# The Challenge of Very Large Container Ships – A Hydrodynamic View

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## Abstract

In this paper the past, present and future of container ship design is briefly discussed. Hydrodynamic aspects such as propulsion concepts, rudder cavitation and parametric rolling are included. Current trends in container ship design are demonstrated on the basis of model tests performed at the Hamburg Ship Model Basin (HSVA) throughout the last decades. Alternative concepts to overcome current limits in ship size and speed are given.

## Keywords

Container Ship, VLCS, Propeller, Rudder, Cavitation, Erosion, Stability, Parametric Rolling

## Introduction

Bigger, better, faster, more – these were the major trends during the last four decades of container ship design. Bigger in terms of absolute ship size, better in terms of economical ship operation, faster in terms of service speed and last but not least more in terms of container capacity. Naturally this evolution was always a cutting edge technology and a lot of research and development work was and is needed to push the limits.
The loading capacity of container ships has increased from a few hundred containers for the first full container ship to more than 8,000 TEU for the most modern vessels now in operation. Over this period of development numerous design and construction problems associated with the increasing size of the vessels and their propellers were overcome. The demand for sufficient stability, higher speeds and low vibration levels has led to new hull forms specific to this type of vessel.
What has not changed over the years is the propulsion concept consisting of a single propeller driven directly by a two-stroke diesel engine, although there was a period before the oil crisis in the 1970s which extremely fast container ships driven by gas turbines and/or two screws were built. Since the oil crisis the single screw and two-stroke diesel engine arrangement has been the optimal solution with regards to both investment cost and overall efficiency. However, with increasing ship size and speed, new hydrodynamic problems are appearing as a result of the higher propeller loading. Thus it seems appropriate to consider alternative propulsion concepts for these ships.
Container ships with higher container capacities have to sail at higher speeds than those ships with lower capacity, because they need more harbour time. This is the reason why the ship speed is of such enormous importance for large container ships.
The steady increase of the ship size leads to hydrodynamic problems which are typical for VLCS:

- <u>Ship speed:</u> the very large single screw containerships can not reach the required service speed with the available main engines.
- <u>Propeller and rudder cavitation:</u> due to the extremely high power density of the propellers they are highly loaded; this also affects the flow over the rudders.
- <u>Parametric rolling</u>: due to their hull form and absolute size VLCS are endangered by parametric rolling.

The causes of these problems are addressed and some hints are given regarding how to avoid them.
In this paper we use the acronym VLCS (Very Large Container Ship) for all Post-Panmax container ships.

## Development of Container Ships – Past and Future

In 1956 the first container line started from Port Newark to Houston, Texas with a converted World War II T2-tanker. The ship's name was "Ideal X" and she was able to carry 58 35' containers. The benefits from the much shorter loading and harbour times were so convincing that American ship owners converted more and more old vessels to carry the new kind of cargo. The first container ship without ship borne loading gear was the "Sea-Land Venture", which entered service only a few years after the "Ideal X" made her maiden voyage as a container ship.
As container shipping was invented in the USA, it is clear that the dimensions of the first containers followed American standards. Later on the ISO defined a standard container with a length of abt. 20 ft (6.058 m), a width of 8 ft (2.438 m) and a height of 8 ft (2.438 m).

This container is the basis for the world-wide used abbreviation TEU (Twenty Feet Equivalent Unit).
The success of the new transport concept was exceptional and the container ships grew very quickly in size and container capacity. In the beginning the ships were classified using the generation concept:
1st Generation with about 1,000 TEU occurred for the first time in about 1966,
2nd Generation with about 2,000 TEU occurred for the first time in about 1969,
3rd Generation with about 3,000 TEU occurred for the first time in about 1972.
For the following ships with higher container capacities the generation classification concept was no longer used. However the ships still grew and especially the geometry of the locks of the Panama channel limited the ship size. The "Panmax" container ship was born and had the following principle dimensions:

Length over all: max. 294.1 m
Width: max. 32.3 m
Draught: max. 12.0 m

Panmax container ships have a maximum container capacity of about 4,500 TEU. This limit was reached in the late 1970's. It took about one further decade before the first container ships were built which could not pass the Panama canal. These ships were consequently called "Post-Panmax" container ships. Nowadays all container ships with a capacity exceeding about 5,000 TEU are Post-Panmax ships.
Fig. 1 shows the currently world largest container ship. It is the "OOCL Shenzhen" with an official container capacity of 8,063 TEU
Generally the width of container ships is defined by the number of container stacks in the transverse direction. Thus, the width of the ships increases in steps of about 8 ft. Up till now a width of 43 m corresponding to 17 container stacks abreast has been built. In the cargo holds nine tiers of containers are stowed, while seven tiers are usual on deck. The draught increased to a maximum of about 14.5 m. Here the limiting factor is the water depth in the harbours which are economically reasonable and capable of serving the very large container ships. Only few harbours are on this list nowadays, and for future ultra large container ships the list is even shorter.


