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Principal Aspects of Thruster Selection

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PRINCIPLE ASPECTS OF THRUSTER SELECTION

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Preface

A propulsion system applied for dynamic positioning of vessels must be able to generate counter forces against environmental forces such as wind, current, and waves, as well as forces resulting from the drag of a deployed array, pipes, risers, etc. during stationkeeping operations. Environmental forces are omni-directional; therefore, propulsion systems or devices must have the ability to generate thrust in the full 360 degrees. In order to move the vessel from location to location, the propulsion system installed on DP vessels needs to generate the conventional propulsion forces in the longitudinal direction of the vessel.

The following report discusses several design problems which are specifically associated with the design and selection of the propulsion of dynamically positioned vessels. These problems are not encompassed by traditional Marine Engineering or Naval Architecture, and there is currently little information available regarding some of these problems.

Generally, it is far more difficult to accurately select, size, design, and predict the performance of a propulsion system intended for DP service than to do so for the propulsion system of a conventional ship.

Empirical information based on systematic model tests or exact analytical methods is not available for some of the design problem areas, and since the state of the environment cannot be controlled or manipulated by man–current and wind at various velocities and angles cannot be generated on demand–field testing is difficult.

In many aspects, the design of a propulsion system for DP applications varies from that of a conventional propulsion system. A conservative design philosophy must be used when designing a propulsion system intended for dynamic positioning. While the design objective for a conventional propulsion system places peak efficiency on or near the system’s maximum continuous rating, a propulsion system designed for DP service should be selected and sized to meet the absolute survival requirements; the emphasis of the system efficiency, however, should be placed on the system’s anticipated average power level.

1 INTRODUCTION

Basic System Requirements

In many ways, the basic requirements for thrusters used for dynamic positioning applications vary from those for propulsion devices utilized on conventional vessels.

1.1 Efficiency

The standard propulsion system found on a conventional vessel is designed and optimized for the peak efficiency at design point, i.e., the vessel service speed at full of near full power (maximum continuous rating, MCR), since this is the chief mode in which a commercial vessel works and, thus, produces revenue. A DP vessel, however, is designed to operate in and survive extreme environmental conditions, although statistically these conditions occur very rarely. The DP vessel runs at median or lower power levels during the majority of operation. Records from a number of DP drillships show a mean load of less than 40% of maximum load on the propulsion system. Therefore, a DP propulsion system should be designed for peak efficiency at lower power levels rather than at full load.

The efficiency of the thrusters is a predominant factor for the successful and economical operation of a DP propulsion system. Inefficient propulsion leads to more than just higher fuel expenditures; such inefficiency also results in logistical problems and a reduction in endurance (the number of operational days without refurbishment). The use of highly inefficient thrusters results in increased component size, weight, and, in particular, costs.

1.2 Multiple Modes of Operation

The ability to economically and successfully perform in two extremely different modes of operation is a further consideration when designing propulsion devices for DP. A typical DP vessel is outfitted with a twin main propeller arrangement for thrust in longitudinal direction during both transit and DP operation.

During DP operation, forces in transverse direction are generated by several thrusters which are installed at 90 degrees to the ships axis. The simultaneous operation of the main propellers and thrusters can create forces in oblique angles. The main propellers must be designed in such a way that they propel the vessel at service speed at full power during transit. They operate at a maximum current speed of four knots during stationkeeping operations, when the maximum power load is generally less than 50% of the power requirements for cruising mode. During stationkeeping at very low inflow velocities, the propellers' torque characteristic is very different from the characteristic at transit speed. It is very difficult for many propeller/drive machinery combinations to match their characteristics for these two modes. Other multi-mode vessels e.g., fishing trawlers, ocean-going tugs, and ice breakers experience similar problems.

1.3 Low Noise Levels

Acoustic reference systems are used for positioning control systems on the majority of DP vessels.

For successful and reliable DP operation, the prevention of any acoustic interference between the reference systems and the noises generated by the propulsion devices is mandatory.

Propeller wake acting on the bottom of the hull or cavitation on the propeller blades may result in detrimental interference problems. Emphasis must be placed on designing a propeller for cavitation-free operation. Whenever possible, the wake pattern of the propeller should stay clear of the hull. Also, in order to reduce mutual interference, the hydrophones and propellers must be strategically located.

1.4 Reliability

Reliability is one of the primary design requirements for a propulsion system intended for DP operation. A vessel may lose station as a result of a system malfunction or breakdown; such system failure may lead to damage in peripheral equipment (e.g., marine risers or other underwater gear), pollution of the environment, and even the endangerment of human lives in the case of DP diving support vessels.

The reliability of a DP propulsion system must be affirmed by an uncompromising design philosophy regarding the system and components. Components which are subjected to dynamic loads and wear–such as controllable pitch propellers, shaft bearings, shaft seals, and reduction gears–are especially affected. The access to components or their easy removal for onboard repairs should be considered when designing and installing the system and components. A typical DP vessel stays on remote locations for extended periods of time, unlike most commercial vessels; therefore, shipyard repairs and auxiliary supports (such as crane barges) may not be available or may result in extended delays of the operation.

In most cases, a control system intended for DP operations is designed as a fully redundant system. Should certain key propulsion devices fail, the system is designed to continue operation at a reduced level.

One example of a non-redundant DP propulsion system is that of a single screw tanker being converted into a DP floating production facility. Although this type of arrangement is seldom utilized, it is often proposed and discussed. Longitudinal forces are provided by the existing single propeller arrangement, whereas transverse forces are generated by several retrofitted thrusters.

1.5 Control of Thrust

The thrust generated by the individual propulsion devices for DP application must be controllable in step-less increments over the entire operating range, from zero to maximum power. In order to accomplish this, either a controllable pitch (CP) propeller or a fixed pitch propeller driven by an electric power system allowing RPM control and a match of the propeller torque characteristics over the entire range of operation must be utilized. Although it is applied in the majority of commercial vessels, the typical Diesel driven propulsion arrangement is less qualified for this DP application:

- The RPM of the engine cannot be controlled below a certain minimum RPM (engine idling RPM, approximately 40% to 50% of rated RPM).
- Increased engine maintenance problems occur when operating a Diesel engine continuously at lower power levels (lower than 50% to 60% of rated power for many engines).
- The Diesel engine is able to match the torque characteristic of the propeller only at the design point, i.e., at full rated power.

The availability of thrust in both directions is a further requirement for DP propulsion. A commercial vessel only occasionally uses reverse thrust during reversing or stopping maneuvers. Propulsion for DP must provide thrust continuously and efficiently in both directions of operation. Selection of the prime mover and/or the selection of the type of propeller is influenced by this requirement.

2 PROPULSION SYSTEM ARRANGEMENTS

2.1 General

The propulsion system for DP service must generate forces capable of keeping the vessel in position against any number of environmental forces which may attack the vessel at any angle. Also, DP thrusters usually provide the propulsion for transit (cruising) from location to location. Exceptions include vessels which use different systems for each propulsion task, such as the (converted) core sampling vessel WIMPEY SEALAB and the flexible pipe laying vessel Coflexip SUNRISE. For transit, these vessels use their original propulsion systems, whereas several retractable and rotatable thrusters are used for DP operation.

Several propulsion system arrangements typical of DP vessels are described in the following chapter. (Emphasis is placed on ship-shaped drill vessels.)

2.2 DP Drill Ships

This vessel is intentionally built with a ship-shaped hull, and it is equipped with drilling equipment for operation in deep water. Examples for this type of vessel include the following DP drillships:

- SEDCO 445, 471, and 472
- Offshore Company's DISCOVERER SEVEN SEAS and DISCOVERER 534
- PELICAN series of FDP drillships
- GLOMAR EXPLORER

The vessel is intended to drill offshore oil wells. A relatively high efficiency of the DP operation, long endurance between logistic replenishment, and high load capabilities are among the major advantages of this vessel. The ship shape of the hull results in a very low drag in the vessel's longitudinal axis. As far the operation allows, the vessel selects a heading which points into the direction of minimum environmental forces during DP operation.

Mobility is a further advantage of the drill vessel, which is capable of cruising to a different location with the speed and efficiency of a regular commercial vessel. This feature greatly reduces the down-time between remote locations.

The propulsion system consists of a conventional twin-screw arrangement for DP propulsion and cruising in the longitudinal direction. The twin propellers are designed for maximum power during cruising mode (13-15 knots). Only about 50% of the installed power is utilized in DP propulsion, which does, however, require propeller thrust in ahead as well in astern direction. The propeller acceleration and reversing maneuvers have to be executed at a fast rate of response. Both fixed pitch propellers with variable speed and reversing drives and propellers with controllable pitch which operating at constant RPM are utilized.

During DP operation, the forces in transverse direction are generated by thrusters with fixed axis propellers, installed either as tunnel thrusters inside the hull, or as retractable thrusters with propellers operating under the hull of the vessel. This type of thruster is retracted into the hull during transit to reduce the added resistance caused by the extended thrusters, and to reduce the draft of the vessel.

The arrangement of the propulsion devices in fixed direction is inherently less effective than an arrangement of thrusters with control of the direction of thrust (i.e. to satisfy a thrust vector command at 45 degrees, the combined thrust from the longitudinal and transverse thrusters needs to be approximately 40% higher than the thrust of a rotatable thruster pointed into the desired direction.

