6023  | 0.0546 | 0.0546 | 0.0546 |
| 2.6413  | 0.0553 | 0.0553 | 0.0553 |
| 2.6803  | 0.0560 | 0.0560 | 0.0560 |
| 2.7193  | 0.0567 | 0.0567 | 0.0567 |
| 2.7583  | 0.0574 | 0.0574 | 0.0574 |
| 2.7973  | 0.0581 | 0.0581 | 0.0581 |
| 2.8363  | 0.0588 | 0.0588 | 0.0588 |
| 2.8753  | 0.0595 | 0.0595 | 0.0595 |
| 2.9143  | 0.0602 | 0.0602 | 0.0602 |
| 2.9533  | 0.0609 | 0.0609 | 0.0609 |
| 2.9923  | 0.0616 | 0.0616 | 0.0616 |
| 3.0313  | 0.0623 | 0.0623 | 0.0623 |
| 3.0703  | 0.0630 | 0.0630 | 0.0630 |
| 3.1093  | 0.0637 | 0.0637 | 0.0637 |
| 3.1483  | 0.0644 | 0.0644 | 0.0644 |
| 3.1873  | 0.0651 | 0.0651 | 0.0651 |
| 3.2263  | 0.0658 | 0.0658 | 0.0658 |
| 3.2653  | 0.0665 | 0.0665 | 0.0665 |
| 3.3043  | 0.0672 | 0.0672 | 0.0672 |
| 3.3433  | 0.0679 | 0.0679 | 0.0679 |
| 3.3823  | 0.0686 | 0.0686 | 0.0686 |
| 3.4213  | 0.0693 | 0.0693 | 0.0693 |
| 3.4603  | 0.0700 | 0.0700 | 0.0700 |
| 3.4993  | 0.0707 | 0.0707 | 0.0707 |
| 3.5383  | 0.0714 | 0.0714 | 0.0714 |
| 3.5773  | 0.0721 | 0.0721 | 0.0721 |
| 3.6163  | 0.0728 | 0.0728 | 0.0728 |
| 3.6553  | 0.0735 | 0.0735 | 0.0735 |
| 3.6943  | 0.0742 | 0.0742 | 0.0742 |
| 3.7333  | 0.0749 | 0.0749 | 0.0749 |
| 3.7723  | 0.0756 | 0.0756 | 0.0756 |
| 3.8113  | 0.0763 | 0.0763 | 0.0763 |
| 3.8503  | 0.0770 | 0.0770 | 0.0770 |
| 3.8893  | 0.0777 | 0.0777 | 0.0777 |
| 3.9283  | 0.0784 | 0.0784 | 0.0784 |
| 3.9673  | 0.0791 | 0.0791 | 0.0791 |
| 4.0063  | 0.0798 | 0.0798 | 0.0798 |
| 4.0453  | 0.0805 | 0.0805 | 0.0805 |
| 4.0843  | 0.0812 | 0.0812 | 0.0812 |
| 4.1233  | 0.0819 | 0.0819 | 0.0819 |
| 4.1623  | 0.0826 | 0.0826 | 0.0826 |
| 4.2013  | 0.0833 | 0.0833 | 0.0833 |
| 4.2403  | 0.0840 | 0.0840 | 0.0840 |
| 4.2793  | 0.0847 | 0.0847 | 0.0847 |
| 4.3183  | 0.0854 | 0.0854 | 0.0854 |
| 4.3573  | 0.0861 | 0.0861 | 0.0861 |
| 4.3963  | 0.0868 | 0.0868 | 0.0868 |
| 4.4353  | 0.0875 | 0.0875 | 0.0875 |
| 4.4743  | 0.0882 | 0.0882 | 0.0882 |
| 4.5133  | 0.0889 | 0.0889 | 0.0889 |
| 4.5523  | 0.0896 | 0.0896 | 0.0896 |
| 4.5913  | 0.0903 | 0.0903 | 0.0903 |
| 4.6303  | 0.0910 | 0.0910 | 0.0910 |
| 4.6693  | 0.0917 | 0.0917 | 0.0917 |
| 4.7083  | 0.0924 | 0.0924 | 0.0924 |
| 4.7473  | 0.0931 | 0.0931 | 0.0931 |
| 4.7863  | 0.0938 | 0.0938 | 0.0938 |
| 4.8253  | 0.0945 | 0.0945 | 0.0945 |
| 4.8643  | 0.0952 | 0.0952 | 0.0952 |
| 4.9033  | 0.0959 | 0.0959 | 0.0959 |
| 4.9423  | 0.0966 | 0.0966 | 0.0966 |
| 4.9813  | 0.0973 | 0.0973 | 0.0973 |
| 5.0203  | 0.0980 | 0.0980 | 0.0980 |
| 5.0593  | 0.0987 | 0.0987 | 0.0987 |
| 5.0983  | 0.0994 | 0.0994 | 0.0994 |
| 5.1373  | 0.1001 | 0.1001 | 0.1001 |
| 5.1763  | 0.1008 | 0.1008 | 0.1008 |
| 5.2153  | 0.1015 | 0.1015 | 0.1015 |
| 5.2543  | 0.1022 | 0.1022 | 0.1022 |
| 5.2933  | 0.1029 | 0.1029 | 0.1029 |
| 5.3323  | 0.1036 | 0.1036 | 0.1036 |
| 5.3713  | 0.1043 | 0.1043 | 0.1043 |
| 5.4103  | 0.1050 | 0.1050 | 0.1050 |
| 5.4493  | 0.1057 | 0.1057 | 0.1057 |
| 5.4883  | 0.1064 | 0.1064 | 0.1064 |
| 5.5273  | 0.1071 | 0.1071 | 0.1071 |
| 5.5663  | 0.1078 | 0.1078 | 0.1078 |
| 5.6053  | 0.1085 | 0.1085 | 0.1085 |
| 5.6443  | 0.1092 | 0.1092 | 0.1092 |
| 5.6833  | 0.1099 | 0.1099 | 0.1099 |
| 5.7223  | 0.1106 | 0.1106 | 0.1106 |
| 5.7613  | 0.1113 | 0.1113 | 0.1113 |
| 5.8003  | 0.1120 | 0.1120 | 0.1120 |
| 5.8393  | 0.1127 | 0.1127 | 0.1127 |
| 5.8783  | 0.1134 | 0.1134 | 0.1134 |
| 5.9173  | 0.1141 | 0.1141 | 0.1141 |
| 5.9563  | 0.1148 | 0.1148 | 0.1148 |
| 5.9953  | 0.1155 | 0.1155 | 0.1155 |
| 6.0343  | 0.1162 | 0.1162 | 0.1162 |
| 6.0733  | 0.1169 | 0.1169 | 0.1169 |
| 6.1123  | 0.1176 | 0.1176 | 0.1176 |
| 6.1513  | 0.1183 | 0.1183 | 0.1183 |
| 6.1903  | 0.1190 | 0.1190 | 0.1190 |
| 6.2293  | 0.1197 | 0.1197 | 0.1197 |
| 6.2683  | 0.1204 | 0.1204 | 0.1204 |
| 6.3073  | 0.1211 | 0.1211 | 0.1211 |
| 6.3463  | 0.1218 | 0.1218 | 0.1218 |
| 6.3853  | 0.1225 | 0.1225 | 0.1225 |
| 6.4243  | 0.1232 | 0.1232 | 0.1232 |
| 6.4633  | 0.1239 | 0.1239 | 0.1239 |
| 6.5023  | 0.1246 | 0.1246 | 0.1246 |
| 6.5413  | 0.1253 | 0.1253 | 0.1253 |
| 6.5803  | 0.1260 | 0.1260 | 0.1260 |
| 6.6193  | 0.1267 | 0.1267 | 0.1267 |
| 6.6583  | 0.1274 | 0.1274 | 0.1274 |
| 6.6973  | 0.1281 | 0.1281 | 0.1281 |
| 6.7363  | 0.1288 | 0.1288 | 0.1288 |
| 6.7753  | 0.1295 | 0.1295 | 0.1295 |
| 6.8143  | 0.1302 | 0.1302 | 0.1302 |
| 6.8533  | 0.1309 | 0.1309 | 0.1309 |
| 6.8923  | 0.1316 | 0.1316 | 0.1316 |
| 6.9313  | 0.1323 | 0.1323 | 0.1323 |
| 6.9703  | 0.1330 | 0.1330 | 0.1330 |
| 7.0093  | 0.1337 | 0.1337 | 0.1337 |
| 7.0483  | 0.1344 | 0.1344 | 0.1344 |
| 7.0873  | 0.1351 | 0.1351 | 0.1351 |
| 7.1263  | 0.1358 | 0.1358 | 0.1358 |
| 7.1653  | 0.1365 | 0.1365 | 0.1365 |
| 7.2043  | 0.1372 | 0.1372 | 0.1372 |
| 7.2433  | 0.1379 | 0.1379 | 0.1379 |
| 7.2823  | 0.1386 | 0.1386 | 0.1386 |
| 7.3213  | 0.1393 | 0.1393 | 0.1393 |
| 7.3603  | 0.1400 | 0.1400 | 0.1400 |
| 7.3993  | 0.1407 | 0.1407 | 0.1407 |
| 7.4383  | 0.1414 | 0.1414 | 0.1414 |
| 7.4773  | 0.1421 | 0.1421 | 0.1421 |
| 7.5163  | 0.1428 | 0.1428 | 0.1428 |
| 7.5553  | 0.1435 | 0.1435 | 0.1435 |
| 7.5943  | 0.1442 | 0.1442 | 0.1442 |
| 7.6333  | 0.1449 | 0.1449 | 0.1449 |
| 7.6723  | 0.1456 | 0.1456 | 0.1456 |
| 7.7113  | 0.1463 | 0.1463 | 0.1463 |
| 7.7503  | 0.1470 | 0.1470 | 0.1470 |
| 7.7893  | 0.1477 | 0.1477 | 0.1477 |
| 7.8283  | 0.1484 | 0.1484 | 0.1484 |
| 7.8673  | 0.1491 | 0.1491 | 0.1491 |
| 7.9063  | 0.1498 | 0.1498 | 0.1498 |
| 7.9453  | 0.1505 | 0.1505 | 0.1505 |
| 7.9843  | 0.1512 | 0.1512 | 0.1512 |
| 8.0233  | 0.1519 | 0.1519 | 0.1519 |
| 8.0623  | 0.1526 | 0.1526 | 0.1526 |
| 8.1013  | 0.1533 | 0.1533 | 0.1533 |
| 8.1403  | 0.1540 | 0.1540 | 0.1540 |
| 8.1793  | 0.1547 | 0.1547 | 0.1547 |
| 8.2183  | 0.1554 | 0.1554 | 0.1554 |
| 8.2573  | 0.1561 | 0.1561 | 0.1561 |
| 8.2963  | 0.1568 | 0.1568 | 0.1568 |
| 8.3353  | 0.1575 | 0.1575 | 0.1575 |
| 8.3743  | 0.1582 | 0.1582 | 0.1582 |
| 8.4133  | 0.1589 | 0.1589 | 0.1589 |
| 8.4523  | 0.1596 | 0.1596 | 0.1596 |
| 8.4913  | 0.1603 | 0.1603 | 0.1603 |
| 8.5303  | 0.1610 | 0.1610 | 0.1610 |
| 8.5693  | 0.1617 | 0.1617 | 0.1617 |
| 8.6083  | 0.1624 | 0.1624 | 0.1624 |
| 8.6473  | 0.1631 | 0.1631 | 0.1631 |
| 8.6863  | 0.1638 | 0.1638 | 0.1638 |
| 8.7253  | 0.1645 | 0.1645 | 0.1645 |
| 8.7643  | 0.1652 | 0.1652 | 0.1652 |
| 8.8033  | 0.1659 | 0.1659 | 0.1659 |
| 8.8423  | 0.1666 | 0.1666 | 0.1666 |
| 8.8813  | 0.1673 | 0.1673 | 0.1673 |
| 8.9203  | 0.1680 | 0.1680 | 0.1680 |
| 8.9593  | 0.1687 | 0.1687 | 0.1687 |
| 8.9983  | 0.1694 | 0.1694 | 0.1694 |
| 9.0373  | 0.1701 | 0.1701 | 0.1701 |
| 9.0763  | 0.1708 | 0.1708 | 0.1708 |
| 9.1153  | 0.1715 | 0.1715 |        |



## 3.3 Hull Form Fairing

### Hull Form Fairing

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#### Objective

- To increase the quality of the hull form
- A kind of touch-up process for the hull form
- In general, the hull form fairing is performed manually.
- The quality can be checked roughly with the  $C_p$  curve.