**Fig. 1: „OOCL Shenzhen", 8,063 TEU, World Largest Container Ship**

In Table 1 the main particulars are summarised for some historical container ships.
The container capacity of the largest vessels increased throughout the last decades almost constantly. The speed of growth slowed down a little between 1979 and 1988, but then in 1988 the Panmax limitations were left behind. Since that time the growth accelerated and is still getting faster. Fig. 2 shows that the first container vessel carrying 12,000 TEU can be expected to enter service not before 2015. Assuming an average growth of 170 TEU/year we will probably have to wait about 10 years longer.
Today it is likely that the size of container ships will continue to increase within the near future. Ships with a capacity of 9,200 TEU are under construction.
Furthermore, it is likely that the upcoming giant container ships will be single screw vessels. Due to economic reasons twin screw vessels are currently not competitive.

**Table 1: Main Particulars of Historical Container Ships**

| Year | Capacity [TEU] | Name | Yard | L [m] | B [m] | T [m] | V [kts] | $P_B$ [MW] |
|---|---|---|---|---|---|---|---|---|
| 1956 | 58 (35') | Ideal X | (U.S.) | (174.2) | (23.6) | ? | (18.0) | (2x ?) |
| 1968 | 730 | ELBE EXPRESS | B&V | 171.0 | 24.5 | 7.9 | 20.0 | ? |
| 1981 | 3,430 | FRANKFURT EXPRESS | HDW | 271.0 | 32.28 | 11.5 | 23.0 | 2x 20.0 |
| 1991 | 4,407 | HANNOVER EXPRESS | Samsung | 281.6 | 32.3 | 13.5 | 23.0 | 36.5 |
| 1995 | 4,832 | APL CHINA | HDW | 262.0 | 40.0 | 12.0 | 24.6 | 48.8 |
| 1996 | (6,700 ?) | Regina Maersk | Odense | 302.3 | 42.8 | 12.2 | 24.6 | 54.9 |
| 2001 | 7,506 | HAMBURG EXPRESS | Hyundai | 304.0 | 42.8 | 14.5 | 25.0 | 68.6 |
| 2003 | 8,063 | OOCL Shenzhen | Samsung | 319.0 | 42.8 | 14.5 | 25.2 | 68.6 |

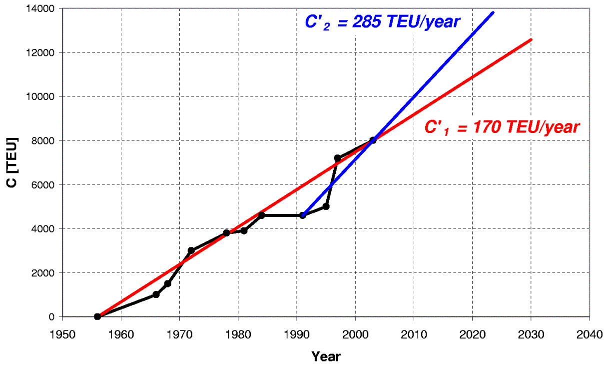


**Fig. 2: Development of Container Capacity in the Past and the Future**

The larger the container ships are, the faster they have to sail from port to port in order to maintain acceptable container line schedules and to successfully compete with smaller container ships (see Fig. 6). Nowadays the largest two stroke diesel engine with 12 cylinders offers a brake power of 68.6 MW. With this installed power it is possible to have an 8,000 TEU container ship sailing at a service speed of about 25.2 kts. Generally this speed is considered to be too low for the anticipated container service.

With increasing size of the container ships the required installed power of the main engines increases too. Table 2 gives a rough overview of the ship capacities and the corresponding required ship speeds and engine powers.

**Table 2: Single Screw, Required Speed and Power**

| Capacity [TEU] | Required Service Speed [kts] | Required Engine Power (MCR) [MW] |
|---|---|---|
| 8,000 | 25.4 | 70 |
| 10,000 | 25.7 | 82 |
| 12,000 | 26.0 | 95 |

In Table 3 the main particulars of some projects for future VLCS are summarised. Comparing these data with the data from Table 2 it is obvious that none of the projected container ships is likely to reach the required service speed. The 9,200 TEU C/V project by Samsung is the only real project in Table 3 which is being realised. This vessel is under construction and will be delivered at the end of 2005.

## The Challenge of Ever Larger Container Ships

Since more than 40 years the container capacity of container vessels has been increasing at an almost steady rate of 170 TEU/year. After the first appearance of Panmax container ships in 1988 this rate increased to currently about 285 TEU/year, Fig 2. If this rate is maintained throughout the next years the first 12.000 TEU container ship will enter service in about 10 to 15 years.