The major disadvantage of the ship-shaped drill vessel is its higher degree of motion in waves which reduces its operational efficiency during operations in heavier weather.

The first full-size DP drill vessel exclusively equipped with propulsion devices which allow control of thrust in 360 degrees is the SAIPEM DUE. This vessel is equipped with Voith-Schneider cycloidal propellers.

A new trend in the design of DP drillships started in 1996. Amoco in cooperation with Transocean Offshore inc., as well as CONOCO in cooperation with Reading & Bates, designed a new generation of DP drillships. These vessels are considerably larger than any previously built drillships. They all differ in several features:

- The hull is optimized for the application as drillship, not for transit speed.
- The vessels are not equipped with a conventional main propulsion system augmented by transverse thruster for stationkeeping. They are exclusively equipped with azimuthing thruster which are used for stationkeeping and transit propulsion. This feature increases the stationkeeping efficiency, but increases considerably the draft of the vessels.

  New conversions include the Diamond Offshore OCEAN CLIPPER. This vessel uses the stern propulsion system in conjunction with five transverse tunnel thrusters and one azimuthing thruster. The upgrade of the Glomar EXPLORER, originally equipped with a main propulsion system and five transverse tunnel thrusters, includes the installation of four additional azimuthing thrusters.

2.3 DP Semisubmersibles

Due to its better motion characteristics, the semisubmersible became the predominant platform for offshore drilling and support operations. A semisubmersible drilling rig, multi-purpose vessel or crane barge is optimized for low motions and not for transit speed as a conventional commercial vessel. The low motion characteristic is present during operation in the semi-submerged condition. In this condition, the resistance of the hull against current and waves (even wind) is nearly constant through 360 degrees. Due to the large submerged area, the magnitude of the resistance is very great.

The propulsion is sized for the requirements of the DP operation. During transit, only a part of the installed propulsion power is applied to propel the semisubmersible. Due to the asymptotic characteristic of the semisubmersible's hull resistance, an application of the full installed power during cruising would cause only a marginal increase of the vessel's speed at very low efficiency.

Multiple installation of propulsion devices which can generate thrust through 360 degrees are the preferred choice for DP semisubmersibles. The majority of the existing DP semisubmersibles in service are equipped with rotatable thrusters. They differ widely in the number of thrusters, power per unit, method of installation and type of power supply..

2.4 Special Purpose Vessels

Several ship-shaped special purpose vessels are in service today which were purposely built for DP operation. These vessels include multi-purpose vessels (maintenance, supply, firefighting, etc.), diving support vessels, pipe laying vessels, and various oceanographic and seismographic research vessels. They were basically designed according to the parameters described above for drill vessels. Often smaller in size than drill vessels, they require mostly a smaller degree of accuracy and reliability from the DP system. The main propulsion is frequently provided by rotatable thrusters which enhances the DP system's efficiency. Transverse forces are generated by tunnel thrusters, retractable rotatable thrusters, or combinations of both.

2.5 Conversions

Conversions of existing vessels into DP service vessels are found throughout the history of dynamic positioning. Prominent examples is the WIMPEY SEALAB and Coflexip SUNRISE. These vessels have a close commonality in their propulsion arrangement: They kept their original propulsion system in place and installed for the DP propulsion requirements several rotatable and retractable thrusters.

The propulsion system of a typical commercial vessel is designed to provide economical power for the cruising speed range of the vessel. The majority of the systems are unable to provide continuous low power output of the propulsion devices in both directions of operation (ahead and astern); in addition, the control of the drive machinery cannot interface with electronic control systems and is unable to respond to small command increments.

In conclusion, it is very difficult, and, in most cases, unfeasible to apply an existing propulsion plant for DP service without major cost intensive modifications.

3 PROPULSION DEVICES

This section describes the available and applied types of propulsion devices used for stationkeeping. Discussed are function, performance, efficiency, application, and installation. The hydrodynamic characteristics of the various devices are discussed in more detail in Section 4 of this report.

3.1 Conventional Propeller Arrangements

This term *Conventional Propeller Arrangement* is applied throughout this report for the propeller installations in the stern of a commercial vessel. Due to the requirements for system redundancy, DP vessels use twin-screw installations. This arrangement is used on most of the ship-shaped DP vessels (drill vessels and others). The prime movers (electric motors in most applications) drive the propeller through a reduction gear and propulsion shafting. The shaft is supported by one or several bearings inside of the hull. The shaft penetration through the hull is accomplished by a stern tube assembly, which includes two bearings (oil or water lubricated) and a shaft seal. This arrangement is simple and reliable. The propeller is designed for the maximum speed requirements; only partial power is needed during DP service. The space in the stern of the vessel allows the installation of a propeller with a relatively large diameter which yields a high specific thrust during bollard pull (zero inflow velocity) and low current speed DP operation.

Larger DP vessels (drillships) are equipped with open propellers whereas smaller vessels are frequently equipped with propellers operating in nozzles.

Propellers with fixed pitch and variable RPM are used on most U.S. drillships (Transocean Offshore Company, SEDCO, Global Marine); European drill vessels (PELICAN series) use controllable pitch propellers operating at constant RPM.

The conventional propeller arrangement features a high propulsion efficiency; the mechanical systems are simple and reliable; components—shafting, bearings, seals—are of proven design.

Disadvantages of these systems are few:

- Inspection, maintenance and repair of the propeller require drydocking of the vessel

- The propeller operates behind the hull. Inflow into the propeller is disturbed by the presence of the hull. This affects the performance of the propeller, in particular in the reverse condition. The capability of the propulsion to produce reverse thrust is limited, even with propellers (and nozzles) specifically designed for bi-directional operation. Since most of the drill vessels use only a part of the system design power during DP, the limited reverse capability is acceptable.

3.2 Rotatable (Azimuthing) Thrusters

The first DP vessels, EUREKA and CALDRILL, were equipped with small rotatable thrusters. Since the early 1970s,the larger (2000 hp and above) rotatable thrusters became the predominant propulsion devices for self-propelled drilling semisubmersibles. The first DP semisubmersible, SEDCO 709, was built in 1975 with eight rotatable thrusters of 3000 hp each. Ship-shaped vessels also utilized rotatable thrusters: the converted DP vessel WIMPEY SEALAB was retrofitted with retractable thrusters for stationkeeping propulsion; new designs of DP drillships (Amoco/Transocean, Conoco/R&B) use azimuthing thrusters exclusively for stationkeeping as well as for transit.

The major advantage of a rotatable thruster is its capability to deliver thrust in every desired direction.

Rotatable thrusters are special design right angle gear drives . A prime mover transmits power through a vertical pinion shaft, (or, through a horizontal drive shaft and a top right-angle gear for Z-drive thrusters) and a right angle gear to the propeller shaft. The propeller operates in a Kort nozzle; the entire gear and shafting arrangement is rotatable around a vertical axis. Though the basic power train is of a standard design, the rotating feature increases complexity. Systems and components have to be added such as the steering (or azimuthing) drive machinery, an azimuth seal arrangement, hydraulic slip rings for the supply of lubrication oil, and, in the case of a CP propeller, hydraulic power for the pitch changing mechanism. The CP propeller is also equipped with a mechanical or electrical pitch feedback device. Its signal needs to be transmitted from the rotating part to the stationary part of the thruster.

While the Kort nozzle augments the propeller thrust, it also increases highly the steering torque required to rotate the thrust unit (gear housing including propeller and nozzle).

3.2.1 Type of Installations of Rotatable Thrusters

Bottom Mounted Thrusters: In a ship-shaped hull, the simplest type of installation of a thruster is a permanent bottom mounted type. The thrust unit is mounted into a base in the bottom or stern of the vessel. This type of installation requires drydocking of the vessel for maintenance on the underwater part of the thruster.

Encapsulated Thrusters: The first installations of rotatable thrusters featured the encapsulated type. The thrust unit is installed in the bottom of a watertight container. The prime mover and auxiliary machinery for cooling, lubrication, pitch control and steering hydraulic, are installed inside of the capsule. For navigation of the semisubmersible in shallow water, the entire capsule is retracted into a shallow water stowage position. The retraction is accomplished with the assistance of a crane barge or a special onboard lifting arrangement (this is not a "retractable thruster"). For major overhauls, the entire capsule is lifted on the upper deck of the semisubmersible. The weight of an encapsulated thruster of 2000 to 3000 hp is 100 to 120 tons. This type of installation is also applied on the DP drillships GLOMAR EXPLORER. She will be equipped with 4x3000 hp encapsulated thrusters in addition to the transverse tunnel thrusters.

During manufacture, the entire propulsion system is assembled, with all cabling, piping, etc. The system can be functionally tested—the power train with full propeller RPM, the azimuth drive, the pitch control system, etc. The interface with the shipyard is minimized, thus reducing construction time.

Detachable Thrusters: Today, the standard type installation of large thrusters in semisubmersibles, and, since approximately 1996, on DP drillships (Transocean, Diamond Offshore, Conoco-R&B), is a thruster which can be mounted and detached underwater while the vessel is afloat in shallow draft. The technique of this type of installation was developed by KaMeWa in the 1970s. Every major thruster manufacturer adopted the idea and is offering now its own version of a underwater detachable thruster.