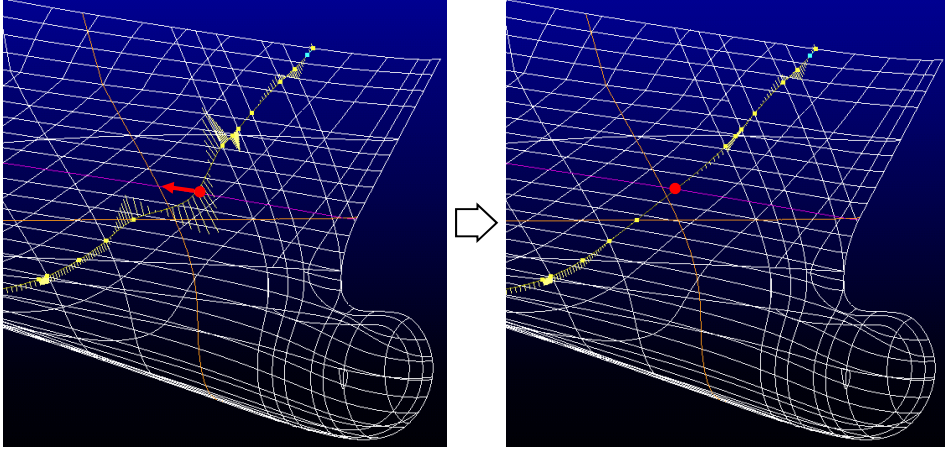
#### Hull Form Fairing Method

- Modification of hull form curves through moving, inserting, and deleting points on the curves

### Example of Hull Form Fairing (1/3)

Example of a twin-skeg container ship

Moving an existing point



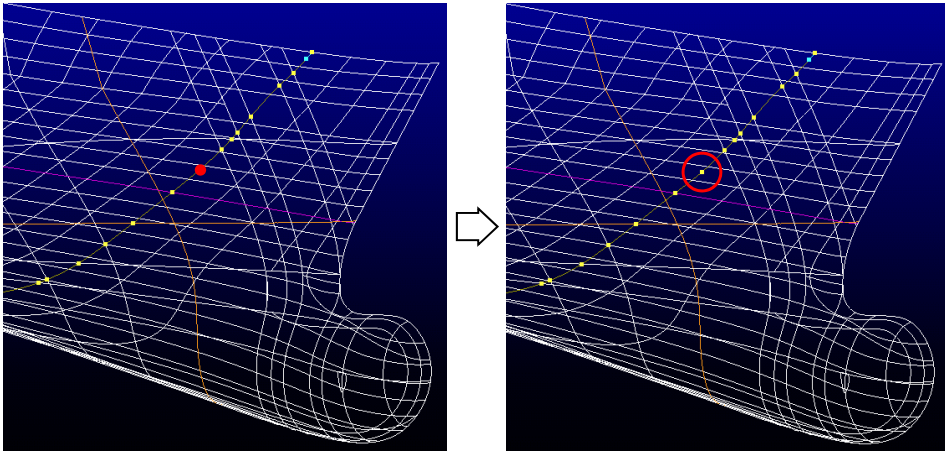
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### Example of Hull Form Fairing (2/3)

Example of a twin-skeg container ship

Inserting a new point



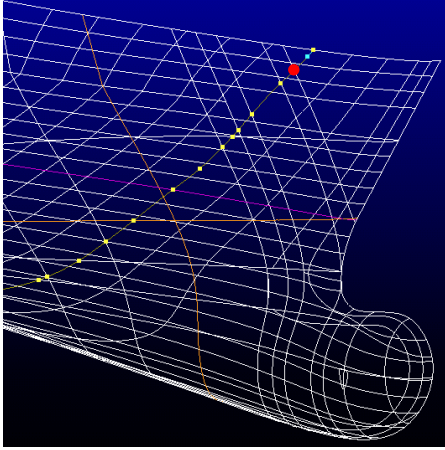
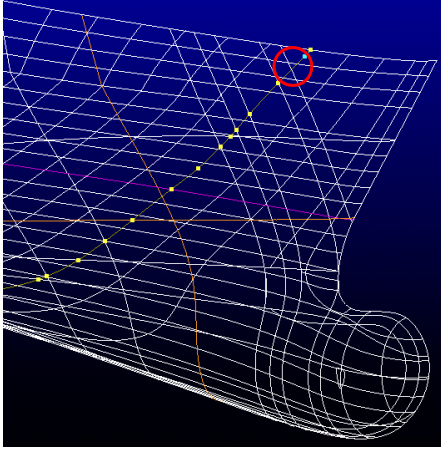
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### Example of Hull Form Fairing (3/3)

Example of a twin-skeg container ship

Deleting an existing point

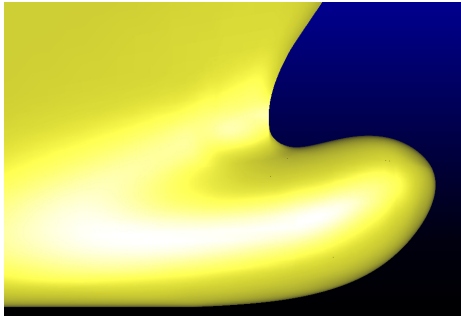

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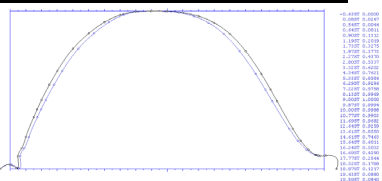

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### Example of Hull Form of High Quality

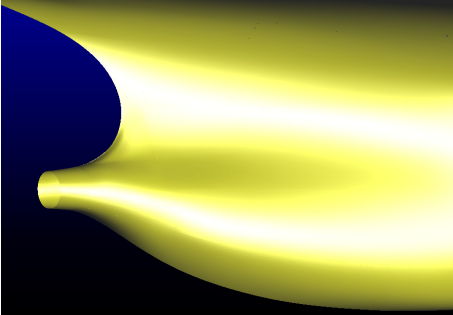
Example of a single skeg container ship




Fore body



after body



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

### Example of a missile destroyer (DDG-51)

Model: sp5, sp6, sp7, sp8, sp9, sp10, sp11, sp12, sp13, sp14, sp15, sp16, sp17, sp18, sp19, sp20, sp21, sp22, sp23, sp24, sp25, sp26, sp27, sp28, sp29, sp30, sp31, sp32, sp33, sp34, sp35, sp36, sp37, sp38, sp39, sp40, sp41, sp42, sp43, sp44, sp45, sp46, sp47, sp48, sp49, sp50, sp51, sp52, sp53, sp54, sp55, sp56, sp57, sp58, sp59, sp60, sp61, sp62, sp63, sp64, sp65, sp66, sp67, sp68, sp69, sp70, sp71, sp72, sp73, sp74, sp75, sp76, sp77, sp78, sp79, sp80, sp81, sp82, sp83, sp84, sp85, sp86, sp87, sp88, sp89, sp90, sp91, sp92, sp93, sp94, sp95, sp96, sp97, sp98, sp99, sp100, sp101, sp102, sp103, sp104, sp105, sp106, sp107, sp108, sp109, sp110, sp111, sp112, sp113, sp114, sp115, sp116, sp117, sp118, sp119, sp120, sp121, sp122, sp123, sp124, sp125, sp126, sp127, sp128, sp129, sp130, sp131, sp132, sp133, sp134, sp135, sp136, sp137, sp138, sp139, sp140, sp141, sp142, sp143, sp144, sp145, sp146, sp147, sp148, sp149, sp150, sp151, sp152, sp153, sp154, sp155, sp156, sp157, sp158, sp159, sp160, 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## Example of Hull Form of Low Quality (2/2)

### Example of a missile destroyer (DDG-51)

-0.178T 0.0591  
 -0.008T 0.0611  
 1.008T 0.1315  
 2.008T 0.2722  
 3.008T 0.4381  
 4.008T 0.6070  
 5.008T 0.7402  
 6.008T 0.8389  
 7.008T 0.9133  
 8.008T 0.9564  
 9.008T 0.9694  
 10.008T 1.0000

10.008T 1.0000  
 10.148T 0.9977  
 11.008T 0.9561  
 12.008T 0.8906  
 13.008T 0.8193  
 14.008T 0.7414  
 15.008T 0.6445  
 16.008T 0.5367  
 17.008T 0.4130  
 18.008T 0.2748  
 18.768T 0.1823  
 19.278T 0.1715  
 19.528T 0.2526  
 19.778T 0.2420  
 20.008T 0.1408  
 20.288T 0.0000

CP = 0.6261  
 CPF = 0.6095  
 CPA = 0.6427

< D I M E N S I O N S >  
 L O A = 153.78 M  
 L B P = 142.04 M  
 BEAM = 17.98 M  
 DEPTH = 12.00 M  
 DRAFT = 6.40 M(TA)  
 SPEED = 0.00 KTS  
 PW = 0.0000

L/B = 7.7903  
 B/T = 2.6796  
 CB = 0.5080  
 CBF = 0.4994  
 CBA = 0.5269  
 LCB = -0.20 % LPP  
 VCB = 4.03 M  
 CM = 0.8276  
 CW = 0.0000  
 KMT = 4.0289

LE = 69.050 M(49.30 %)  
 LM = 0.000 M(0.00 %)  
 LR = 71.020 M(50.70 %)  
 AFP = 14.054 M\*2(14.08 % AM)  
 BL = 0.000 M(0.00 % LPP)  
 SCH = 0.000 M  
 DIA = 0.000 M  
 WTS = 2936.2 M\*2  
 VOL = 8756.6 M\*3

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## 3.4 Performance Evaluation of a Hull Form

### Performance Evaluation of a Hull Form

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#### 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)

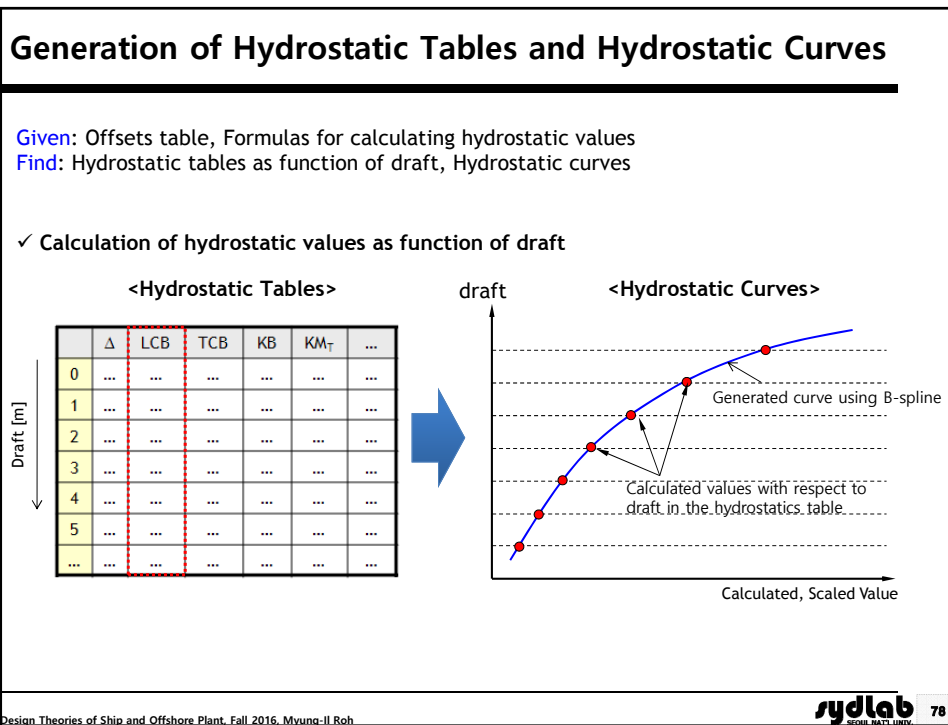
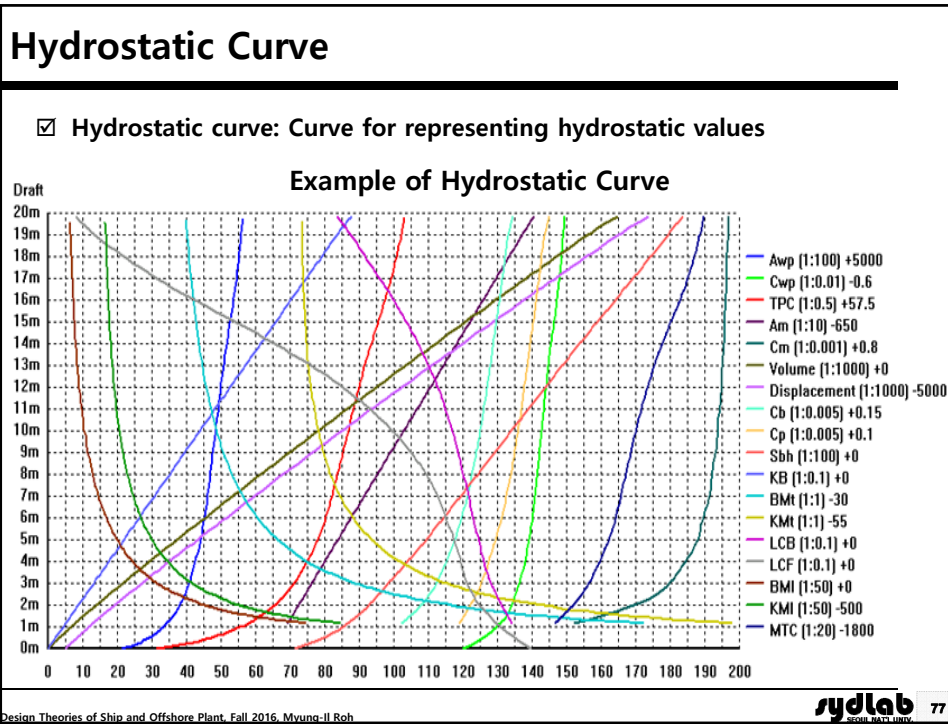
#### Maneuverability