What are the reasons for this development? Of course economic reasons commonly known as economy of scale, play the major role. The larger the vessel is the cheaper is the transport of one cargo unit. Since the freight rates are independent of the ship size a larger vessel offers a higher profit than a smaller vessel.

Fig. 3 shows the transport costs for a container as a function of the container capacity of single screw container ships.

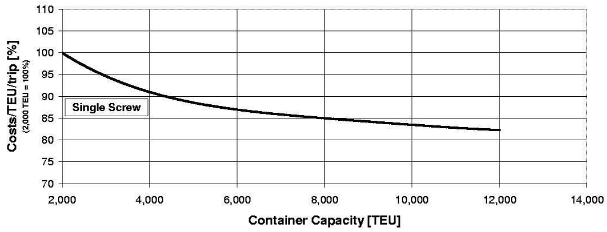


**Fig. 3: Economy of Scale, Relative Costs per TEU (Source: Stopford, 2002)**

The diagram shows that the transport costs decrease with increasing ship size.

**Table 3: Possible Main Particulars for Future ULCS**

| Capacity [TEU] | Type | Source | L [m] | B [m] | T [m] | V [kts] | $P_B$ [MW] |
|---|---|---|---|---|---|---|---|
| 8,000 | Single Screw | HDW (1996) | 325.00 | 46.00 | 13.00 | 25.3 | 68.6 |
| 9,200 | Single Screw | Samsung (2005) | 321.00 | 45.60 | 15.00 | 25.0 | 68.6 |
| 10,000 | Single Screw | HSVA | 360.00 | 50.00 | 14.00 | 25.5 | 80.0 |
| 10,000 | Single Screw | MARIN-Wärtsilä | 349.00 | 49.00 | 14.00 | 25 | 80.0 |
| 12,000 | Single Screw | MAN B&W | 380.00 | 52.50 | 14.60 | 25.5 (?) | 85.8 |
| 12,000 | Twin Screw | MAN B&W | 380.00 | 52.50 | 14.60 | 25.5 (?) | 2x 42.8 |
| 12,500 | Twin Screw | BV / K.E. Hansen | 378.00 | 54.20 | 14.50 | ? | 2x 40.0 |
| 18,000 | Twin Screw | MAN B&W | 450.00 | 60.00 | 15.70 | 25.5 (?) | 2x 51.4 |

Tozer (2001) presents in his paper similar results for very large container ships, see Table 4.

**Table 4: Costs per TEU/trip (Source: Tozer, 2001)**

| Container Capacity [TEU] | 6,800 | 8,800 | 10,700 | 12,500 |
|---|---|---|---|---|
| Single Screw [%] | 100 | 88 | 79 | 75 |
| Twin Screw | -- | -- | 85 | 80 |

The table clearly shows that, due to higher capital costs, twin screw vessels are significantly more expensive than single screw vessels.

Tozer also presents an interesting comparison of different types of costs for VLCS which shows that almost independent of the ship size about 40% of the total costs are capital costs. Further 40% of the costs are fuel costs and 20% are operating costs. Only 5% of the total costs are personnel costs.

The daily costs at sea increase to 135% for a single screw vessel with 12,500 TEU in comparison with a 6,800 TEU vessel. The daily harbour costs increase to 133%, and the container capacity is 84% higher. For this comparison the same ship speed of 25 kts is assumed for all ship sizes. The given figures are based on the prices in 2001. But with rising prices for oil the share of fuel costs as well as the advantage of the larger vessels increases.

For the whole transport chain from house to house the ship related costs are only a fraction of the total costs as the following list shows (Source: Stopford, 2002):

Container Transport Costs:

- 23% Ship (capital, fuel, operating)
- 18% Containers
- 21% Ports and Terminals
- 25% Inland Transport
- 13% Other Costs

Economy of scale only applies to the ship related costs. The other costs are independent of the ship size, and some of them rise with increasing ship size like port and terminal costs.

In Fig. 4 the specific power requirement for container ships related to the number of transported TEU for several ship speeds are given for container ships with a capacity from 2,000 TEU to 10,000 TEU. The figure shows that the specific power requirement at the same speed decreases with increased ship size. E.g. a 4,000 TEU ship requires about 8.7 kW/TEU at a ship speed of 25 kts. A 10,000 TEU ship only requires about 5.7 kW/TEU at the same speed. Taking into account the required ship speeds as shown in Fig. 6 the corresponding figures are 8.0 kW/TEU and 6.5 kW/TEU. This is a reduction of the required specific power by about 20%.