This type of thruster is installed in the bottom of the hull. For maintenance and/or repairs, the lower thrust unit including gear housing, propeller, and nozzle can be separated from its seating, lowered on guide cables, and removed with lifting gear. The azimuth drive, the prime mover, and the auxiliary machinery systems remain installed inside the vessel.

(Further topics regarding detachable thrusters are described in Section 6: Mechanical Aspects of Propulsion Devices, chapters *Bottom Detachable Thrusters* and *Underwater Handling Methods*).

The detaching techniques vary to some extend between the different manufacturers. All detaching operations need the assistance of divers, cranes, and/or anchor handling supply vessels. In the latest designs, a remotely operated vehicle can be used in lieu of diver assistance.

The design of the vessel needs to consider the requirements of the thruster handling with regard to installation location of the thruster, and the location, capacity, and reach of cranes. The underwater removal or installation of a thruster requires a water depth deep enough to allow the "keel hauling." The required water depth varies between types and sizes of thrusters.

A new detachable method had been introduced by Aquamaster, the so-called Bottom mounted, underwater mounting from top. This method seems to be very desirable for the application on a DP drillship. The thruster is mounted from the top inside a well. It is installed on a watertight bottom receptacle. The drive arrangement is a typical Z-drive, with a horizontal electric motor driving the thruster through an intermediate shaft and a top right-angle gear. For removal of the thruster assembly, the intermediate shaft is removed, and the well trunk is closed by a watertight cover. The azimuth section is also covered by a shroud. After these preparations, the thruster is secured for lifting, the locking latches are disengaged (from top side), the well is flooded with water, and lifting can proceed.

3.2.2 Performance and Efficiency

Rotatable thrusters have been built up to 7000 hp, and are available up to approximately 8000 hp, with propeller diameters up to 5.0 meters (16.4 feet).

The capability of generating directional thrust together with the high thrust output of the nozzled propeller make a well designed and optimized rotatable thruster the most efficient propulsion device for DP applications.

The following possible problem areas need to be observed:

- Though the propeller is not installed behind a hull (in the majority of the applications), a hull/propeller interaction can occur.
- A rotatable thruster installed on one hull of a twin hull semisubmersible may cause negative hull effects while aiming its wake toward the second hull.
- The propellers of multiple thruster installations may interfere with each other. A propeller exposed to the wake from another thruster produces a lower level

of thrust. The thrust allocation logic of the DP control system has to take this fact into account by applying an “anti-spoiling logic”.

3.3 Transverse Thrusters

Transverse thrusters are propulsion devices with a fixed propeller shaft installed 90 degrees to the longitudinal axis of the vessel. They are used to provide side thrust, and, in conjunction with conventional propellers installed in longitudinal axis, forces in oblique directions. They are inactive during transit operation. Transverse thrusters include tunnel thrusters, and retractable thrusters operating under the hull of the vessel.

3.3.1 Tunnel Thrusters

Tunnel thrusters are applied for maneuvering on commercial vessels since the early 1950s. The first larger DP drill vessel, the GLOMAR CHALLENGER, used tunnel thrusters for transverse thrust, as did later the GLOMAR EXPLORER and other DP vessels from Global Marine. The first European DP drill vessels (IHC PELICAN series of vessels) were also equipped with tunnel thrusters, whereas the earlier U.S. DP drill vessels (SEDCO 445, Transocean DISCOVERER 534 and DISCOVERER SEVEN SEAS, and SEDCO 471 and 472) were equipped with retractable transverse thrusters.

The major advantage of the tunnel thruster is the simplicity of its installation.

To be effective for yaw maneuvers, tunnel thrusters are installed in the extreme ends of the hull, i.e. in the bow and in the stern.

Performance and Efficiency: The tunnel thruster has a lower efficiency than a conventional propeller arrangement or a rotatable thruster. In many cases, an optimum tunnel length cannot be achieved due to hull and installation restrictions. The optimum tunnel length is approximately 1.5 x propeller diameter. A long tunnel causes increased friction losses, and a too short tunnel causes losses due to turbulence. The configuration of the tunnel exits also influences the performance of the thruster. Hull angles to the center line of the propeller other than 90 degrees cause additional losses; the installation of protective bars in the tunnels restrict the flow of water. All of the above factors accumulate to substantial losses.

Since practically every tunnel configuration is different, an optimization of the individual thruster requires a propeller with an optimized pitch or a drive system which can be tuned to the individual thruster.
The tunnel openings can cause a noticeable increase of the resistance of the vessel at service speed.

At shallow draft, the propeller of the tunnel thruster may ventilate (sucking air) and/or cavitate. Both phenomena are associated with a reduction of thrust. This condition can also occur when the vessel is pitching in heavy weather. More details on tunnel thruster performance are discussed in Section 4.

Installation: The thrust unit should be installed in a way that the propeller is located in the center (½ length) of the tunnel. The typical thrust unit is installed and removed through the tunnel. This operation requires drydocking of the vessel (emergency repairs on location were successfully accomplished by sealing temporarily the tunnel ends with cofferdams). Attempts to install mechanically operated doors at the tunnel ends proved to be impractical.

Depending on the available space, the prime mover can be installed vertically on top of the thrust unit, or horizontally with the pinion shaft of the thrust unit turned into horizontal position.

Tunnel thrusters are available with fixed pitch propellers as well as CP propellers. Some CP propeller designs require a hatch in the tunnel for the radial removal of a propeller blade to the inside of the vessel. Electric motors are exclusively used as prime movers for tunnel thrusters in DP service.

3.3.2 Retractable Transverse Thrusters

A great number of very successful DP drill vessels (SEDCO 445, Transocean SUPER DISCOVERER and DISCOVERER 534, SEDCO 471 and 472) use custom designed retractable transverse thrusters.

Installation: These thrusters are stored inside the hull during transit. Upon arrival at the drilling location, the thrusters are lowered hydraulically into an operation position with the propeller/nozzle positioned under the hull. In all of the above mentioned applications, the entire assembly consisting of the thrust unit (including propeller and nozzle, a capsule containing prime movers and auxiliary machinery for cooling, lubrication, etc.), and the access trunk is lowered and retracted. This design eliminates long drive shafts. Penalties include a higher weight and higher costs. For maintenance, the entire assembly can be removed.

While tunnel thrusters can be used also for maneuvering, a retractable thruster is usually in the stowage position during transit and maneuvering. The thruster in the extended position increases the draft of the vessel considerably and adequate water depth is often not present during maneuvering situations.

Performance and Efficiency: The design objective for a transverse thruster is the generation of a maximum amount of thrust at a given power into both directions, port and starboard. Since the propeller axis is fixed, the direction of propeller thrust has to be reversible. This is accomplished by reversing the pitch in the case of a CP propeller, or reversing the direction of rotation in the case of a propeller with fixed pitch.

An optimum design for maximum thrust of a propeller or a propeller/nozzle system can only be achieved for a unidirectional system.

A transverse thruster is equipped with a propeller/nozzle system which is designed for an equal output of thrust into both directions of operation. It employs symmetrical bi-directional propeller profiles of lower efficiency than the hydrofoil profiles of an unidirectional propeller. The nozzle also is of a compromise design which improves the performance in reverse by sacrificing some performance in ahead direction. Simplified, the efficiency of the transverse thruster is in between the tunnel thruster and the rotatable thruster.

The ideal position for the installation of a retractable transverse thruster is on the center line of the vessel. Superstructures and other space requirements frequently prohibit an installation of a thruster at the center line, and locations towards the sides of the hull are preferred.

The action of a propeller under the hull of a vessel causes interaction problems. The inflow of water into the nozzle/propeller may be restricted, and/or the wake of the propeller causes low pressure fields on the hull, which, in turn, creates forces acting on the vessel which are opposite to the propeller thrust. If the thruster is not installed on the center line of the vessel, the hull interaction and subsequent deduction of thrust can be very different for the two directions of operation. While the propeller produces actually the same amount of thrust at the same power level, the effective side force acting upon the vessel can be very different in both directions.

3.4 Other Propulsion Devices

This chapter describes several devices which are in few cases used for DP propulsion or are used for maneuvering propulsion.

Voith Schneider Cycloidal Propellers (VSP): This type of propulsion device produces thrust which is controllable in magnitude and direction by the variation of the blade positions of the cycloidal propeller. This feature could make this device the ideal propulsion for DP application. VSP drives are in successful use in shallow draft vessels. Its large diameter rotary seals are limited to very low pressure and rule out an installation in a deep draft semisubmersible. The major question regarding the application of a cycloidal propeller is its efficiency at low speeds. Analytical methods to calculate the performance are practically not available. The manufacturer has not published useful information.

The PELICAN DP drill vessel series was originally designed with VSP propulsion. Propulsion tests with model VSPs were conducted at the Netherlands Ship Model Basin. The performance of the VSPs was far below the expected values. The design was subsequently changed and a conventional propulsion system was installed in conjunction with several tunnel thrusters.

Shortly afterwards the DP drill vessel SAIPEM II was built with VSP propulsion; two VSPs were installed in the stern of the vessel and two propellers in the bow. After several years of operation a retractable and rotatable thruster was installed in the bow to replace one (or two) of the VSPs.

The controllability of thrust in magnitude and direction of the VSP is excellent. A high number of successful harbor tugs and ferries are propelled by VSPs. The device is mechanically complex and expensive. Its qualification for a certain application in DP service must be diligently investigated and the manufacturer should be contacted in the earliest stages to assist in the hull design to prevent hull interaction losses associated with propulsion devices operating under the hull of a vessel.