- Dependent on couple effect between hull form and rudder

## Stability Performance

## Hydrostatic Values

- ☑  $\text{Draft}_{\text{Mid}}$ ,  $\text{Draft}_{\text{Scant}}$ : Draft from base line, moulded / scantling (m)
- ☑  $\text{Volume}_{\text{Mid}}(\nabla)$ ,  $\text{Volume}_{\text{Ext}}$ : Displacement volume, moulded / extreme ( $\text{m}^3$ )
- ☑  $\text{Displacement}_{\text{Mid}}(\Delta)$ ,  $\text{Displacement}_{\text{Ext}}$ : 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)
- ☑  $\text{KM}_T$ : Transverse metacenter height above base line (m)
- ☑  $\text{KM}_L$ : Longitudinal metacenter height above base line (m)
- ☑ MTC: Moment to change trim one centimeter (ton-m)
- ☑ TPC: Increase in  $\text{Displacement}_{\text{Mid}}$  (ton) per one centimeter immersion
- ☑ WSA: Wetted surface area ( $\text{m}^2$ )
- ☑  $C_B$ : Block coefficient
- ☑  $C_{\text{WP}}$ : Water plane area coefficient
- ☑  $C_M$ : Midship section area coefficient
- ☑  $C_P$ : Prismatic coefficient
- ☑ Trim: Trim(= after draft – forward draft) (m)



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

| DRAFT (M) | DISP MLD(M <sup>3</sup> ) | DISP EXT(Ton) | VCB (M) | LCB (M) | LCF (M) | KM (M) | KM <sub>L</sub> (M) | MTC (T-M) | TPC (Ton) | WSA (M <sup>2</sup> ) | C <sub>B</sub> | C <sub>w</sub> | C <sub>p</sub> | C <sub>M</sub> |
|-----------|---------------------------|---------------|---------|---------|---------|--------|---------------------|-----------|-----------|-----------------------|----------------|----------------|----------------|----------------|
| 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         |
| ...       |                           |               |         |         |         |        |                     |           |           |                       |                |                |                |                |

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

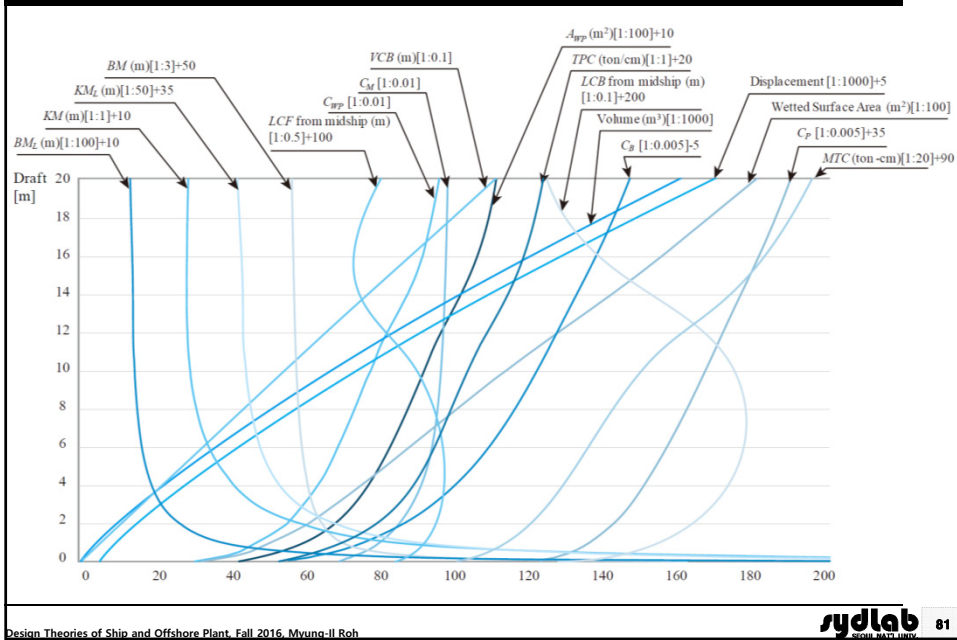
| DRAFT (M) | DISP MLD(M <sup>3</sup> ) | DISP EXT(Ton) | VCB (M) | LCB (M) | LCF (M) | KM (M) | KM <sub>L</sub> (M) | MTC (T-M) | TPC (Ton) | WSA (M <sup>2</sup> ) | C <sub>B</sub> | C <sub>w</sub> | C <sub>p</sub> | C <sub>M</sub> |
|-----------|---------------------------|---------------|---------|---------|---------|--------|---------------------|-----------|-----------|-----------------------|----------------|----------------|----------------|----------------|
| 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    | 83834.1                   | 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      | 14670.0               | 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         |

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



### Resistance Performance





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

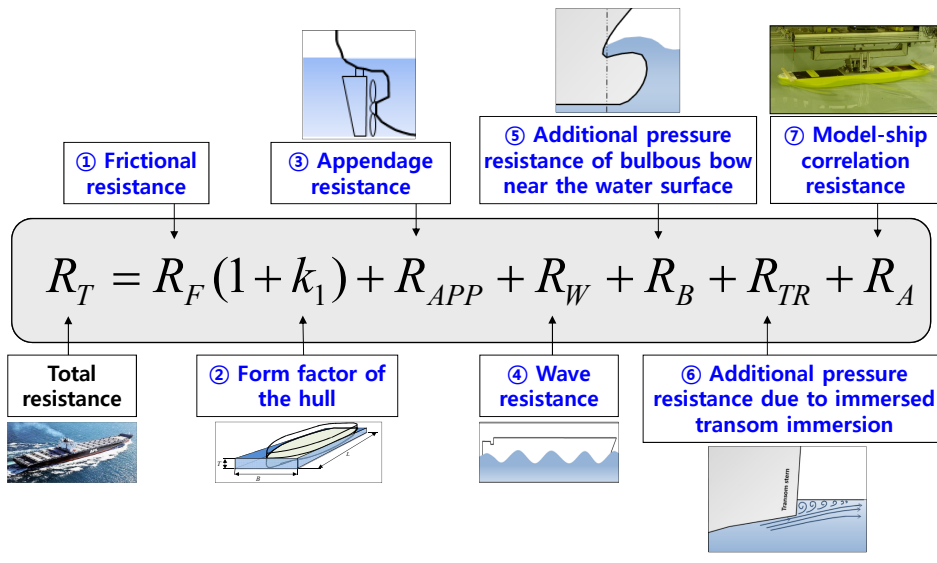
Therefore, a statistical method was presented for the determination of the required propulsive power in the initial design stage.

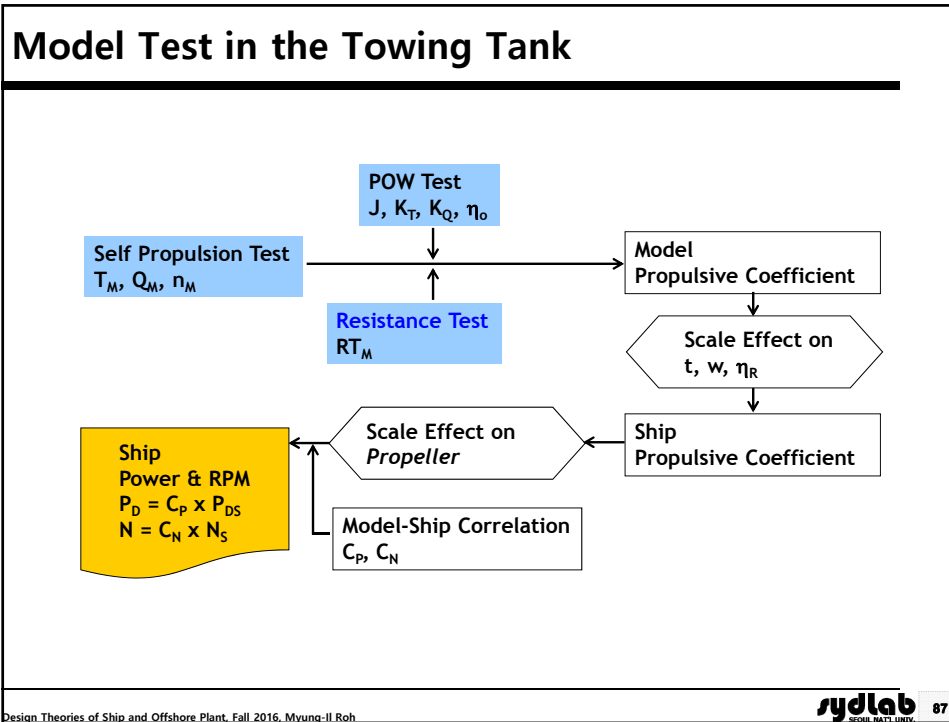
This method was developed through a regression analysis of random model experiments and full-scale data.

Many naval architects use the method, generally in the form presented in 1984 and find it gives acceptable results although it has to be 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**


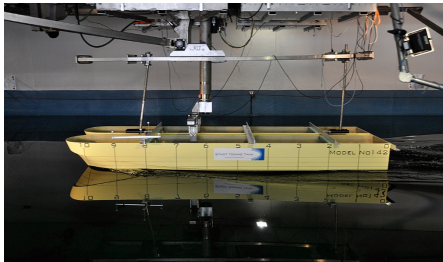




## Classifications of Model Test (1/9)

**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 ( $R_{TM}$ )**

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\* Reference: MARIN, Stadt Towing Tank  
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## Classifications of Model Test (2/9)

### ☑ Resistance Test (continued)

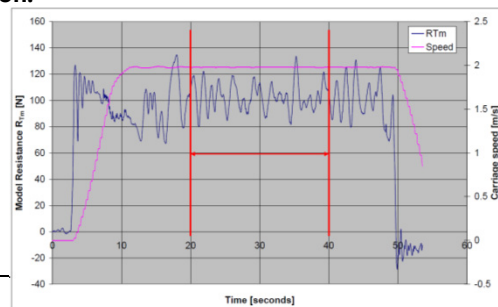
#### ■ Test procedure

- The model is accelerated to wanted speed with the carriage.
- Speed is kept constant for at least 10 seconds (or at least 10 load cycles).
- Average values of the measurements for the period of constant speed is calculated.