Due to the extreme cut back of the transport costs caused by the growth of transoceanic container vessels the transport of a container e.g. from Far East to Europe by ship is cheaper than the transport of the same container from the harbour to the addressee. This is one reason why it is possible to produce goods world wide at that place with the lowest production costs. Thus it is one of the important basic factors for the globalisation of the world's economy.

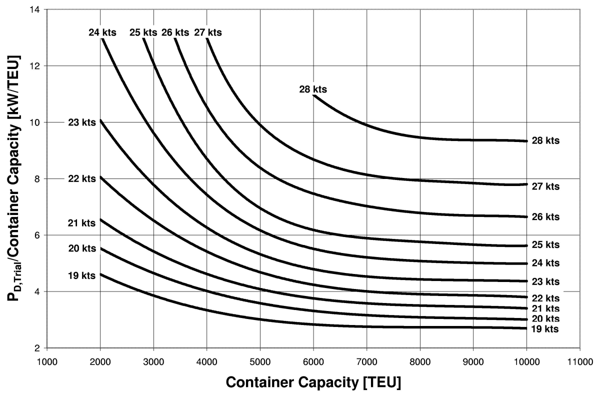


**Fig.4: Specific Power Requirements for Container Ships**

## The Speed Problem

Container ships with higher container capacities have to sail at higher speeds than those ships with lower capacity, if they want to be competitive. The reason is simply the longer time in the harbour which is needed to load and unload the high number of containers. This is the reason why the ship speed is of so enormous importance for large container ships. Container ships carrying more than 6,000 TEU have to sail with service speeds of more than 25 kts.

Nowadays two-stroke engines drive the propeller directly. Thus, the available most powerful main engine limits the speed of very large container ships. Currently these most powerful motors are the 12K 98MC designed by MAN B&W and the 12RTA96C designed by Sulzer. These motors have shaft speeds of 94 rpm, 102 rpm or 104 rpm. The twelve cylinders of these motors develop a brake power of 68,640 kW.

During service not the theoretical maximum power (MCR) is available at the propeller, but a much lower power. The example in Table 5 shows that during sea trials only about 74% (with 20% sea margin) of the installed engine power is taken into account at the propeller for the determination of the service speed.

The calculation of the maximum available power at the propeller during sea trial (contract power) depends on the selected sea margin. Most often a sea margin of 15% is used for large container ships. But ship owners who operate the ships themselves often use a sea margin of 20% in order to ensure that the schedule can be maintained. In the example given in Table 5 the power available during sea trial is calculated with 15% sea margin (yard's point of view) and 20% sea margin (ship owner's point of view) for the currently most powerful main engines.

**Table 5: Exemplary Calculation of the Contract Power $P_D$**

| | | | |
|---|---|---|---|
| MCR | 68,640 kW | | $P_{B\ max}$ |
| NCR (e.g. 90% MCR) | 61,780 kW | | $P_B$ |
| Shaft Losses 1% (-620 kW) | 61,160 kW | | $P_{D\ service}$ |
| Sea Margin | 15% | 20% | |
| Contract Power (Trial) | 53,180 kW | 50,970 kW | $P_{D\ trial}$ |

Fig. 5 presents the required ship speed and the corresponding required delivered power as functions of the container capacity of single screw container ships. It also shows that due to the limited available power of the main engine nowadays only container ships with about 7,800 TEU (owner's view) or 8,300 TEU (yard's view) can be operated with the required ship speed. Larger vessels cannot sail fast enough to offer a competitive container line service until more powerful main engines are built and become available.

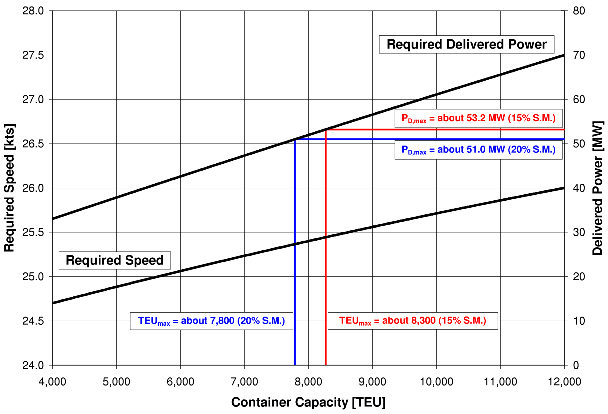


**Fig. 5: Required Speed and Delivered Power for Trial Conditions (20% sea margin)**

Fig. 6 shows the attainable speed with the currently most powerful main engine as well as the required speed according to Fig. 5 for container ships with a capacity from 4,000 TEU to 12,000 TEU.