White Gill Thruster: This propulsion device is used for maneuvering in smaller vessels. An impeller sucks water from an opening in the bottom of the vessel and discharges the water through a bottom mounted guide vane assembly. The passage of the water through the Gill unit creates friction losses which lower the effectiveness of the device. The manufacturer quotes specific thrust values of a approximately 16 lb/hp which is about half of the value which can be achieved with a well designed propeller/nozzle arrangement.

The installation of the White Gill thruster is very simple, and in some cases this thruster is the only device which fits into restricted installation conditions. It is available only in sizes up to 1000 hp.

Omnithruster: The Omnithruster is a maneuvering propulsion device which takes in water through an opening in the bottom of the hull and discharges above the water line either to port or to starboard through an arrangement of large elbows. The direction of flow is switched by two butterfly-valve type flaps. The hydraulic losses are of similar magnitude as of the White Gill thruster. The manufacturer claims a specific lateral thrust in the range of 18 to 20 lb/hp. Omnithrusters are available up to 1000 hp. The bottom intake eliminates a loss of suction during pitching of the vessel, a danger with tunnel thrusters. For space restricted installations on smaller vessels, this type of thruster may be considered. In other cases a more efficient arrangement would be a better choice.

3.5 New Propulsion Concepts

A new design of larger power thrusters emerged within the past few years in the wake of advancements in variable speed AC drives. These thrusters employ a horizontally-mounted electric motor which directly drives a propeller.[1]
Advances in the technology of variable speed AC drives have greatly benefitted the marine and thruster industry. For conventional thrusters or propulsion systems, propeller speed control is now available for highly efficient, high-voltage AC propulsion motors. Until previously, variable speed electric drives were only available as DC drives, with lower efficiency, very limited voltage, and mechanically and electrically complex motors. The disadvantages of these variable speed AC drives include high costs and a high degree of complexity of the electronic components.

Direct-drive electric thrusters: The availability of devices for the rpm control of AC motors (while operating the power plant at constant frequency and voltage) lead to the utilization of AC motors for propulsion applications. Today, numerous vessels, ranging from offshore service vessels to cruise ships, are equipped with variable speed AC propulsion drives in conventional, in-line motor-shafting arrangements.

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[1] The design principle is not a new one; since the 1950s, many such thrusters have been built in a power range up to 1000 hp. These thrusters, which utilize a water-filled (for cooling and lubrication) submersible AC induction motor, have been applied as fixed-direction tunnel thrusters and azimuthing thrusters (widely used as APUs (Auxiliary Propulsion Units)) on single-screw Navy vessels (corvettes and nuclear submarines). The drawback of these drives is the lack of reliable speed control of the motor/propeller.

Only a few years ago, several large electric companies started with the development of a modular steerable or azimuthing propeller drive. In this drive, the drive motor is installed inside a streamlined housing (pod). The motor drives directly (or, in some cases, through a reduction gear) a propeller. The entire housing is watertight and azimuthing for directional control of thrust. This “podded” propulsion device is available from approximately 5,000 hp to 25,000 hp. ABB recently installed 25,000 hp drives. CEGELEG and SIEMENS are working on designs and proposals for electric thrusters of various sizes. This type of thruster may be applied for stationkeeping applications in power ranges above 5000 hp per thruster.

4 PERFORMANCE CHARACTERISTIC OF PROPULSION DEVICES

4.1 General

This section describes the hydrodynamic performance criteria of the propulsion devices used for DP applications. Discussed are basic characteristics, performance and efficiencies at different operating conditions (free running and stationary) and various power levels (maximum load and off-design low loads).

The discussion regarding the performance of propellers distinguishes characteristics of the propeller operating in the vicinity of the hull (the real, installed condition) and in open water without the presence of a hull.

The expression "open water" is used to describe an hydrodynamically undisturbed environment. It is understood to be the condition of a propeller operating in an environment undisturbed by the presence of a hull.

To optimize the design of a DP propulsion system, it is mandatory to know the propeller characteristics in open water as well as behind or under the hull. The presence of the hull affects the performance of the propeller to a high degree. Section 5 of this report discusses this subject of propeller-hull interaction.

The prediction of the performance of a propeller can be achieved through analytical methods or through open water model tests.

A very practical determination of the performance of a propeller is achieved by the use of propeller charts. These charts represent the results of systematic propeller tests. The tests are performed by model basins according to the laws of similitude. The use of reliable propeller charts supplies useful and accurate results.

4.2 Open Water Tests

The results of model tests for propeller series are presented in "open water test diagrams." In an "open water test," the performance of a model propeller is tested in a condition which eliminates any flow disturbances to a high degree. The test is usually conducted with the propeller attached to a recording dynamometer installed into a streamlined hull with the shaft protruding forward. The test complies with the conditions for geometrical, kinematic and dynamic similarity.

The results are presented in the typical open water test diagram which presents the propeller data in dimensionless coefficients for thrust and torque and the efficiency of the propeller versus the advance speed of the propeller.

As the diagrams indicate, a fixed pitch propeller has a rigid characteristic. The propeller design can be optimized for one point only. A propeller selected for the bollard condition is less efficient in cruising condition, and vice versa. To operate the propeller in different condition, its characteristic has to be matched by the characteristic of the prime mover. Very few prime mover types are capable of matching their characteristics with the one of the propeller. For this reason, for instance, a diesel engine is inadequate to drive a fixed pitch propeller for DP service.

4.3 Open Propellers

The term open propeller is used for propellers which are installed in a conventional way, without thrust augmenting devices such as a Kort Nozzle.

4.3.1 Performance Characteristic

The basic description of the propeller efficiency is derived from the momentum theory for an open propeller. It states that the efficiency of a propeller increases with the decrease of the velocity change at the propeller and with the increase of the mass of fluid flowing through the propeller per unit time. The ideal propeller is a propeller which accelerates as little as possible a fluid mass as great as possible.

This conclusion is applicable to propellers operating in ideal fluids, without friction losses. The operation in a real fluid introduces some boundaries, but the basic theorem is still applicable.

The optimum propeller diameter in an ideal fluid is the largest feasible diameter. In a real fluid, the increase of the propeller diameter is limited by the friction losses.

4.3.2 Selection of an Open Propeller

The performance of an open propeller can be calculated with the aid of open water diagrams. After selecting of the propeller for the design point, the off-design conditions can be calculated for every desired condition.

The following guide lines shall assist in the selection of the propeller parameters:

Number of Propeller Blades: The efficiency of a propeller decreases with the increase of the number of blades. A typical commercial propeller has four blades. A lower number is unpractical from a vibration point of view. In some cases, a higher number of blades is advised if the reduction of noise, cavitation, or vibration is desired.

For the project stage, the selection of a four-bladed propeller is advised.

Blade Area: This parameter is expressed as the ratio between the actual projected or developed blade area and the propeller disc area. A greater blade area causes higher friction losses, a lower area increases the risk of cavitation. For the project stage, it is recommended to start with an area ratio of .5 to .6, and to correct the area ratio, if necessary, after a cavitation check.

Pitch or Pitch/Diameter Ratio: This parameter affects all other propeller values such as RPM, torque, thrust, etc. Simplified it can be stated that an open propeller should be selected with a low pitch/diameter ratio for an optimization at bollard pull, and/or a high P/D ratio for optimum efficiency at transit speed.

Number of Revolutions: The RPM of the propeller is again interrelated with all of the rest of the propeller parameters. For the project stage, a peripheral propeller speed of 26 to 33 meters per second may be selected. The lower value should be applied for operations with high risks for cavitation (bollard pull), higher figures (up to 40 m/s) can be applied for transit conditions.

Propeller Diameter: The propeller diameter is the most critical parameter in the propeller selection process. A large propeller diameter affects directly the thrust (in particular in bollard pull condition), and indirectly other factors such as costs of the system. A large propeller diameter is associated with a low propeller RPM. At a given power, the resulting high torque in the power train increases costs as well as weights of all power transmitting parts such as shafting, shafting supports (seals, bearings), reduction gears, component housings, etc.

A cost analysis could determine the cost increase versus thrust increase to establish a point of economic optimum for the system design.

Design Pitch: A fixed pitch propeller has a very rigid characteristic. Thrust output and torque are a function of RPM and the velocity of the water flowing into the propeller. These parameters are fixed in one design point. This design point must match exactly the characteristic of the prime mover; furthermore, the thrust has to be in equilibrium with the resistance of the vessel at a certain speed. This speed, in turn, is the factor which determines the velocity of the water flowing into the propeller.

As an example, a propeller designed to adsorb full power and RPM at cruising speed of the vessel, cannot be operated at full RPM at bollard pull (zero inflow velocity). Due to the high pitch, designed for high speed, the propeller would be greatly overloaded. On the contrary, if a propeller is optimized for bollard pull, it can develop maximum RPM while cruising, but it cannot reach its rated power level.