#### ■ The tow force might fluctuate considerably, especially for models with low drag/displacement ratio and large displacement.

#### ■ In such cases, we need at least ten oscillations in the time series.

#### ■ We must make sure to leave out the transient part of the time series, which is due to the acceleration.



\* Reference: MARIN, Stadt Towing Tank  
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## Classifications of Model Test (3/9)

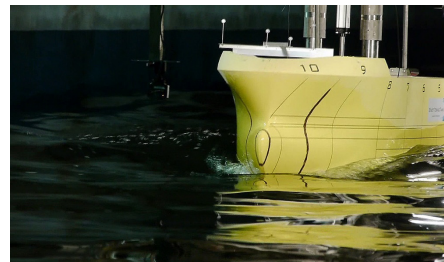
### ☑ Self Propulsion Test

#### ■ 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 ( $n_M$ ), Sinkage (Fore/Aft)



\* Reference: MARIN, Stadt Towing Tank  
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## Classifications of Model Test (4/9)

### ☑ Self Propulsion Test (continued)

#### ■ Test procedure (Continental method)

- The model is accelerated to wanted speed with its own electric motor (self propulsion).
- Propeller RPMs are adjusted so that the model is getting the same speed as the carriage, and then the model is released.
- Measurement is made with found RPMs for at least 10 seconds.
- Average values of the measurements for the period of constant speed is calculated.

#### ■ Test procedure (British method)

- The model is accelerated to wanted speed with its own electric motor (self propulsion).
- Propeller RPMs are set to constant value (the model speed can be different from the carriage speed).
- Applied towing force is measured.
- The test is repeated with other values of propeller RPMs (at least three values).
- Values of thrust, torque, and RPMs for correcting towing force are found by interpolation.

#### ■ Pros and Cons of British method

- Re-analyses with other towing force values are possible.
- Availability of propeller over- and under-load results
- More time consuming

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## Classifications of Model Test (5/9)

### ☑ Propeller Open Water (POW) Test

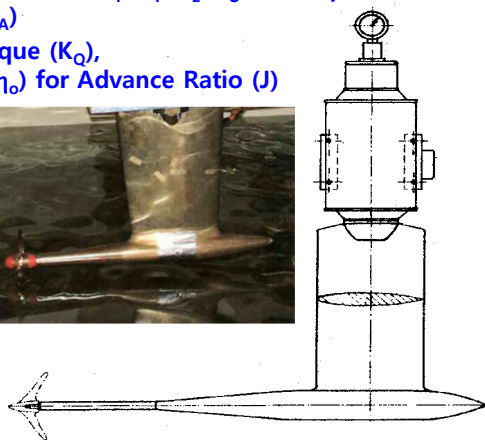
- This test is carried out under ideal condition in which the propeller does not get disturbed by the hull.

- 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 ( $\eta_D$ ) for Advance Ratio ( $J$ )



Water speed  
(Uniform flow,  $V_A$ )



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## Classifications of Model Test (6/9)

### ☑ Propeller Open Water (POW) Test (continued)

#### ■ Test procedure

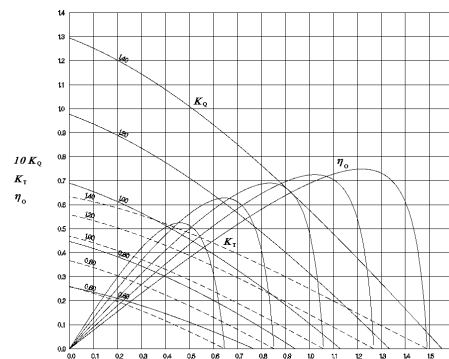
- Propeller RPMs are kept constant.
- Carriage speed (water speed) is varied in steps from zero speed to zero propeller thrust.
- Tests are performed at same RPMs as expected for design speed in self propulsion tests.
- Tests might be repeated at higher propeller RPMs (attempted full scale condition).
- Results are presented in non-dimensional form.

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_p^4}$$

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D_p^5}$$

$$J = \frac{V_A}{n \cdot D_p}$$

$$\eta_o = \frac{J \cdot K_T}{2\pi \cdot K_Q}$$

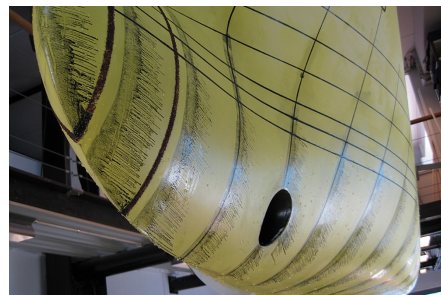
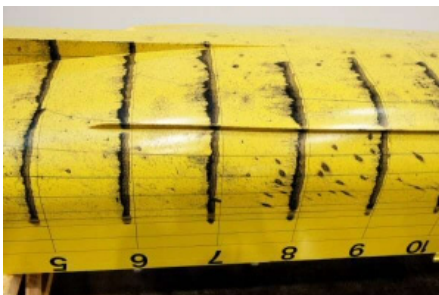


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## Classifications of Model Test (7/9)

### ☑ 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.



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## Classifications of Model Test (8/9)

### ☑ Cavitation test

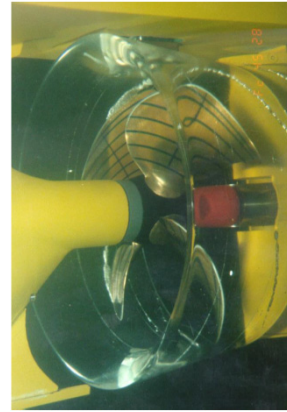
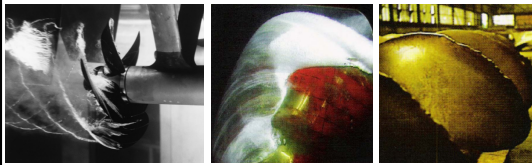
- This test is performed to investigate cavitation induced erosion of propeller blades, effect of cavitation on propulsion efficiency, vibrations, and noise

- **Given: Propeller Dimensions ( $D_p$ ,  $P_i$ ,  $A_E/A_{O_i}$ ,  $z$ ), Propeller RPM ( $n$ ), Tunnel Water Speed (Speed of Advance,  $V_A$ )**

- **Find: Pressure pulse, Propeller noise**

#### ■ Test types

- Cavitation observation
- Pressure pulses
- Noise measurements
- Cavitation erosion



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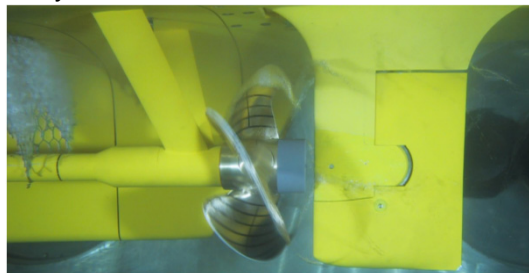
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## Classifications of Model Test (9/9)

### ☑ Cavitation test (continued)

#### ■ Test procedure

- Choose water speed in test section according to actual advance ratio ( $J$ ).
- Install aft-body model and adjust wake field by mesh screens.
- Install propeller model.
- With atmospheric pressure in the tunnel, adjust propeller RPM (and/or water speed) until the propeller torque is correct according to the self propulsion test in the towing tank (equal  $K_Q$ ). This is called the "torque identity" principle.
- Keeping water speed and RPM constant, reduce the tunnel pressure until the specified cavitation number is achieved.
- Do necessary cavitation observation and measurements.

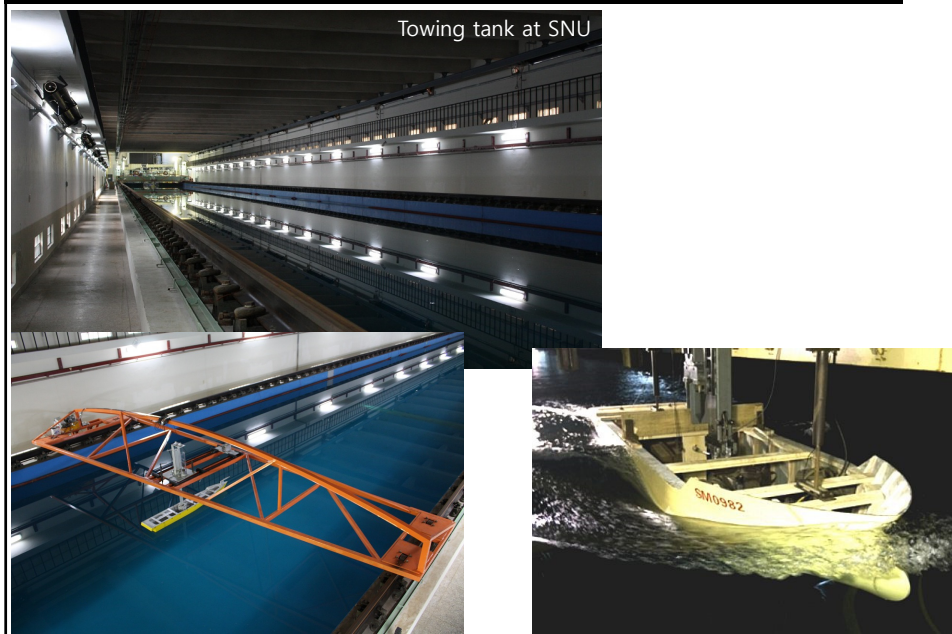


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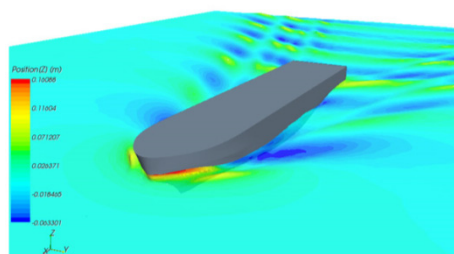


## Example of Resistance Test in the Towing Tank

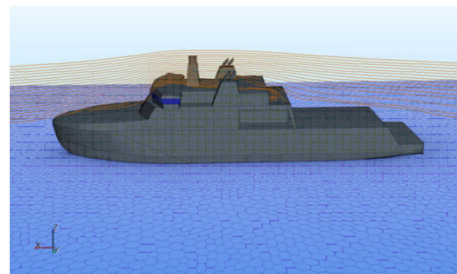


## Computational Fluid Dynamics (CFD) (1/3)

- ☑ 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

## Computational Fluid Dynamics (CFD) (2/3)

### ☑ Procedures for CFD

#### ■ Preprocessing

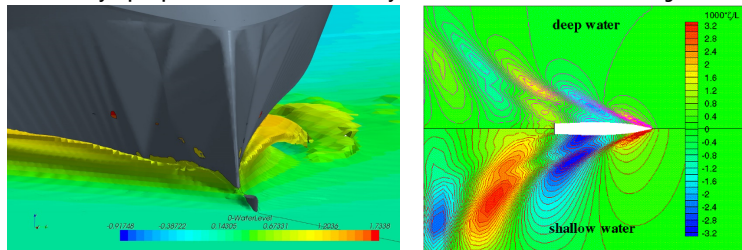
- The geometry (physical bounds) of the problem is defined.
- The volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or non-uniform.
- The physical modeling is defined – for example, the equations of motion + enthalpy + radiation + species conservation
- Boundary 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.