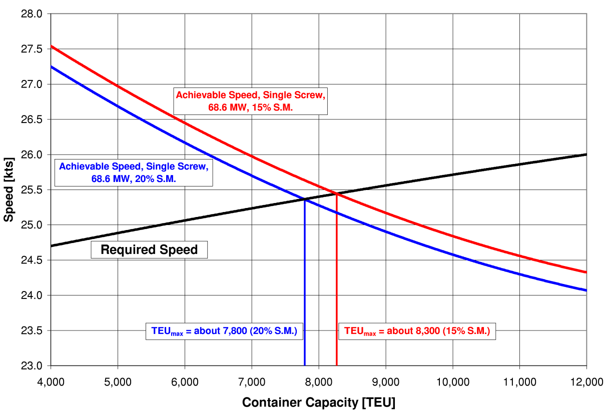


**Fig. 6: Required and Achievable Speed for Single Screw Container Ships with the Most Powerful Main Engine (MCR = 68,640 kW) Currently Available**

## Possible Solutions of the Speed Problem

Nobody is able to predict the future, but with knowledge about history it is possible to identify trends which might extend into the future.
Within the last 10 years the capacity of a single container ship increased by about 30% from 6,000 TEU to more than 8,000 TEU. Nowadays the motor required to drive a single screw container ship with 10,000 TEU at a speed of more than 25 kts is not available. But the past has shown that the limits have been continuously pushed towards higher power levels.
Up till now the problems were solved by extensive optimisation of ship lines, propeller efficiency and ship/propeller/rudder arrangement. But vessels larger than 8,000 TEU can not achieve the required service speed with the largest engine available.
In the following sections some alternative propulsion concepts for ultra large container ships are discussed.

### *Larger Engines*

The most likely option is the development, manufacture and installation of more powerful two-stroke diesel engines.
If the main engines get more powerful the loads on the propeller and the rudders will further increase. Since propeller diameters significantly larger than 9.0 m are not feasible (due to the limited draught of the container ships) and the engine speed are too high (94-102 rpm) serious problems with propeller and rudder cavitation and erosion are expected (also see sections „Propeller Cavitation" and „Rudder Cavitation").

**Table 6: Main Particulars of Present and Possible Future Engines**

| Power [MW] | Cylinder | Length [m] | Height [m] | Mass [ton] |
|---|---|---|---|---|
| 68.6 | 12 | 24.6 | 13.6 | 2146 |
| 80.1 | 14 | 28.1 | 13.6 | 2446 |
| 102.9 | 18 | 35.1 | 13.6 | 3006 |

In Table 6 the principle dimensions of the currently largest existing main engine (MAN B&W 12K98MC) with 12 cylinders are shown together with those for engines of the same type with a higher number of cylinders. Engines of this type with 14 or more cylinders have not been built yet.
MAN B&W-Group offers an engine family with a larger bore of 1080 mm. The type 12K108ME-C develops 83,400 kW at 94 rpm.
MAN B&W Diesel AS, Copenhagen, currently develops main engines with 14 cylinders in V-configuration (type: 14V108MC/E-C). Jensen, 2004, lists a maximum power of 97,300 kW at 94 rpm. The weight is expected to be only 2631 t and would be more than 10% lower than the weight of the theoretical engine with 18 cylinders in one row.
Sulzer has developed a 14 cylinder version of their well known RTA96C two stroke main engine. This motor has a maximum continuous rating of 80,080 kW at

102 rpm (type: 14RTA96C). Motors of this type has been ordered recently.
Main engines with more than 14 cylinders seem not to be very likely nowadays. It is expected that main engines with a larger bore will be preferred.

*Single Screw – Lower Speed*

It seems that the most reasonable alternative is the reduction of the ship speed. As an example: For a speed of 20 kts a VLCS requires about 50% less power than for a speed of 25 kts, Fig. 7. However, according to the statements of ship owners this alternative is not feasible since the VLCS would not be competitive in comparison with the smaller container ships.
Nonetheless the authors think that a significant increase in the cost for fuel oil would result in the realisation of this variant.

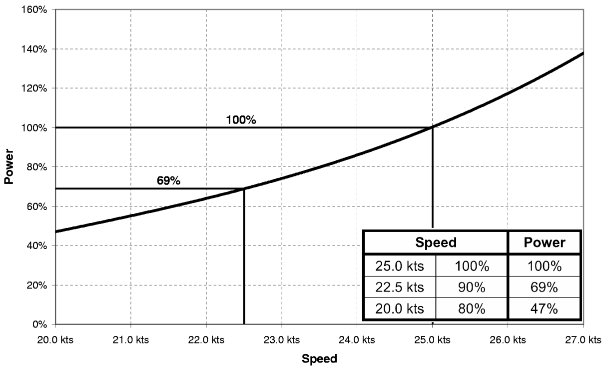


**Fig. 7: Speed and Power of a VLCS**

*Twin Screw*

If the trend to higher container capacities is maintained, the twin screw container ship will be chosen. Due to the higher investment costs a twin screw container ship can only be operated economically nowadays if it can carry more than 12,000 TEU. The ships of this type will be very wide (B > 50 m) in order to be within the limits for the draught. Twin skeg arrangements are investigated with propulsion efficiencies as good as or better than single screw arrangements. A VLCS with more than 12,000 TEU, a service speed of 26 kts and a limited draught necessarily will be a twin screw vessel since the propeller load will be too high for only one propeller.