Depending on the specific requirements, the design of the DP propeller has to compromise between the different operational requirements. The point of maximum operational economy has to be placed on the time-wise predominant operational power level.
In the majority of the applications, the propeller is sized for cruising. The propeller power requirements for the service speed of a DP drill vessel are typically larger than the requirements for stationkeeping. The propeller can easily satisfy the lower thrust and power requirements during DP operation. The problem in this case, however, is the match of the propeller characteristic with the prime mover characteristic in two different modes of operation. Only a prime mover which is capable to satisfy these requirements can be utilized for DP propulsion. It is not feasible to meet this requirements with a direct or geared diesel engine drive. Only electric drives such as a SCR controlled DC motor or pulse width modulated (PWM) AC motors are qualified for this service.

Control of Thrust of an Open Propeller with Fixed Pitch: The thrust output of a fixed pitch (FP) propeller in magnitude and direction is controlled by varying the RPM and reversing the direction of rotation of the propeller shaft. Fixed pitch propellers require propulsion machinery which can provide this controllability. The FP propeller is marginally more efficient at design point (usually maximum continuous rating), operating at full power. In low load conditions the fixed pitch propeller is considerably higher in efficiency than a CP propeller operating at constant, maximum RPM. The differences are less for the CP propellers which can control the RPM. Obviously, a FP propeller consumes zero power during stand-by mode (zero RPM), whereas a CP propeller consumes approximately 20% of its rated power operating at 100% speed, and 6% during reduced RPM (66% RPM assuming an electric AC drive, reducing the line frequency from 60 Hz to 40 Hz).

Reversing the direction of thrust of the FP propeller requires reversing the direction of rotation. The propeller advances now with the trailing edge of the blade and the suction side of the blade in ahead is the pressure side in astern. This causes a high reduction in propeller reverse efficiency.

For the majority of the commercial vessels, reverse operation is only used during short periods of maneuvering and stopping. Reverse efficiency is of no concern.

Reversing of the propeller while the vessel is moving can cause complex torque situations. If the prime mover is stopped while the vessel is still moving by its inertia, the propeller is subjected to negative torque from the water moving into the propeller (wind milling effect). Reversing a propeller in this condition can result in torque peaks which are far greater than the design torque of the system. This effect is of lesser impact during DP operation due to the stationary condition of the vessel and the relatively low current speeds. During the system design phase, however, this problem has to be addressed. Design details depend on the type of propulsion machinery and the speed of response requirements of the DP control system.

Open Propellers with Controllable Pitch: An open propeller with controllable pitch (CP) is a propeller which has the capability to vary the angle of the propeller blades relative to a radial pivoting axis. The blade movement is accomplished by a hydraulically actuated mechanism installed inside the propeller hub. The hydraulic power is supplied to the propeller hub through passages inside the propeller shaft. In spite of the complexity of the mechanisms involved, the CP propeller is considered to be a reliable device and is used for numerous DP applications.

CP Propeller Performance: Certain inherent design features affect the performance of a CP propeller. Due to the space requirements for the internal pitch actuating mechanism, the hub of a CP propeller is considerably larger than the hub of a fixed pitch propeller. This leads to a small reduction in the useful blade area and subsequently to a small reduction in efficiency. Also, due to the limited diameter of the pivoting blade base, the root profiles of the CP blades are shorter and of less effective design. Both of the above effects cause a marginal reduction in the overall efficiency of the CP propeller in comparison with a fixed pitch propeller.

CP Propeller Design Point: Rather than controlling the actual pitch, the CP propeller is able to control the position of the blades relative to a vertical pivoting axis. Therefore, the design can only be optimized for one design point. Off-design conditions at different blade angles are compromises at slightly reduced efficiencies.

The CP propeller design point should be selected for the design condition for which optimum economical operation is desired. For DP propulsion, this condition is a stationkeeping mode during which the propeller is working under very low inflow velocities. A blade designed for lower load, and hence lower pitch, also causes less idling losses during stand-by in neutral thrust/zero pitch position. The penalty for a low design pitch is a slight reduction of efficiency in the cruising mode.

Control of Thrust of a CP Propeller: Thrust in magnitude and direction (ahead/astern) is controlled by the CP propeller by varying the angle of the blades. The prime mover RPM is either constant or reduced simultaneously with the pitch.

- Diesel driven CP propellers installed on commercial vessels vary the engine speed between full RPM and minimum idling RPM.
- The PELICAN series of DP drill vessels drive the CP propellers of the main propulsion system and thrusters with constant RPM AC induction motors.
- The DP semisubmersibles SEDCO 709 and SEDCO 710 operate CP propellers with synchronous motors at constant RPM.

The variable speed drive of a CP propeller allows the propeller to operate at better efficiency during lower loads. A typical CP propeller driven by a constant RPM prime mover is comparable in efficiency with a variable speed propeller only at full load conditions. In partial load conditions, and in particular during neutral (zero thrust) operation, the CP propeller is less efficient than a fixed pitch propeller. A CP propeller, while idling at full RPM in neutral blade position, consumes approximately 20% (or more, depending on the blade design and the condition of the blade surfaces) of its rated power, e.g. eight 3000 hp propellers on a DP semisubmersible during stand-by mode, producing zero thrust, continuously adsorb nearly 5000 hp.

For some applications, efficiency during low load service may be of secondary concern. For a DP vessel, however, which operates most of its mission in low load conditions, a low efficiency during low loads may cause a considerable increase in logistic and operating costs. Many installations of large CP propeller thrusters for DP service (European offshore service vessels, Coflexip SUNRISE) feature two-speed operation of the propulsion (two-speed AC induction motors) for increased low load efficiency.

Reversing of the direction of thrust is also accomplished by varying the propeller blade angle. The prime mover continues to rotate in one direction. This feature allows the application of some prime movers for propulsion which can only be operated in one sense of operation, i.e. gas turbines. Also, the strain on the machinery during reversal maneuvers is less than in systems requiring a change in the direction of rotation.

The reverse thrust capability of a CP propeller is better than the one of a FP propeller. Since the CP propeller does not change the direction of rotation, the blade advances even in reverse with its leading edge. Only the suction and pressure side of the blade is reversed. A fixed pitch propeller advances in reverse with its trailing edge, and reverses the suction and pressure side.

Performance Calculation of the CP Propeller: Systematic series tests for controllable pitch propellers are available from MARIN. These tests were run for the full operating range of a CP propeller, from full ahead through zero to full reverse pitch. The diagrams allow a simple but reliable performance calculation for an open CP propeller. They can be used to calculate the idling losses at zero pitch (neutral thrust) blade position. As mentioned earlier, the determination and/or reduction of these losses is mandatory for an application of a CP propeller for DP service. The idling losses can cause a considerable inefficiency for a CP propeller while idling at zero pitch position and full RPM.

Bi-Directional Propellers: To achieve maximum performance, normal propellers utilize highly efficient hydrofoil type blade profiles. Reversing these profiles results in poor performance.

For applications which require a better reverse performance or even equal thrust in both directions, a propeller can be designed utilizing elliptical blade profiles. The performance of such a propeller is somewhat lower than propellers with hydrofoil sections. The reverse thrust, however, is highly improved over normal propellers. The total ahead thrust plus astern thrust of a symmetrical propeller is typically larger than the total thrust of a hydrofoil propeller.

4.3.3 Application of Open Propellers

Open propellers are applied for DP service only on vessels with ship-shaped hulls. The open propeller is installed in the stern of the vessel in a conventional, twin-screw arrangement. A twin-screw arrangement is selected for redundancy and thrust balance. The propeller is sized for cruising at full power; during DP service, the propeller supplies the forces in longitudinal direction of the vessel. Since these forces for a ship-shaped vessel are lower than the forces required for full speed, the propeller operates at a lower load condition during DP service. During this condition, the specific thrust (thrust per input power) is very high.

All purposely built DP drill vessels are equipped with open propeller, twin-screw propulsion. While nozzled propellers would augment the thrust during DP mode, the nozzle would have a detrimental influence during service speed.

All U.S. DP drill vessels (GLOMAR CHALLENGER, GLOMAR EXPLORER, GLOMAR ATLANTIC, GLOMAR PACIFIC, DISCOVERER SEVEN SEAS, DISCOVERER 534, SEDCO 445,471 & 472) are equipped with fixed pitch propellers which are driven by SCR controlled DC motors.

The European PELICAN class (IHC-designed) drill vessels are equipped with open CP propellers which are driven by AC motors and operated at constant RPM.

4.4 Propellers in Nozzles

The idea to install the propeller in a duct goes back a long way. But only since Kort's work (1934) is the nozzle in practical application. Kort's approach to the design of the propeller/nozzle system was mainly based on experiments. After WWII, a number of European hydrodynamicists published theoretical studies on ducted propellers. The Netherlands Ship Model Basin (now MARIN) combined analytical research with systematic testing of ducted propellers in the 1950s and 1960s. Their publications of the test results of systematic nozzled propeller series contributed to the wide acceptance of the nozzled propeller. This documentation provided the design fundamentals for the practicing naval architect.

4.4.1 Performance of Propellers in Nozzles

The nozzled propeller is used for applications which require a high amount of thrust at low inflow velocities. Thrust increases of 30% can be achieved by installing a nozzled propeller in comparison with an open propeller of the same diameter.

The nozzle and the propeller form an integrated system. The action of the shrouded propeller can better be compared to the action of an axial flow pump than to that of an open propeller. The nozzle wall reduces or even eliminates the trailing vortices at the blade tips. The flow through the propeller creates a circulation around the nozzle. The nozzle can be considered as a ring-shaped hydrofoil; the circulation produces additional thrust. A further improvement is explained by the reduction of the exit losses: The contraction of the outflow jet is less in a ducted propeller than in an open propeller.