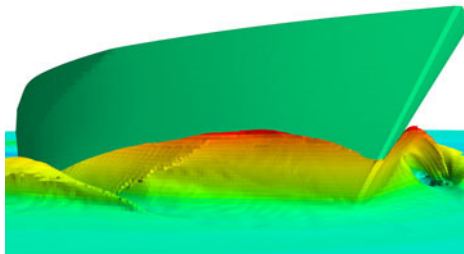
\* Reference: Stadt Towing Tank, Ship and Ocean Industries R&D Center in Taiwan  
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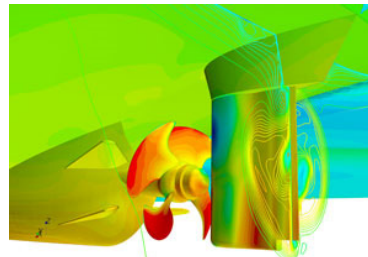
## Computational Fluid Dynamics (CFD) (3/3)

### ☑ 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  
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## 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

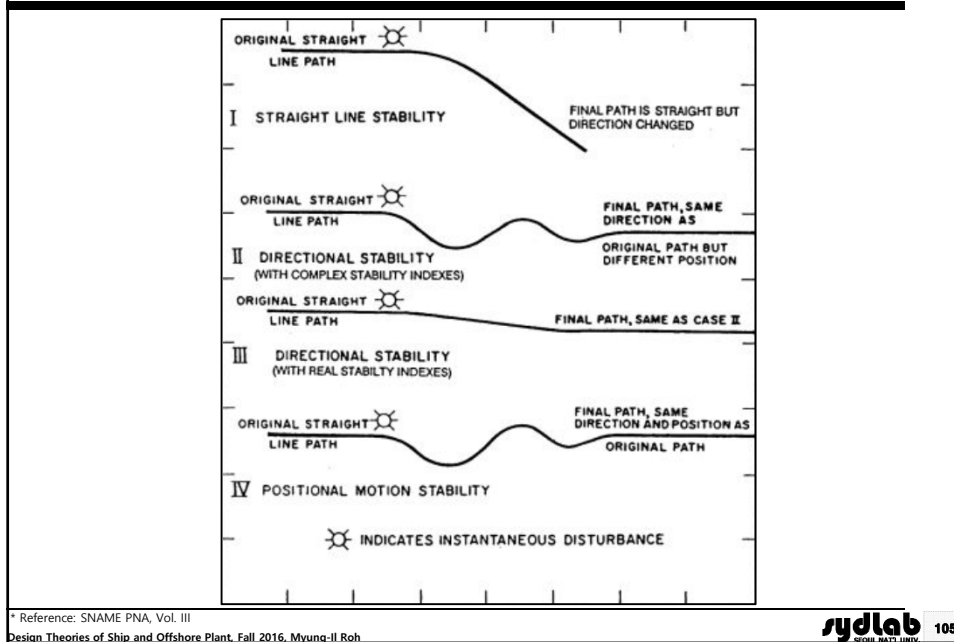
- ☑ Regression Analysis Results from Similar Ships (Semi-empirical Methods)
- ☑ Theoretical Prediction Methods
- ☑ Model Tests (Experiments with Scale Models)
  - Straight line test
  - Rotating arm test
  - Planar Motion Mechanism (PMM) test
  - Free running (radio controlled) model test
- ☑ Full Scale 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                          |
|--|---|--------------------|-----------------------------------|--|
| <i>Required for Optional Class Notation</i>                  |   |                    |                                   |  |
| Turning Ability  | Tactical Diameter                                 | Turning Circle     | $TD < 5L$                         | Rated<br>$Rtd \geq 1$                          |
|  | Advance   |                    | $Ad < 4.5L$                       | Not rated<br>$Ad < 4.5L$                       |
| Course Changing and Yaw Checking Ability                     | First Overshoot Angle                             | 10/10 Zig-zag test | $\alpha 10_1 \leq f_{101}(LV)$    | Rated<br>$Rt\alpha_{10} \geq 1$                |
|  | Second Overshoot Angle                            |                    | $\alpha 10_2 < f_{102}(LV)$       | Not rated<br>$\alpha 10_2 < f_{102}(LV)$       |
|  | First Overshoot Angle                             | 20/20 Zig-zag test | $\alpha 20_1 \leq 25$             | Rated<br>$Rt\alpha_{20} \geq 1$                |
| Initial Turning Ability                                      | Distance traveled before 10-degrees course change | 10/10 Zig-zag test | $\ell_{10} \leq 2.5L$             | Rated<br>$Rti \geq 1$                          |
| Stopping Ability   | Track Reach                                       | Crash stop         | $TR < 15L^{(1)}$                  | Not rated<br>$TR < 15L^{(1)}$                  |
|  | Head Reach  |                    | None                              | Rated<br>$Rts \geq 1$                          |
| <i>Recommended, Not Required for Optional Class Notation</i> |   |                    |                                   |  |
| Straight-line Stability and Course Keeping Ability           | Residual turning rate                             | Pull-out test      | $r \neq 0$                        | Not rated<br>$r \neq 0$                        |
|  | Width of instability <sup>(2)</sup> loop          | Simplified spiral  | $\alpha_{cr} \leq f_{\alpha}(LV)$ | Not rated<br>$\alpha_{cr} \leq f_{\alpha}(LV)$ |

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

## Types of Straight Line Stability



## 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.

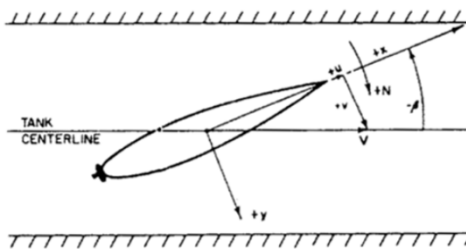
## Model Tests

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

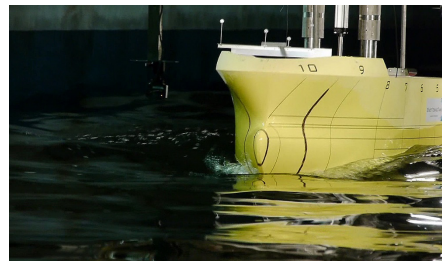
☑ **Types of Model Tests**

- Straight line test
- Rotating arm test
- Planar Motion Mechanism (PMM) test
- Free running (radio controlled) model test

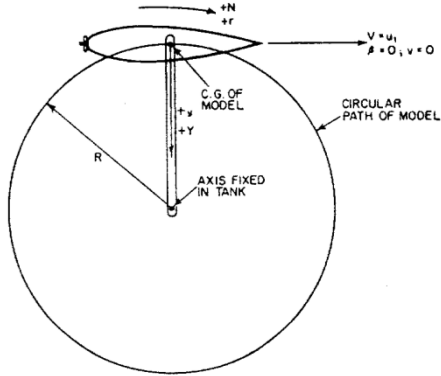
## Model Test - Straight Line Test



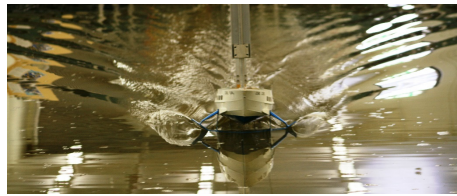
$\beta$  = Drift angle  
 $V$  = Velocity along x - axis  
 in global coordinate system  
 $u$  = velocity along x - axis in  
 ship coordinate system  
 $v$  = velocity along y - axis in  
 ship coordinate system  
 $v = -V \sin \beta$



### Model Test - Rotating Arm Test

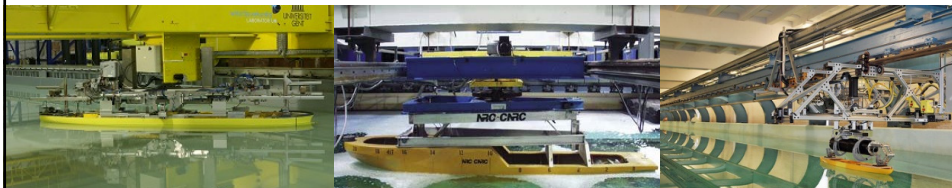
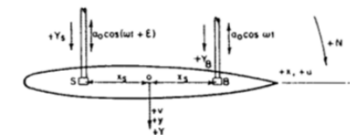
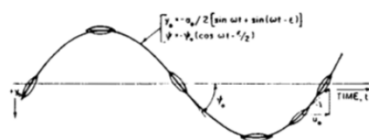
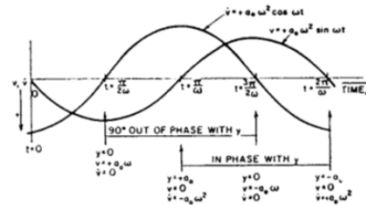
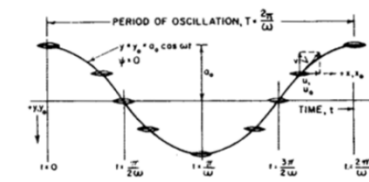


$\beta = 0$   
 $u = V$   
 $v = -V \sin \beta = 0$   
 $R = \text{Arm radius}$   
 $r = \text{angular yaw velocity} = \frac{u}{R} = \frac{d\psi}{dt}$   
 where,  $\psi = \text{yaw oscillation}$



\* Reference: Australian Maritime College  
Design Theories of Ship and Offshore Plant, Fall 2016, Mvungu-Il Roh

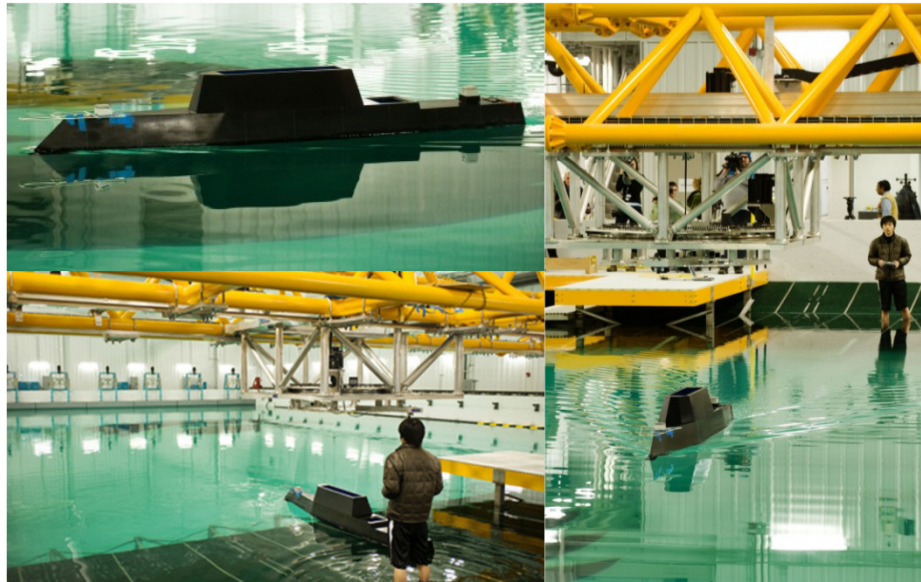
### Model Test - Planar Motion Mechanism (PMM) Test



\* Reference: Ghent University, National Research Council Canada, Davidson Laboratory at Stevens  
Design Theories of Ship and Offshore Plant, Fall 2016, Mvungu-Il Roh

## Model Test

### - Free Running (Radio Controlled) Model Test



\* Reference: University of Iowa  
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## 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

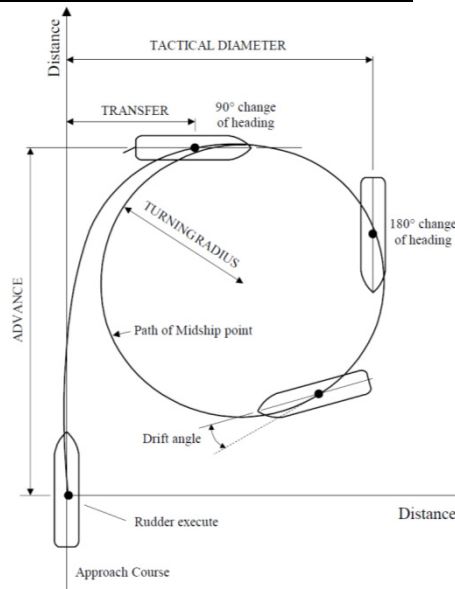
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## Standard Maneuvering Tests - Turning Circle Test

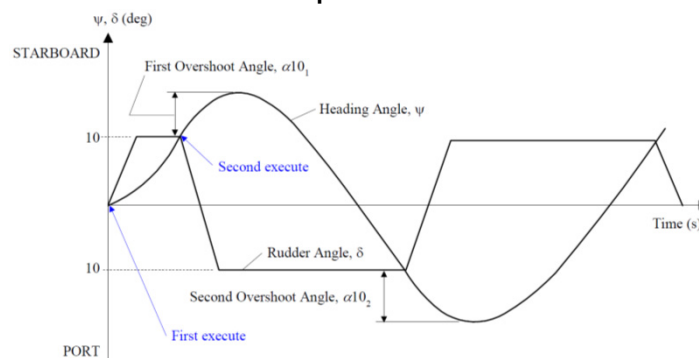
- ☑ Measure of the ability to turn the ship using hard over rudder to determine:
  - Minimum advance at 90° change of heading
  - Transfer
  - Tactical diameter: Transfer at 180° change of heading
  - Speed lost in turn
  - Max roll angle
  - Peak & final yaw rate
  