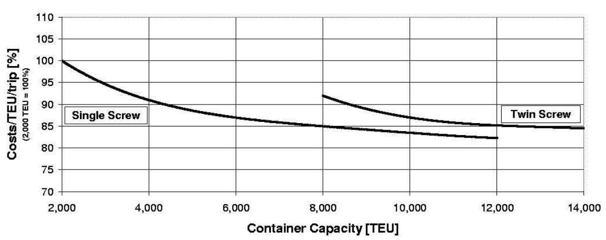


**Fig. 8: Economy of Scale, Relative Costs per TEU Twin Screw/Single Screw**

Fig. 8 shows the costs per TEU and trip as function of the container capacity of the ship. The twin screw is more expensive anyway because of higher building costs.

An example of a body plan for a twin skeg container ship with a capacity of 12,500 TEU is shown in Fig. 9.

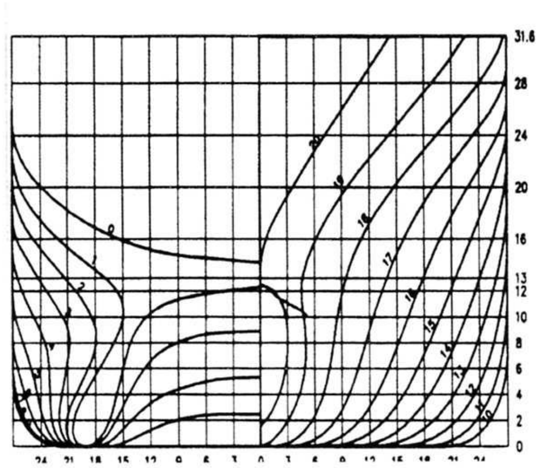


**Fig. 9: Possible Hull Lines of a 12,500 TEU Twin Screw VLCS (Source: Zamburlini, 2003)**

*Pod behind Main Propeller*

Another possibility to increase the power for a “single screw” ship is the installation of an additional electric pod drive behind the main propeller (instead of the rudder). Presently pod drives with up to 22 MW are available. Fig. 10 shows such an installation with contra-rotating propellers in a model which was tested at HSVA. The tests proved that this configuration is very efficient in terms of power consumption. However, the cavitation test with the whole model in HSVA’s HYKAT showed that the pod drive is endangered by cavitation and erosion can be expected. Especially since the pod drive is used to replace the rudder and keep the ship on course, it will be exposed to oblique flow with continuously changing angles and fluctuations in the main propeller slip stream.

**Fig. 10: Pod Drive Behind Main Propeller**

Furthermore, high investment costs for the installation have to be considered.

### *Pods as Booster*

Instead of the installation of one pod drive behind the main propeller, the next alternative is characterised by the installation of two fixed pod drives of maximal 2 x 22 MW aside of the main propeller, see sketch in Fig. 11.

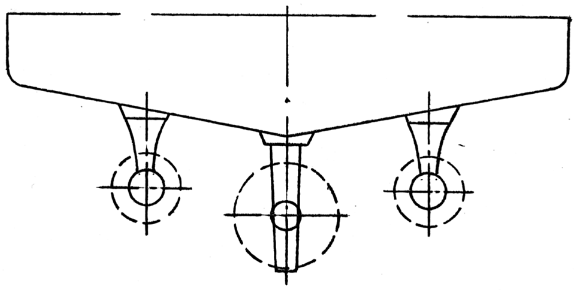

**Fig. 11: Two Pod Drives in Addition to the Main Propeller**

This configuration results in a triple screw vessel with a separate rudder, for which the investment costs are considered to be higher than for a conventional twin screw vessel. Nonetheless this concept could be a reasonable solution for the conversion of an existing single screw vessel.

### *Power Take-In (PTI)*

Another possibility to increase the available power for a single screw vessel is the installation of an additional generator set. The power of this unit is driving an electric motor connected to the shaft line. Such power-take-in arrangements have been installed during conversion and/or speed-ups of existing vessels. Alternatively, the electric power installed for reefer containers could be used at least part time to increase the available propulsion power.
The very large engines have a valuable waste heat recovery potential of about 10% of MCR, Schmid (2004), to generate steam for a turbo generator. The generated electric power could be used for a PTI to raise the delivered power at the propeller.