With increasing vessel speed, the advantages of the propeller/nozzle system are present until the nozzle drag is as great as the thrust augmentation. From this point on, the propeller /nozzle thrust is lower than the thrust of an open propeller.

The location of the trade-off point depends on the propeller/nozzle design. A propeller/nozzle system designed with a large propeller diameter for maximum thrust at bollard pull reaches the trade-off point earlier because of the high friction losses of the large nozzle. This effect has to be noted in considering a propeller/nozzle system which is required to operate at bollard pull and at higher cruising speeds.

The application of the ducted propeller for cruising is limited to moderate speeds. The limits have to be investigated from case to case. However, there is no ducted propeller applied for speeds over approximately 15 knots. As mentioned above, a system optimized for speed has to pay penalties during static conditions.

Further advantages of the nozzled propellers include:

- The reduction in efficiency of a ducted propeller while the vessel is pitching in heavy seas is less than the reduction in efficiency of an open propeller.
- The course stability of the vessel is improved.

Disadvantages of the ducted propeller include:

- With fixed installed nozzles for conventional propulsion arrangements, the steering in reverse is very poor.
- The pressure drop in the nozzle lowers the point of cavitation inception
- The circulation around the nozzle causes more debris, stones, etc. to be sucked into the nozzle at shallow water depths.
- The danger of damage to the nozzle was a great concern in the past. Today, nozzles are widely used for ice breaking vessels, even for shallow water icebreakers.
- Access and removal of the blades of a CP propeller is difficult inside a nozzle.

Bollard Pull Performance of the Ducted Propeller: Theoretically, the ducted propeller can be designed for extreme high thrust output at zero inflow speed; i.e. the Kort designed tug ISE has tested a bollard pull specific thrust of 48 lb/hp. Practical considerations limit the performance of most of the propeller/nozzle designs to 30-35 lb/hp. As mentioned earlier, the thrust is a function of the propeller diameter. A large propeller diameter requires a low propeller RPM at a given power. This low RPM increases the torque of the system, which results in higher component strength requirements. The entire power train—shafting, stern tube, bearings, couplings, reduction gear, etc.—grows in size and weight and with it the displacement of the vessel, which, in turn, requires more power. The economical optimum needs to be established for a specific project.

The majority of the nozzle propellers generate a bollard pull thrust of approximately 29-35 lb/hp. These values are understood as the thrust produced by the propeller and nozzle without any deduction caused by the presence of a hull. In the case of a right-angle gear thruster, the deductions originating from the gear housing gondola and support struts should be included in the thrust figures.

Reverse Characteristic of the Ducted Propeller: A nozzle/propeller system for optimum ahead operation performs very poorly in astern direction. Whereas the open propeller may develop in reverse a thrust of 70% to 80% of the thrust ahead, the ducted propeller develops only approximately 60% of the ahead thrust while operating in reverse.

An improvement of the reverse thrust of the ducted propeller can be accomplished by modifying the trailing edge of the nozzle. A reverse thrust of approximately 65% to 75% of ahead thrust can be achieved with a "fatter" trailing edge while sacrificing only a few percent in the ahead direction.

For peak astern performance MARIN developed a special nozzle, the nozzle No. 37.

4.4.2 Selection of a Propeller/Nozzle System

The performance of a ducted propeller can be calculated by using the NSMB open water test charts for ducted propellers. These charts are based on systematical propeller series which were developed by the NSMB as a part of their extensive research and development work for nozzled propellers. The series are developed for three, four, and five blade propellers in various nozzle configurations.

The propeller was designed for optimum efficiency, low cavitation, and easy manufacture. The propeller blade contour is similar to the Kaplan blades used in axial flow pumps. The main characteristic of the blades is wide tip sections which are less susceptible to cavitation. The distribution of the pitch is uniform and the face sections are flat through the entire blade length.

One of the reasons for selecting this type of pitch distribution and these blade sections is the advantage found when casting this type of propeller. Extensive investigations performed at the NSMB showed that this type of propeller did not have drawbacks with respect to efficiency and cavitation.

The most widely applied system for optimum ahead performance is the Ka 4-70 propeller in nozzle 19B. The propeller has four blades; the area ratio is 0.70. The blades are of the Kaplan type; the large area ratio provides safety against cavitation. For optimum bollard pull, a pitch/diameter ratio of 1.0 should be selected.

The majority of the ducted propellers applied for DP are installed on rotatable (or azimuthing) thrusters. Direction of thrust is controlled by steering the entire nozzle/propeller system. Reversing the direction of thrust is not required. For some applications, such as ducted, fixed-axis transverse thrusters and conventional propulsion arrangements, reversing of the thrust direction is required. For these applications, the use of the nozzle No.37 is recommended. This nozzle features excellent reversing capabilities.

The nozzle-length/propeller diameter ratio of the nozzles tested is 0.50. This value is a good average and the majority of nozzles are built with this length/diameter ratio. A slight improvement in bollard pull can be achieved by increasing the length, whereas improved performance at higher speeds requires a reduction of the nozzle length.

4.4.3 Application of Propellers in Nozzles

With the exception of tunnel thrusters and the open main propellers on DP ship-shaped vessels, practically every propulsion device installed today for DP service features a propeller in a nozzle.

The first DP core sampling vessels EUREKA and CALDRILL were equipped with open propellers for main propulsion and steerable, retrofitted thrusters. The first ducted thrusters for DP service were applied as retractable transverse thrusters with bi-directional nozzles and propellers on the DP drill vessel SEDCO 445. The later vessels DISCOVERER SEVEN SEAS and DISCOVERER 534 were equipped with similar propulsion devices.

WIMPEY SEALAB, a conversion, was equipped with four retractable, steerable thrusters with CP propellers in nozzles. In 1975, the first DP semisubmersible drilling unit, the SEDCO 709, was equipped with eight encapsulated, rotatable thrusters, each with 3000 hp CP propellers in nozzles. The advantages of high thrust in conjunction with the availability of thrust in every direction made the rotatable thruster with a ducted propeller the prime propulsion device for many DP applications.

4.5 Tunnel Thrusters

4.5.1 Performance

Tunnel thrusters are actually axial flow pumps. Their design and performance calculations are based on the theory of axial flow pumps. However, the basic criteria which apply to the screw propeller, also apply to the impeller of the axial flow pump:

High efficiency is achieved by accelerating as little as possible a fluid mass as great as possible.

The following installation parameters influence the performance of the thruster impeller:

- The shape of the hull-tunnel intersection and details such as tunnel fairing, the intersect angles between hull and tunnel, and the location of the propeller all influence the tunnel entrance/exit losses.

- The friction losses are a function of the water velocity in the tunnel, the tunnel length, and the thruster housing geometry.

The calculation of the pitch and an exact determination of the thrust delivered by a tunnel impeller must take into consideration all of the above parameters.

Similar to a conventional propeller, the tunnel thruster impeller develops maximum thrust at zero inflow speed. Thrust decreases with increased inflow velocity when a current flows into the tunnel parallel to the impeller axis.

4.5.2 Impeller Design and Performance Calculations

The above-listed, mutually interfering parameters govern the impeller performance. The impeller performance was calculated using analytical models of axial flow pump theory which have been supplemented by empirical factors. In order to determine the thrust and the exact pitch of the impeller, a detailed analysis which considers all geometry parameters is mandatory. This is especially true for tunnel thrusters with fixed pitch impellers; the thruster will either overload at the rated RPM of the drive machinery (if the pitch is too high) or it will not be able to deliver full power at rated RPM if the impeller pitch is not accurate. This, however, does not apply to tunnel thrusters with CP impellers or fixed impellers with prime movers which allow some variation of their characteristics, such as DC motors with shunt field control.

As mentioned above, the losses of the tunnel thrusters are a function of the geometry of the thruster and of the tunnel. For a typical drill vessel with multiple transverse tunnel thrusters, separate computations must be carried out for each tunnel of different geometry. In the worst case, this could result in impellers with a different pitch for each of the tunnel thrusters.

A manual calculation of the impeller performance is feasible but impractical. The computation should be performed by a company specialized in this field reputed or a thruster manufacturer.

Impeller Pitch Distribution: The uniform distribution of the impeller pitch over the radius of the tunnel is the standard design procedure for a tunnel thruster impeller. The presence of the gear housing inside the tunnel and the boundary layer at the tunnel walls create a certain velocity profile. The pitch distribution of a tunnel thruster impeller can be adapted to this velocity profile similar to the wake-adapted propeller design for conventional vessels. Although it does not increase the thrust of the impeller, this design increases the point of cavitation inception.

Type of Impeller Blades: Optimum performance in both flow directions must be provided by the tunnel thrusters. A symmetrical blade profile (NACA 16) may be selected for the blade sections.

Reduction in Thrust due to Ventilation and/or Cavitation: Air will leak from the surface to the suction side of the impeller whenever the submergence of the tunnel thruster is reduced beyond a certain minimum dimension. The impeller operates in a medium of reduced density

when this occurs. The non-uniform amount and distribution of the air in the water results in an increase of the hydrodynamic noise produced by the impeller. Furthermore, the reduction of the static water pressure acting upon the propeller blades, lowers the point of cavitation inception.