- ☑ Performed to both starboard and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



\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
Design Theories of Ship and Offshore Plant, Fall 2016, Mvung-Il Roh

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

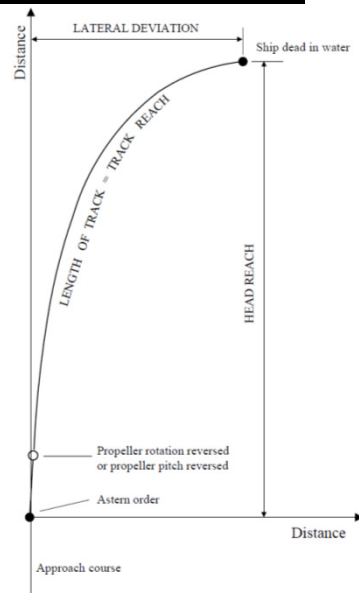
- ☑ Initial turning
  - Change of heading response to a moderate rudder control, measured using: Distance traveled before course change, Time to 2<sup>nd</sup> execute
- ☑ Course changing & yaw checking
  - Measure of the response to counter-rudder applied in a certain state of turning using heading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



\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
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## Standard Maneuvering Tests - Stopping Ability Test

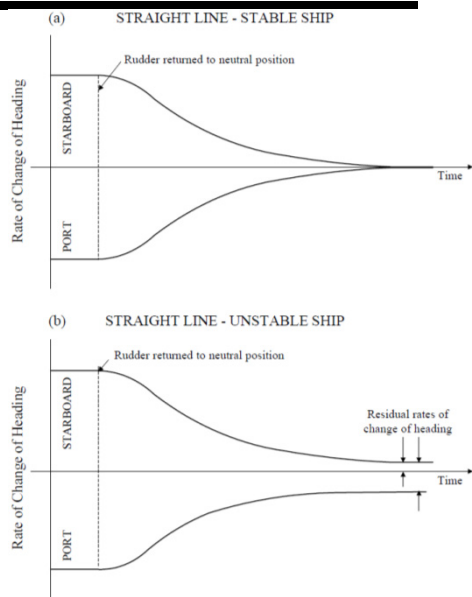
- ☑ Engine stop and full astern maneuver performed after a steady approach at test speed to measure:
  - Track reach: Distance along the ship's track that the ship covers from the moment that the "full astern" command was given until ahead speed changes sign
  - Head reach: Distance along the direction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



\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
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## 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 are used to assess whether a ship is straight line stable or not.



\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
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## Non-standard Maneuvering Tests - Simplified Spiral Test (1/2)

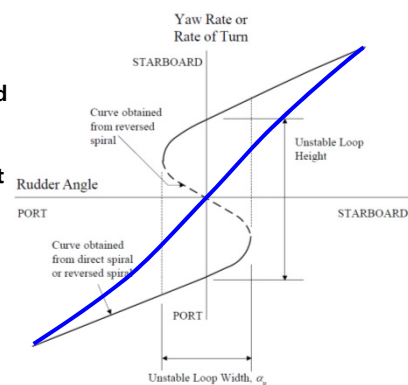
- ☑ If the ship is found to be straight line unstable by the pull-out test, one of spiral tests may also be performed.
- ☑ Direct spiral maneuver (Dieudonné Spiral)
  - The ship is brought to a steady course and speed according to the specific initial condition.
  - The recording of data starts.
  - The rudder is turned about 15 degrees and held until the yaw rate remains constant for approximately one minute.
  - The rudder angle is then decreased in approximately 5 degree increments. At each increment the rudder is held fixed until a steady yaw rate is obtained, measured and then decreased again.
  - This is repeated for different rudder angles starting from large angles to both port and starboard.
  - When a sufficient number of points is defined, data recording stops.

\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
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## Non-standard Maneuvering Tests - Simplified Spiral Test (2/2)

- ☑ Reverse spiral (Bech Spiral) test
  - The ship is steered to obtain a constant yaw rate.
  - The mean rudder angle to produce this yaw rate is measured.
  - This is repeated for several yaw rates, and the curve of yaw rate vs. rudder angle is created.
  - ◆ More rapid method than direct spiral test
  - ◆ It requires very accurate yaw rate measurement instrument.

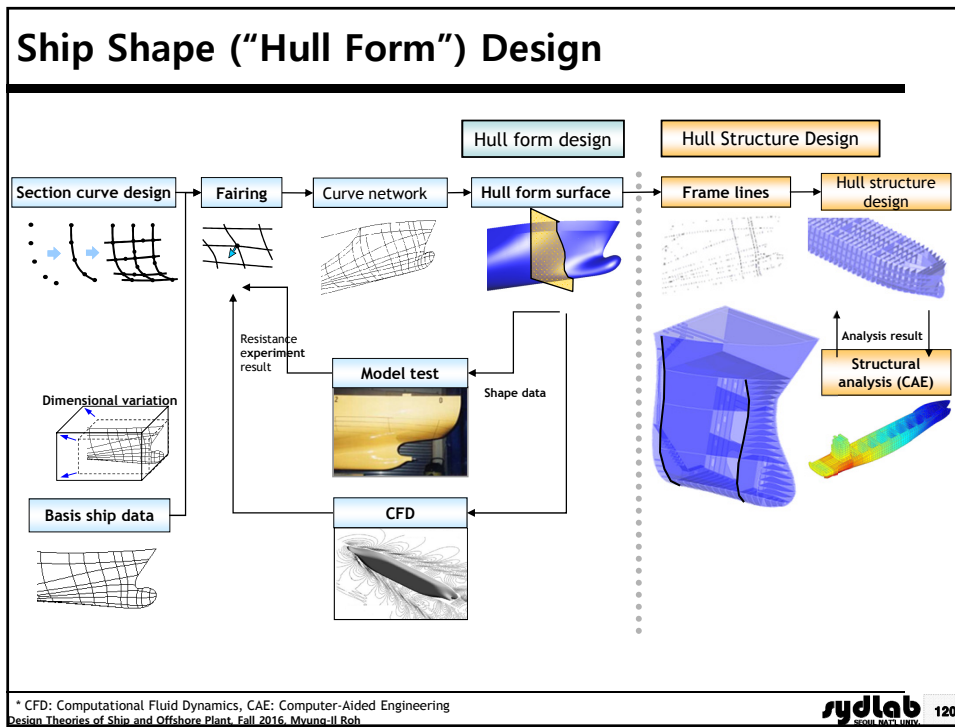


Relation between Rudder Angle and Yaw (Turn) Rate for Straight line Unstable Ship

\* Reference: ABS, Guide for Vessel Maneuverability, 2006  
Design Theories of Ship and Offshore Plant, Fall 2016, Mvung-II Roh


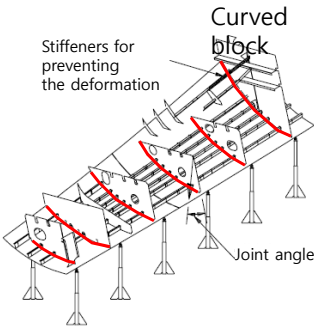
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### 3.5 Generation of Hull Form Surface



## 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.

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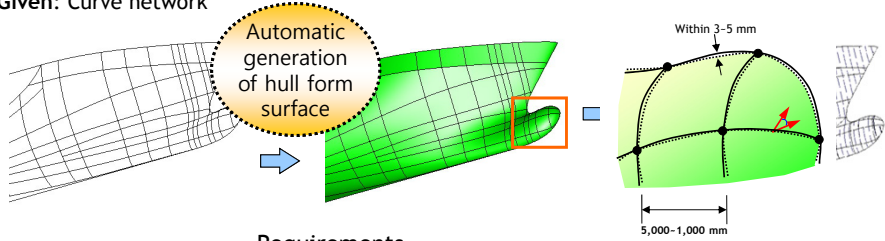
## Quality Requirement of a Hull Form Surface

Initial hull form design

Detailed design / Production design

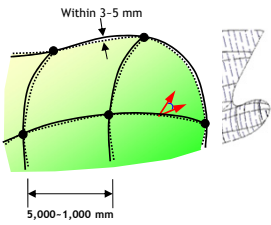
Find: Smooth hull form surfaces

Given: Curve network



Automatic generation of hull form surface

Within 3-5 mm



5,000-1,000 mm

**Requirements**

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

- 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<sup>1</sup>\*\*

- Intersection between surfaces and plane
- Validation of the fairness

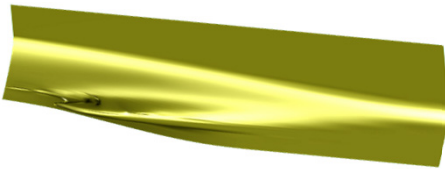
\* Acceptable tolerance in shipbuilding industry is about 3-5 mm.  
\*\* G<sup>1</sup> means geometric continuity or tangential plane continuity. IntelliShip requires exact G<sup>1</sup> hull form surfaces.

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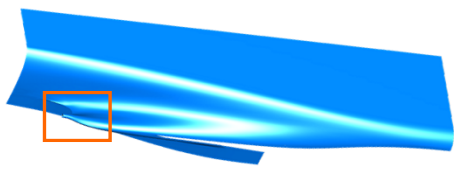
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## Hull Surface Modeling by Single Patch Approach and Piecewise Patch Approach

▪ Single patch approach



▪ Piecewise patch approach

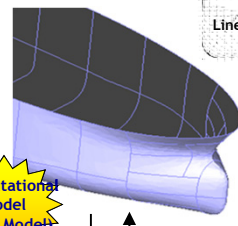


| Method       | Single patch approach   | Piecewise patch approach  |
|--------------|---|---|
| Advantage    | <ul style="list-style-type: none"> <li>Easy to represent the hull surface</li> <li>Mathematically, the 2<sup>nd</sup> derivatives are continuous at all points on the surface(C<sup>2</sup>)</li> </ul> | <ul style="list-style-type: none"> <li>Suitable for representing the complicated free form surface</li> <li>Able to represent the knuckle curve</li> </ul>  |
| Disadvantage | <ul style="list-style-type: none"> <li>A single patch approach cannot exactly represent a complex shape in the bow and stern parts and also knuckle curve.</li> </ul>                                   | <ul style="list-style-type: none"> <li>It should satisfy the complicated continuity equations for tangential plane to generate a fine hull form surface.</li> <li>It needs a special method to handle the region which is not rectangle.</li> </ul> |

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## Initial or Basic Design Stage of a Ship

**Hull form design**



Lines

Computational Model (CAD\* Model)

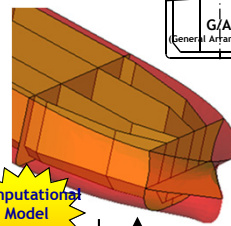
Shape data ↓

Model test

CFD\*

Resistance experiment result ↑

**Compartment design**



G/A (General Arrangement)

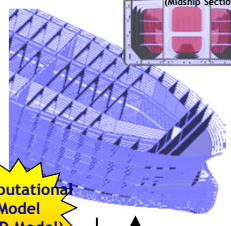
Computational Model (CAD Model)

Shape data ↓

Ship calculation

Ship calculation result ↑

**Hull structure design**



M/S (Midship Section)

Computational Model (CAD Model)