## Special Hydrodynamic Problems

### *Propeller Cavitation and Erosion*

From the hydrodynamic point of view the propeller and the rudder are the most problematic elements of a very large container ship.
Fig. 12 presents the power density and tip speed of container ship propellers as functions of the container capacity. For an 8,000 TEU vessel the power density is about 1,100 kW/m². The corresponding tip speed is about 44 m/s. These values are extremely high and require a very careful design of the propeller as well as of the rudder, which is situated in the slip stream of the propeller.

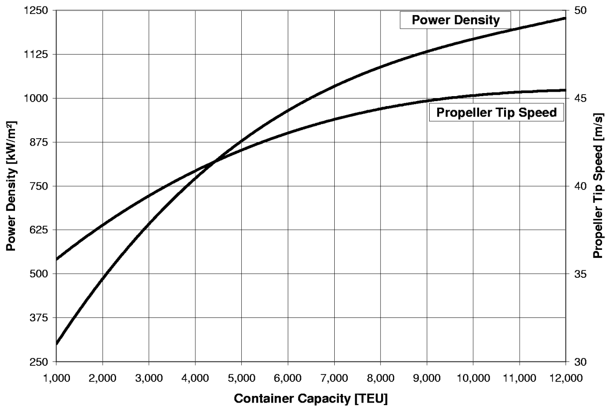


**Fig. 12: Power Density and Propeller Tip Speed for Container Ships (Courtesy of MMG)**

The largest realised propeller diameter for VLCS is about 9.3 m. Fixed pitch propellers are in use exclusively. The number of propeller blades increases for larger ships and delivered powers. Nowadays six bladed propellers for VLCS are state-of-the-art. In order to manage the high delivered powers a blade area ratio of about 90% is required.
One of the limiting factors for the size of the propeller is the casting weight which definitely exceeds 100 t for a 9.0 m propeller. Another limit is set by the draught of the container ships which is usually a maximum of 14.5 m (scantling draught) for container ships with more than 6,000 TEU. The demand for high propeller efficiency, acceptable pressure pulses and the absence of erosive cavitation lead to new and sophisticated propeller blade geometries.
Propeller cavitation is not a special problem of very large container ships alone. But due to the very high power density the propellers of VLCS are more endangered by cavitation than those of smaller container ships. That is why a wake field focused design of the aft body is essential for VLCS.
Fig. 13 shows typical cavitation erosion caused damage of a propeller blade of a container ship.

**Fig. 13: Propeller Blade with Erosion Damage**

### *Rudder Cavitation and Erosion*

Not only the very large container ships themselves and their propellers are huge, but also the rudders are incredibly large. The movable part of the most commonly used semi-balanced rudders is up to 12 m high and often more than 7 m long. Due to the high ship speed and the enormous amount of energy transmitted from the propeller to the water, the rudders are put to a high risk for cavitation even at small rudder angles. These small rudder angles occur very often during service, since small course corrections are required to keep the ship on track. Thus the rudders are highly endangered from cavitation induced erosion. Erosive damages often occur after the first voyages, see Fig. 14. In the last years the number of rudder cavitation investigations in HSVA’s HYKAT facility has increased significantly, Fig. 15. These tests prove that the rudder cavitation problems can be minimised with a well designed rudder.

**Fig. 14: Erosion Appearances at Rudder after a Few Weeks in Service**

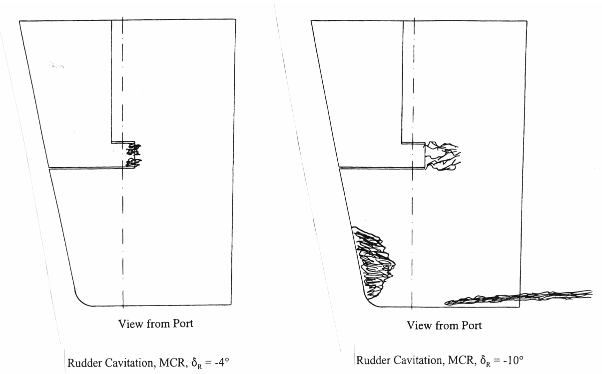


**Fig. 15: Rudder Cavitation at Small Rudder Angles**

The rudder for very large container ships cannot be built just following geometrical rules. It must be designed like a propeller. Asymmetric leading edges and special designs for all gaps in the propeller slipstream and the rudder bottom are required to avoid erosion. The latest trend is to use spade rudders which avoid by principle any gaps in the highly loaded areas. An example is given in Fig. 16.