The analytical treatment of this problem is difficult. A number of factors determined by the wave characteristics and the installation geometry influence it. The presence of waves will lead to considerable changes in the flow velocity and pressure distribution in the tunnel inflow area; this will result in higher losses.

4.5.3 Guidelines for the Selection of Tunnel Thrusters

The thrust which can be achieved with a particular thruster model is usually indicated by the thruster manufacturers. This figure only holds true under certain ideal installation conditions. The following guidelines should be considered when selecting a tunnel thruster model:

- The ratio between power and impeller disc area should not be larger than approximately 330 to 430 hp per square meter.

- The peripheral velocity of the impeller blade tips should be no more than 32 meters per second.

- The ratio between the diameter of the gear housing gondola and the impeller diameter should not exceed 0.42.

- A tunnel thruster should develop a specific side force of 25 lb/hp under optimum installation conditions (including an average tunnel length and vertical tunnel exits with fairings). Any deviation from optimum conditions may cause a severe reduction in the above-quoted side force.

4.5..4 Installation of Tunnel Thrusters

The following guidelines should be considered when selecting the location of the thrusters:

- The thrusters should be installed at the farthest possible distance from the vessel's center of gyration in order to be effective for yaw maneuvers.

- The following installation details should be considered in order to ensure a minimum of hydrodynamic degradation in thruster performance:

    - The center of the length of the tunnel is the preferred location of the propeller. The propeller should be located at least 0.50 D (D = propeller diameter) from the tunnel entrance.

    - The optimum length of the tunnel is approximately 2.0 D. A range of about 1 to 4 D is preferred, but 6 to 7 D is feasible with acceptable penalties. Detailed performance calculations should be carried out for longer tunnel lengths.

    - The optimal angle is a tunnel exit angle of 90 degrees to the hull (hull orthogonal to tunnel axis). Deviations result in a reduction of the thruster performance.

    - Two crucial requirements affect the vertical location of the tunnel: the tunnel should be submerged as deeply as possible in order to avoid cavitation; however, the centerline of the thruster should be located about 1.1 D to 1.5 D (or larger) over the lowest point of the keel in order to avoid circulation around the vessel's keel.

    - A distance of 1.5 D between center lines of thrusters is recommended for multiple thruster installations.

    - The fairing of the tunnel exits/entries affects the efficiency of the thruster as well as the resistance of the vessel. The least amount of added resistance results from a sharp transition between hull and tunnel; however, such a transition is detrimental to the thruster efficiency. The conical fairing of the tunnel entries is a popular compromise.

In order to prevent the intrusion of foreign objects, the tunnel entries are frequently protected by steel bars. This procedure is only advantageous for shallow draft vessels operating in waters which are contaminated by a large amount of floating debris.

The tunnel openings be left unrestricted for larger DP vessels. This prevents objects from being trapped inside the tunnel and results in a higher efficiency of the thruster propeller.

However, an increase in efficiency as well as protection can be achieved by an arrangement of concentrical guide vanes at the tunnel entries in some cases involving extremely short tunnel length.

4.6 Propeller Cavitation and Noise

In order for a propeller to qualify for DP service, it must operate quietly. Noise created by a propeller can interfere with the acoustic position reference system; this may result in a default of the positioning control system.

Noise related to the propulsion devices is created by three different sources:

- Cavitation of the propeller
- High frequency propeller blade vibrations (singing of the propeller)
- Shedding of the propeller jet on the hull (in particular the bottom) of the vessel

Cavitation is the most predominant cause of interference with the acoustic reference system. Although the singing of propellers is a common phenomenon in commercial as well as naval applications, no incidents have been reported concerning this type of noise in DP applications.

4.6.1 Cavitation

Cavitation results from the modification of the flow along the propeller blade elements. It occurs when the pressure in certain places in the flow field decreases below the vapor pressure of the fluid. The fluid changes into vapor in these places, resulting in a disturbed homogeneity of the flow. This leads to a reduction of thrust and a reduction of torque (to a lesser extent), and, therefore, a decrease in the efficiency of the propeller.

The vapor develops as an instationary phenomenon in form of tiny bubbles. The collapse or implosion of the vapor bubbles which then occurs on the surface of the propeller blades can cause mechanical damage to the material. A propeller blade may be damaged by continuous cavitation erosion.

A high level of noise over a wide frequency range results from the collapse of the vapor bubbles on the surface of the blades.

Avoiding Cavitation: The following measures lower the inception of cavitation or decrease the occurrence of cavitation:

Propeller Arrangement

- The propeller or thruster should be installed as deeply as possible, increasing the static pressure acting upon the propeller. Propellers installed under the bottom of the vessel are less prone to cavitation than, for instance, a tunnel thruster propeller. A thruster installed under the hull of a semisubmersible operating in the submerged draft of the vessel during DP mode would be ideal.

- The fairing of the hull, shaft support struts, fairing the gear housing and nozzle support struts at right angle gear thrusters etc., should be optimized; this will improve the inflow into the propeller.

- Operation of the propeller at oblique inflow angles should be avoided. However, this is not feasible in many DP applications, in particular for main propellers and fixed direction transverse thrusters.

Propeller Design

- The propeller blade profiles should be optimized for low cavitation inception.
- A large blade area ratio should be selected; this , however, results in greater friction losses.

Propeller Manufacture

- Polishing the blade surface.
- The propeller design and the manufacturing tolerances should be heeded. During operation, surface damages should be restored whenever possible.

Skewed Propeller Blades: Since the early 1970s, the skewed propeller has been widely used for applications which require high resistance against cavitation and propeller-induced hull pressure fluctuations.

Transocean Offshore Company's DP drill vessels were the first such vessels to be installed with skewed propellers. For DP services skewed propellers can only be applied as CP propellers or ***for*** non-reversible azimuthing thrusters. A fixed-pitch skewed propeller performs poorly in astern operation.

Prediction of Cavitation: The cavitation criteria for the particular propeller application is taken into account in the design of custom propellers which are calculated according to lifting line or lifting surface theories.

Model Tests: The major model test facilities are equipped with special circulating cavitation tanks which can simulate the condition of the propeller under scaled pressure conditions. Typically, these tanks are very limited in size and only allow the testing of a propeller or a propeller/nozzle system. The depressurized towing tank at the NSMB is the only facility which is able to test a model propeller installed on a model of the entire hull. At this institution, the entire model basin is under vacuum in order to simulate the pressure conditions for propeller cavitation. Propeller/hull performance including cavitation, resistance, and propulsion can be tested simultaneously.

The technology of the correlation between model test results of a cavitation test and full scale performance is well established and reliable. The scaling of the noise measured during model tests to the noise level at full scale is not yet developed enough to deliver reliable results.

Cavitation Checks Based on Systematic Tests: Several diagrams which indicate separate areas of cavitation from areas of no cavitation have been published. The most popular diagrams are those by Burril and Van Manen. Both diagrams plot a thrust load coefficient versus the cavitation number and can be used for a preliminary cavitation check.

It is impossible to predict some of the situations which can occur during station-keeping modes, for instance, operating the propeller under oblique inflow angles; therefore, the propeller should be designed with a relatively high safety margin against cavitation.

Singing Propellers: Singing of the propeller is a critical vibration phenomena of the blades, which, in all probability, is the result of fluctuations of the point at which vortices leave the trailing edge of the blade. An anti-singing edge applied to the trailing edge of the propeller blades fixes the separation point of the boundary layer and removes the vibration.

4.6.2 Noise Created by the Propeller Jet

Thruster propellers installed under the bottom of the hull are commonly associated with this problem. The accelerated water masses leave the propeller/nozzle with a high velocity ***shed*** along the bottom of the hull. Cases have been reported in which this wake action generated noises which interfered with the acoustic positioning system. This problem is magnified if the hydrophones are located in or near the passage of the jet. The interference may be reduced by the strategic placement of the hydrophones outside of the jet path or a deflection of the jet at a downward angle away from the hull. Installing guide vanes in the nozzle exit or tilting the propeller axis to a certain extent can deflect the jet.

4.7 Effect of Waves on Propeller Performance

The performance of propulsion devices may be affected by wave action in two different but

related ways:

- Waves cause a non-uniform inflow into the propeller which reduces the relative rotative efficiency of the propeller. The oblique direction of the inflow to the propeller due to waves creates cross-coupled forces. (See also *Fixed Direction Thrusters with Nozzles* in Section 5.)

- Waves cause a periodic change of the submergence of the propeller. A reduction or loss of the submergence may cause cavitation or ventilation of the propeller, resulting in a reduction or, in severe cases, total loss of thrust.

- The above criteria are amplified by the pitching motions of the vessel exposed to waves.

Wave action does not affect the propulsion devices on semisubmersible vessels. The low motions of the vessel in concert with the deep submerged location of the propellers negate the influence of waves on the propeller performance.

Wave action can affect the propulsion devices—main as well as thruster propellers—on ship-shaped vessels.

Tunnel Thrusters: In particular, tunnel thrusters installed in the bow of the vessel are exposed to the loss of submergence due to the combined wave action and pitching motions of the vessel.

It is possible to estimate the thrust deduction on a tunnel thruster caused by the loss of immersion due to the relative motion between ship and waves via analytical methods.

The installation of a tunnel thruster is only advised in applications for which an appropriate submergence of the tunnel is assured during all anticipated operating conditions.