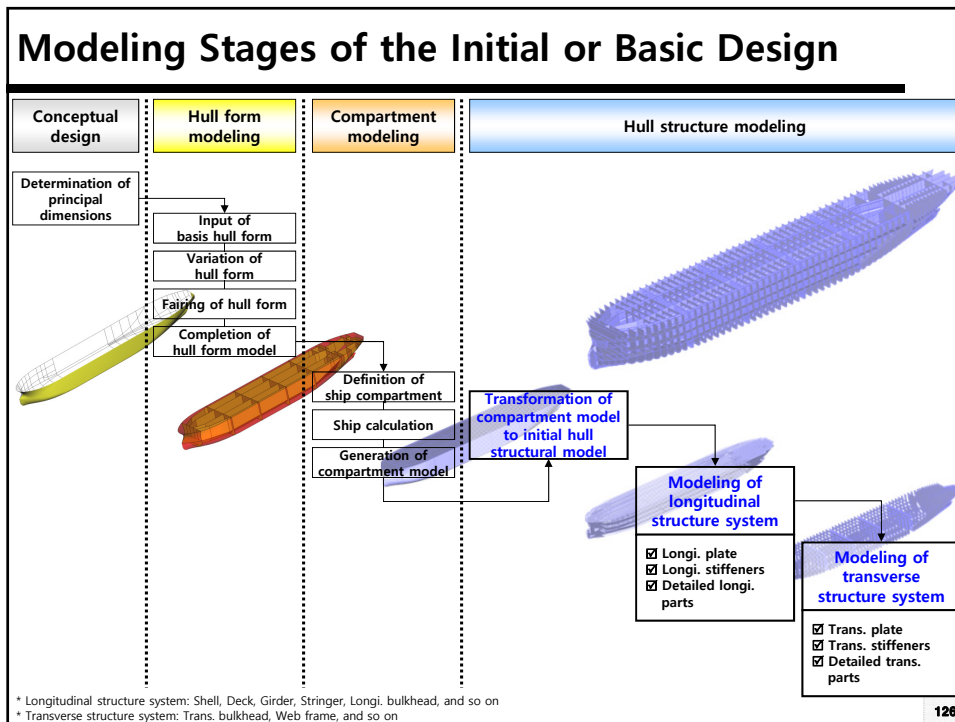
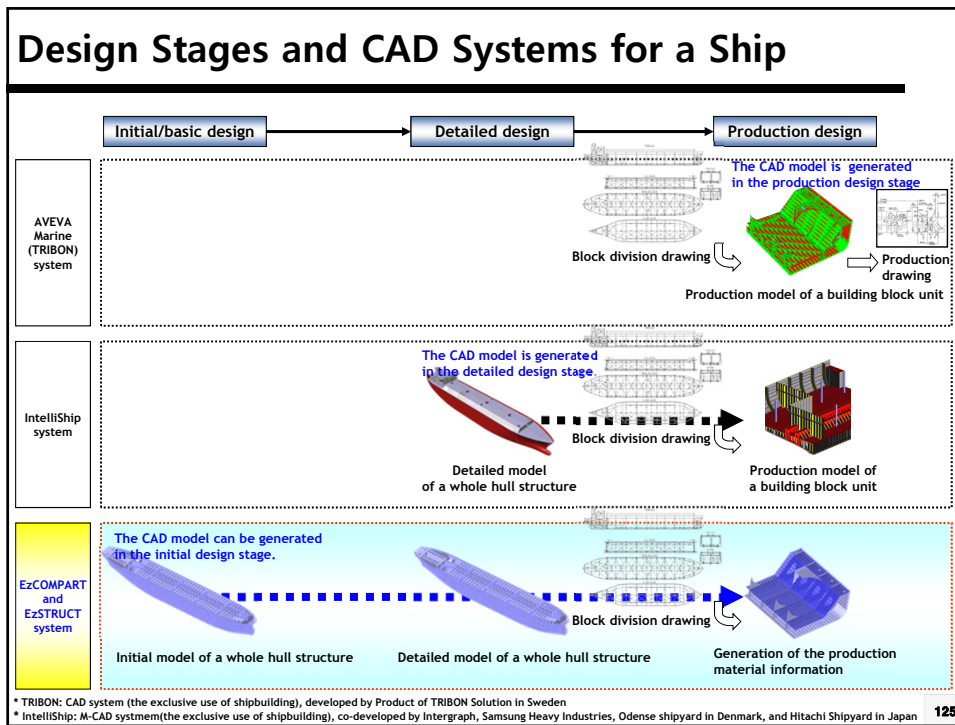
Shape data ↓

Finite element analysis

Structural analysis result ↑

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

Computer Aided Ship Design, II-1, Introduction, Fall 2013, Myung-Il Roh
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## 3.6 Appendage Design

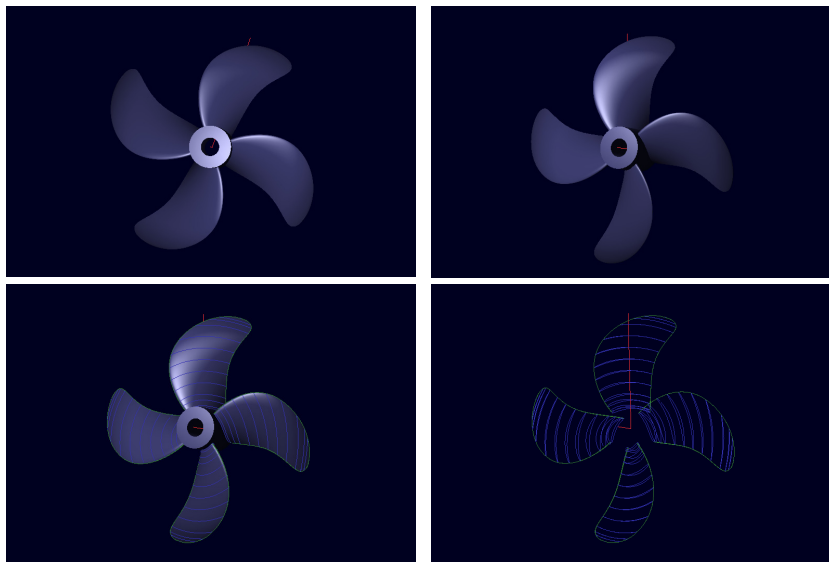
### Appendage Design - Example of a Propeller



- ☑ 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



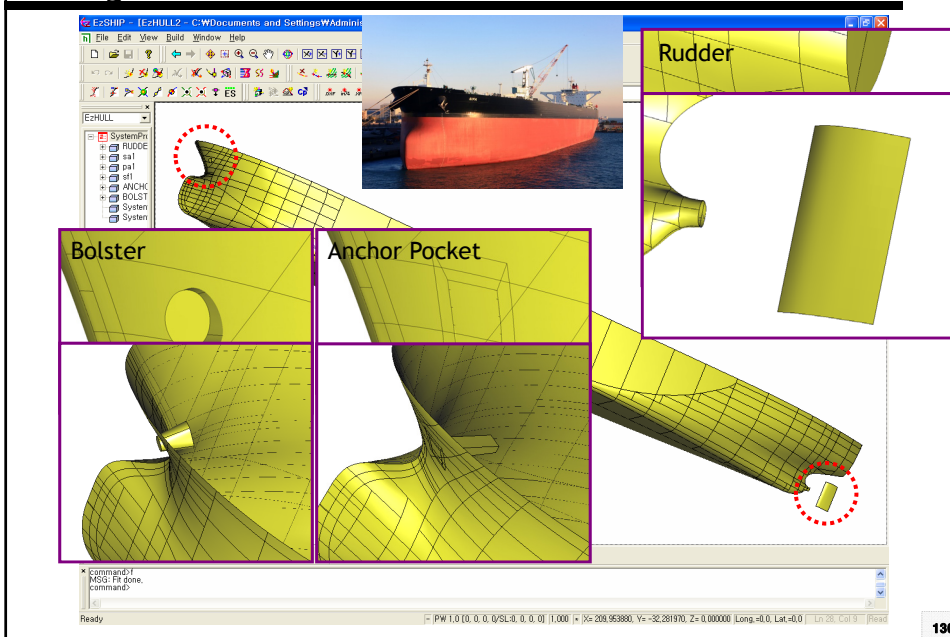
## Appendage Design - Propeller



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



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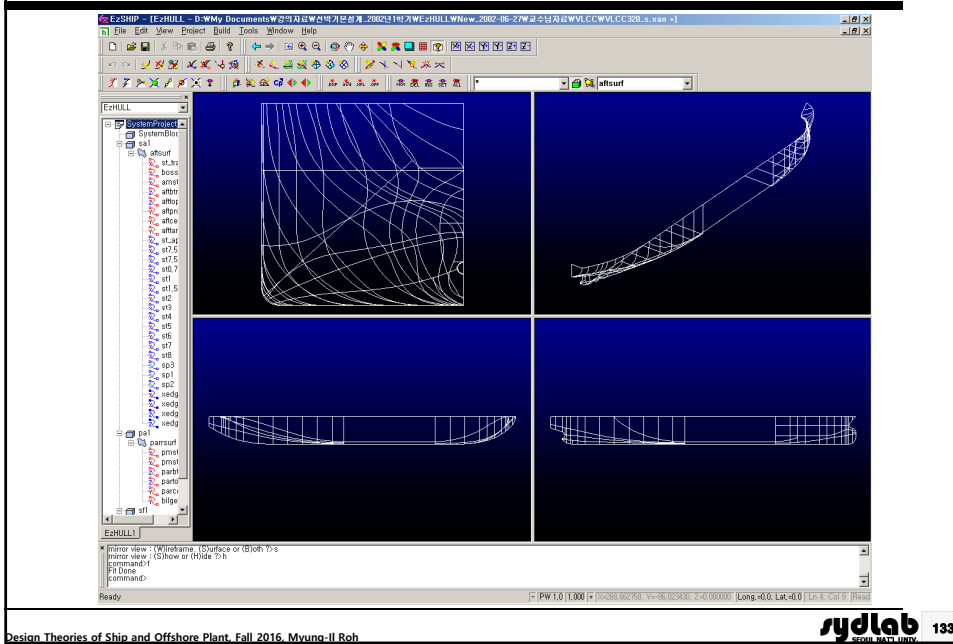
## 3.7 Examples of Hull Form Design

### Hull Form Design of a 320K VLCC

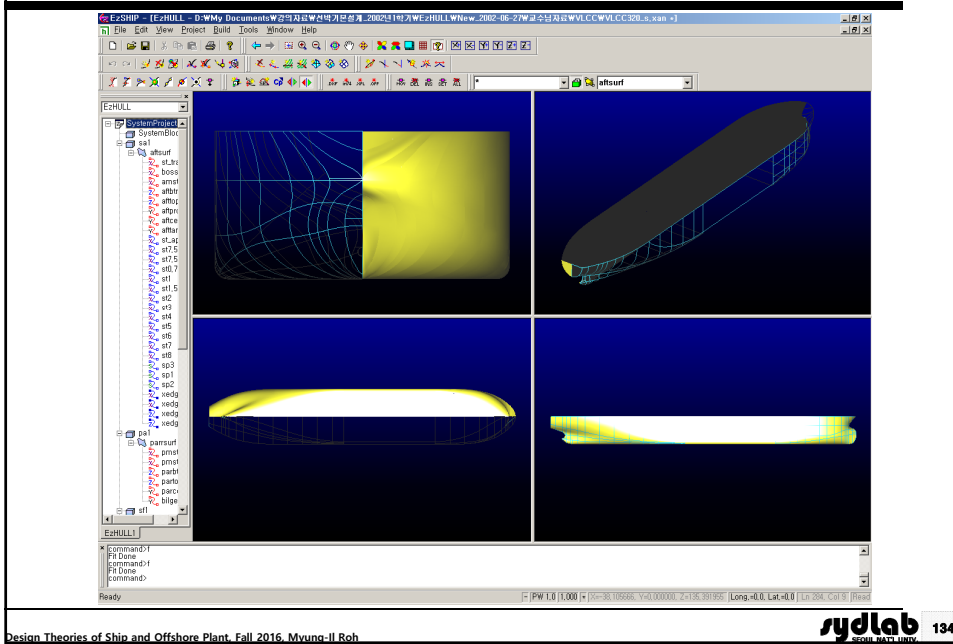
#### Principal Particulars

| 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               |        |

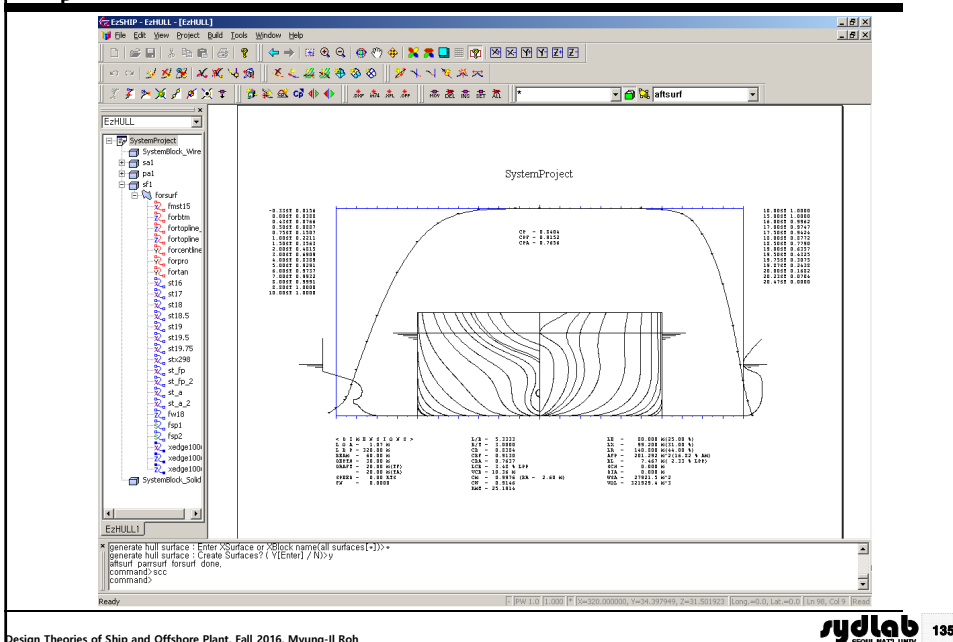
## Hull Form Design of a 320K VLCC - Wireframe Model