Fig. 17 shows such a full spade rudder with asymmetric leading edge which is currently being built for a series of 8,400 TEU container vessels constructed by DSME in Korea. The first rudder of this type will enter service early in 2005.

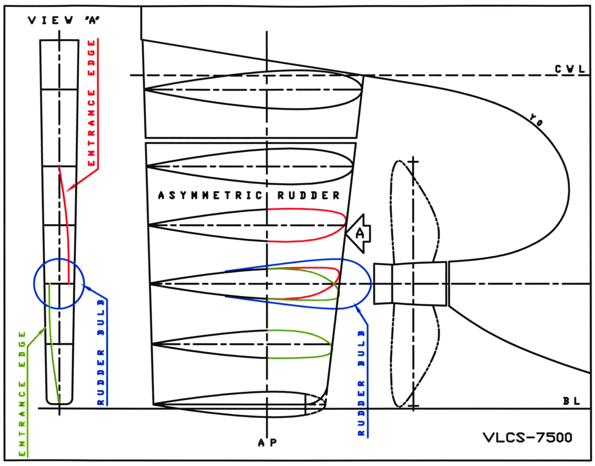


**Fig. 16: Twisted Rudder with Rudder Bulb**

Model tests at HSVA have proven that not only rudder cavitation at small rudder angles is almost completely avoided, but also the manoeuvring performance is satisfactory. Furthermore, the power consumption at design speed was reduced by about 2% as compared to a conventional semi-spade type rudder. Fitting a rudder-bulb close behind the propeller hub can additionally save up to 2% in power.

**Fig. 17: Twisted Rudder for an 8.400 TEU VLCS (Courtesy of BMS)**

### *Parametric Rolling*

Parametric roll motions may develop when the wave length of head or following seas is close to the ship length. Due to the significant changes of the ship stability (high stability in the wave trough and low stability on the wave crest, see Fig. 18) massive roll motions can be induced if the exciting period is a multiple of the ship's half natural rolling period. Under these conditions the roll motions reach the highest amplitudes. In extreme cases the ship may capsize.

In principle the phenomenon of parametric rolling applies to all ships. But very large container ships are especially endangered, since their principle dimensions nicely fit to the significant values of ocean’s waves and their extreme variations in stern waterplane on wave crest and trough. Furthermore, the container ships have very low metacentric heights, i.e. a low transverse stability.

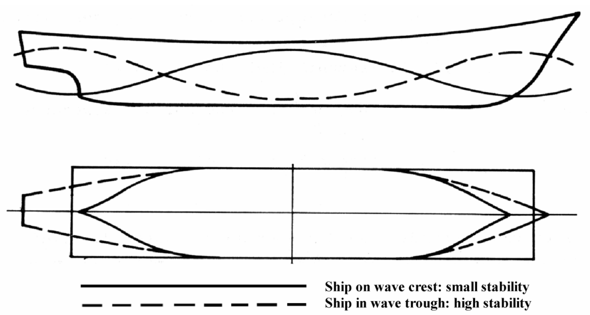


**Fig. 18: Waterplane Area on Wave Crest and in Wave Trough (Source: Schneekluth, 1988)**

Parametric rolling could be counteracted with special hull forms, especially at the ship ends, and active roll damping devices like fin stabilizers or roll damping tanks.
Furthermore, higher metacentric heights could be achieved by correct distribution of cargo and ballast water. And last but not least the risk of parametric rolling can be reduced by choosing the right course and ships speed, in time. Computer controlled systems could be very helpful.
Fig. 19 shows an example for damaged cargo due to parametric rolling.


**Fig. 19: Cargo Damages after Parametric Rolling**

Parametric rolling occurs only very seldom and has not resulted in the sinking of a VLCS yet. The reason simply is that the VLCS partly loose the containers on deck at high roll angles (up to 40 deg have been observed). The containers fall from deck into the sea, the centre of gravity hight is reduced. Consequently the stability increases and the oscillating system are in resonance no longer.

## Conclusions

- The trend for larger container vessels is expected to continue since the transport costs decrease with increased ship size (economy of scale).
- Very large container vessels require a higher service speed than smaller container vessels. However, they cannot reach such speed as single screw vessels with the currently available main engines. It is likely that in the near future more powerful main engines will be available solving the speed problem for single screw vessels with up to 10,000 TEU container capacity. Twin screw vessels will be competitive with a capacity of at least 12,000 TEU.
- The hydrodynamic problems due to the very highly loaded propellers, which are the reasons for significant propeller and rudder erosion, can be solved by new sophisticated designs for the propellers and rudders. If the main engines become more powerful new propeller and rudder related problems may arise.
- Very large container vessels are endangered by parametric rolling. Applicable measures like automatic cruise control systems and active roll damping technologies can eliminate parametric rolling almost completely.

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