## Hull Form Design of a 320K VLCC - Surface Model



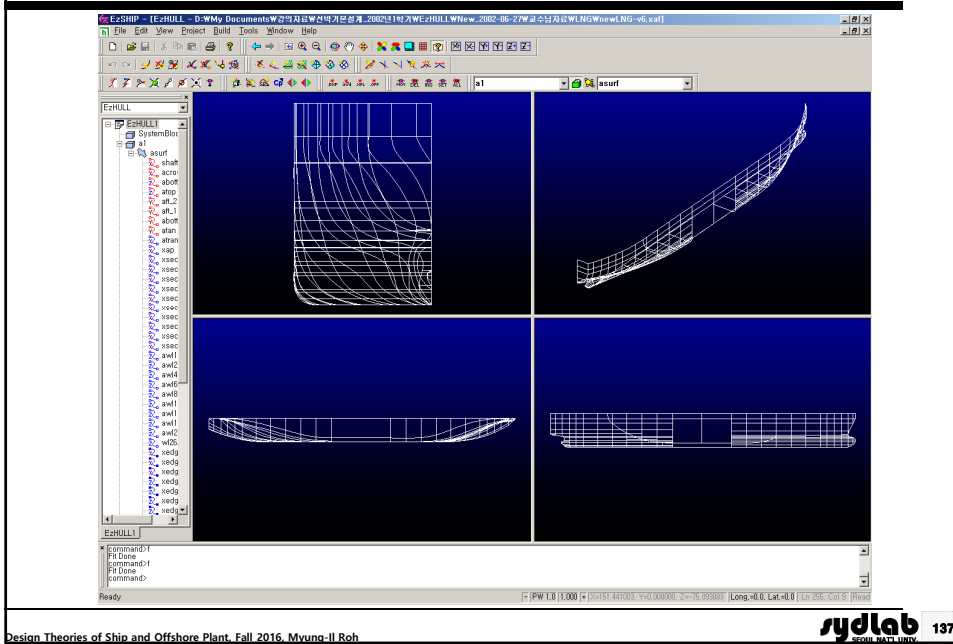
## Hull Form Design of a 320K VLCC - $C_p$ Curve



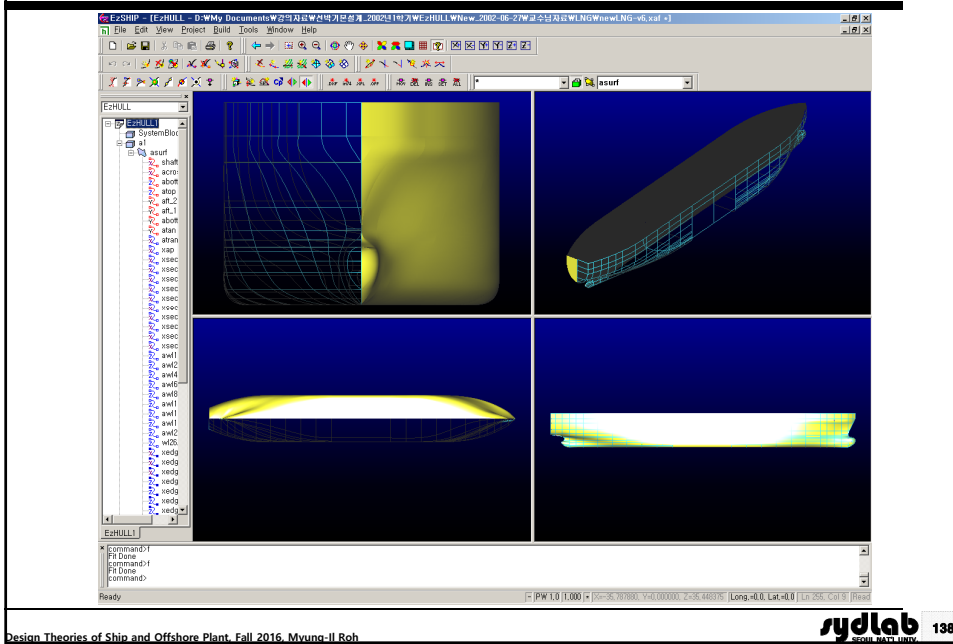
## Hull Form Design of a 145K CBM LNGC

| 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



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

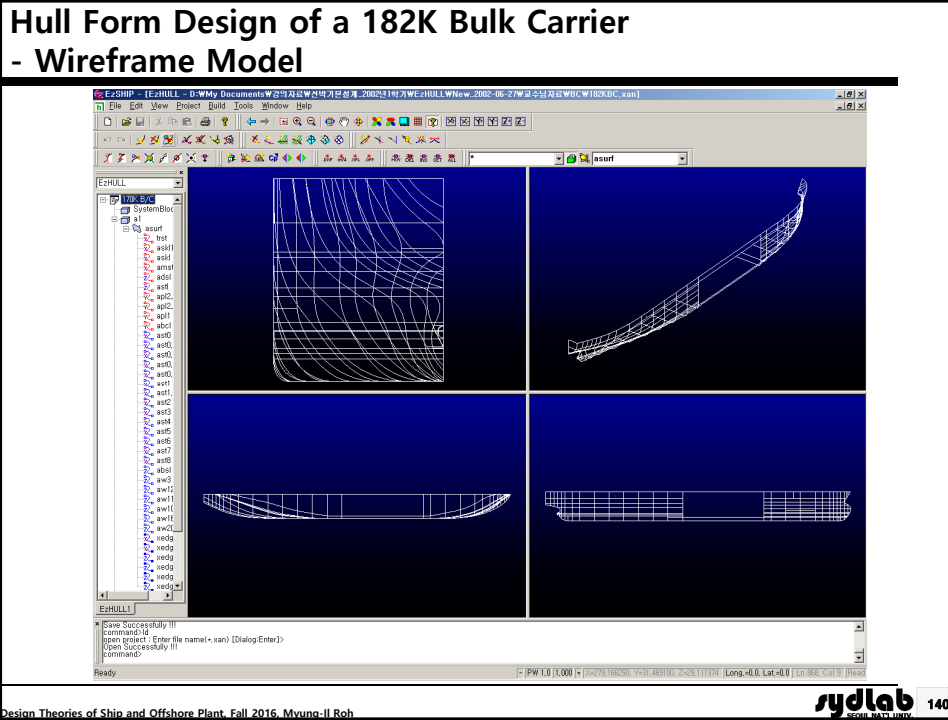


## Hull Form Design of a 182K Bulk Carrier

| 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                |       |

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

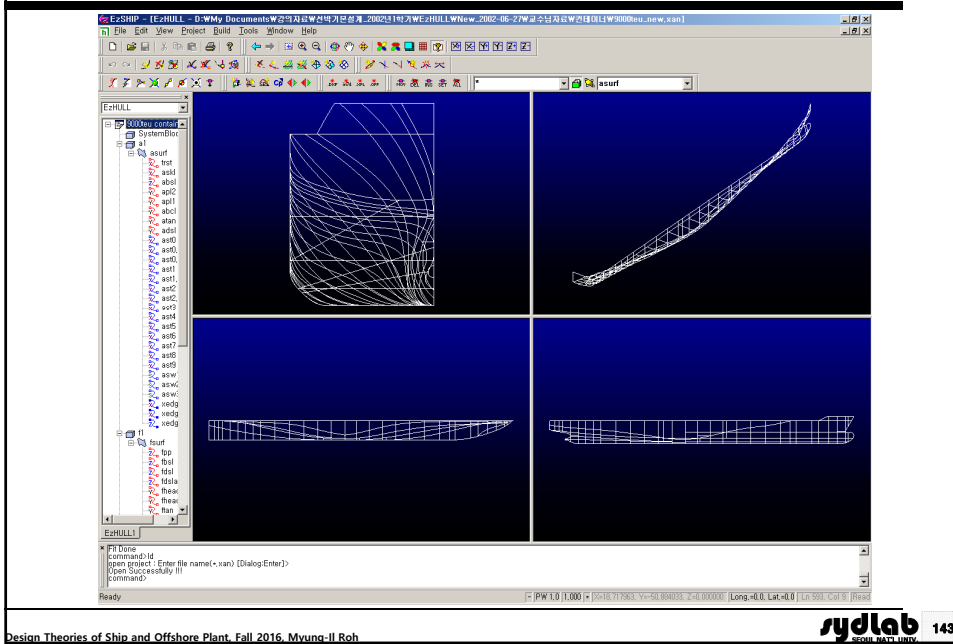
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## Hull Form Design of a 9,000 TEU Container Ship

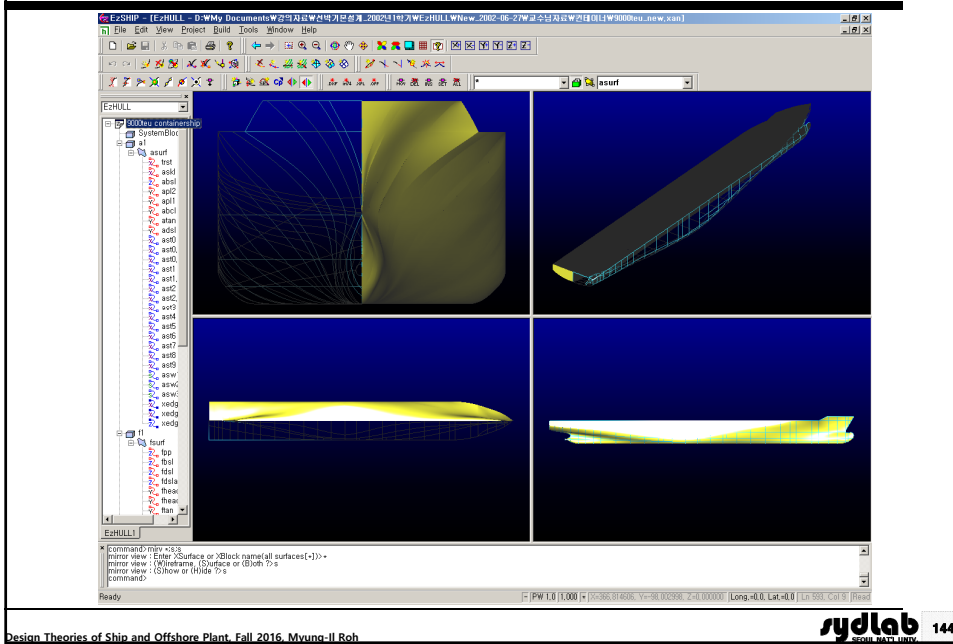
| Principal Particulars |         |                      |        |
|-----------------------|---------|----------------------|--------|
| Item                  |         | Value                | Remark |
| Principal Dimensions  | LOA     | 356.18 m             |        |
|                       | LBP     | 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               |        |

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



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





## Hull Form Design of a Container Ship

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## Hull Form Design of a Guided Missile Destroyer

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## Hull Form Design of a Submarine

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

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