Retractable Transverse Thrusters: Preference should be given to the installation of a retractable transverse thruster in cases where appropriate submergence of a tunnel propeller may be critical. This type of thruster may be only marginally affected by wave action with a ducted propeller installed under the bottom of the hull. (This applies also to other thrusters mounted under the bottom of a vessel.)

4.8 Steering Nozzles

Steering nozzles are used in conjunction with conventional, fixed axis propeller arrangements. The nozzle is capable of pivoting around its vertical axis to a certain angle in both directions. Pivoting the nozzle causes a deflection of the propeller jet, and the resulting force is used to steer the vessel. The rudder is replaced by the steering nozzle, which is widely used on tugs and similar special purpose vessels. In combination with a flap rudder in the exit of the nozzle, a force vector of 90 degrees to the ship's axis can be achieved. For the stationkeeping of smaller vessels, an integration of a steerable nozzle into the DP propulsion system may be considered for the main propellers.

5 INTERACTION BETWEEN PROPELLER AND HULL

The performance characteristics of propulsion devices was discussed in the previous section. These characteristics are needed to establish exact criteria for the evaluation of propulsion devices without the influences of disturbances which may affect the performance.

When a propulsion device is installed under or behind the hull of a vessel, its condition and performance is considerably modified. The propeller then operates in a flow which is disturbed by the presence of the hull.

5.1 Propellers Installed Behind a Ship

Propellers installed in a conventional arrangement at the aft body of a ship operate in an environment which is very different from an open water test arrangement. The hull disturbs the inflow of water into the propeller. The radial velocity distribution is not uniform, the axial water velocity is decelerated, and the low pressure field between propeller and hull increases the resistance of the vessel.

The problem of conventional propeller/hull interaction is a standard topic in naval architecture and is discussed in numerous publications.

The interaction between the hull and the propeller is treated by the introduction of certain factors and efficiencies (such as wake fraction, thrust deduction fraction, and various propulsion efficiencies which are discussed in the following paragraphs). An accurate determination of the quantitative values of these factors can be made with self-propelled model test. These tests deliver values for relative rotative efficiency, thrust deduction fraction, and wake fraction. They are conducted in a model basin on a routine basis according to the standards of the International Towing Tank Conference (ITTC). Analytical approximations can be applied in the absence of model tests, and, in particular, in order to develop preliminary performance estimates in the early stages of a project.

5.1.1 Wake Fraction

The propeller inflow velocity or speed of advance is different from the vessel speed and is affected by the wake of the vessel. The difference between the vessel speed and the speed of advance is the wake speed, which is expressed as a fraction of the vessel speed:

Wake Fraction $w = (V - V_a)/V$ V = vessel speed

Propeller speed of advance behind a hull

$$V_a = V(1 - w)$$

5.1.2 Thrust Deduction Fraction

The pressure over some of the area at the stern is reduced by the action of the propeller behind the hull; this increases the resistance of the vessel. This quasi loss of thrust is expressed as a fraction of the thrust and is called:

Thrust deduction fraction $t = (T - R_T)/T$

R_T is the towing resistance of the vessel without the propeller. T is the propeller thrust.

$R_T = (1 - t)T$

The approximation for the thrust deduction fraction is valid only for the transit condition. No analytical methods are available for the approximate values of thrust deduction under bollard pull and low speeds, ahead and astern.

The following data can be used for an open main twin propeller arrangement for a typical DP drill vessel. These factors were derived for a dynamically positioned drillship with a block coefficient CB = 0.8 from model tests at MARIN.

Thrust Deduction Fraction Values for Stationkeeping

AHEAD:

Va [Knots]	0	1	2	3	4
t	0.05	.075	.1	.125	.15

ASTERN:

Va [Knots]	0	1	2	3	4
t	0.18	.21	.25	..3	..34

It must be noted that the estimated figures for wake and thrust deduction are approximate and average values.

5.1.3 Propulsion Efficiencies

The propulsive efficiency η_D is defined as the ratio between the effective horsepower P_E and the delivered horsepower P_D.

$\eta_D = P_E/P_D$
$PE = R_T V$
η_D = hull efficiency η_H x relative rotative efficiency η_R x open propeller efficiency η_o
Hull efficiency $\eta_H = (1 - t)/(1 - w)$

Relative rotative efficiency expresses the difference in torque of a propeller behind a vessel and in open water at the same thrust and speed of advance. For most vessels, the value of the relative rotative efficiency is usually in the region of 1.0.

SHP expresses the horsepower at the output shaft of the propulsion prime mover while DHP indicates the horsepower delivered to the propeller. DHP excludes the losses of the propulsion shafting due to propeller radial and axial bearings, stuffing boxes, stern tube seals and bearings, etc.

5.1.4 Operation During Stationkeeping

The naval architect standard procedures are tailored to cover the operating conditions which are normally of interest to general commercial vessels. In the past, before the advent of offshore activities, no emphasis had been placed on bollard pull and low speed performance. In most DP applications, the influence of the wake during bollard pull can be neglected. Numerical values for the thrust deduction fraction are presented in this chapter. These values, in particular the values for astern operation, are most significant .

5.1.5 Influence of the Rudder(s)

The typical conventional propulsion arrangement of a DP ship-shaped vessel consists of a twin propeller installation for thrust in longitudinal direction of the vessel. According to marine standard design practice, the propellers operate with opposite directions of rotation. Any indirect steering effects caused by the propellers or the propeller jet action on the rudder are balanced or equalized. However, in the case of a single screw vessel being considered for DP service, the following should be noted:

A direct steering moment is caused by the non-uniform wake flowing into the propeller. The direction of the steering force is opposite to the rotation direction of the propeller blade at the upper half of the propeller.

The rotating propeller jet acting on the rudder causes a further, indirect steering moment. The upper and the lower parts of the rudder are exposed to wake of different velocities. An unequal rudder lift and, hence, a steering moment result. The steering force is introduced into the vessel through the rudder bearings. The aforementioned direct steering effect is transmitted into the vessel through the propulsion shafting.

5.2 Bottom Mounted Propulsion Devices

5.2.1 General

It was not until the offshore industry created a demand for stationkeeping propulsion that the performance of propellers operating under a hull in lieu of behind a hull became a focus (or interest) of the naval architect.

Voith Schneider cycloidal propellers (VSP) have been in use since the 1930s as typical bottom mounted propellers, but little has been published concerning the interaction effects these devices experience under certain conditions. Unexpected hull effects were blamed for the many unsuccessful installations ofVSPs, which in some cases resulted in the replacement of the cycloidal propellers with conventional propellers. Vessels ranging from naval mine sweepers to stern trawlers experienced unacceptable performance with VSPs. After the completion of model tests utilizing scaled VSPs, the PELICAN series of DP drill vessels─which was originally designed for VSP propulsion─was modified to conventional CP propeller arrangements. Even the DP drill vessel SAIPEM II, equipped with VSP propulsion, became subject to modification including the replacement of one VSP by a retractable thruster.

For DP propulsion, the interaction problems of bottom mounted thrusters can be divided into three particular problem areas:

- Interaction of the propeller jet with the hull.

- Intersection of the jet from a thruster mounted on the bottom of a semisubmersible hull with the adjacent hull.

- Interaction between thrusters on multiple thruster installations.

The above interaction phenomena occur in situations where several hydrodynamic effects

coincide and mutually affect each other. It would be unfeasible to develop accurate and reliable analytical methods which can be applied to any shape of vessel and to a variety of propeller and installation configurations. (It may be mentioned that even the interaction of a conventional propeller behind a hull can be analytically determined only as a rough approximation.) Only model propulsion tests deliver accurate results.

For DP applications, model tests create many problems. The typical DP vessel—either a semisubmersible or a conventional ship-shaped vessel—is equipped with a multitude of propulsion devices. While the performance of a commercial vessel is only investigated in longitudinal direction, the performance of a DP vessel must usually be explored in every direction. A large model scale must be selected for the propulsion devices in order to achieve accurate results from propulsion tests and to limit the influence of scale effects. The hull must also be scaled to the same ratio, which leads to a model of a size which exceeds the physical boundaries of practically every model basin. Unlike a conventional propulsion test for which the model is towed in its normal, longitudinal direction, DP tests require testing of the vessel in other directions including a 90-degree position, which exceeds the capabilities of the model tanks. In addition to the size restraints, budgetary restraints also frequently prevent a project from being investigated thoroughly. A scaled model of a semisubmersible with six rotatable thruster models, each one equipped with the instrumentation to measure propeller torque and thrust at different angles of attack, is extremely expensive. The complete test program would consist of numerous runs considering all propulsion conditions needed for an accurate performance prediction.

The tests conducted in the past for DP vessels all suffered from various restrictions and compromises. Very few systematic test were conducted by model basins to achieve generally valid information. However, despite all of these complications, a great deal of knowledge regarding the interaction of unconventional propulsion devices has been gained in the last two decades. Combining the fractions of available information should make it feasible to analytically predict the performance of a propulsion system within an accuracy of 10% to 15%. A very conservative approach should be applied to basic engineering philosophy. Every possible detrimental effect should be addressed and considered. The availability of reliable data concerning the basic hydrodynamic data of the propulsion devices as well as the resistance of the hull against current and wind for every angle of attack is imperative for a successful performance prediction. The reliability of a performance prediction for propulsion can only be as good as the information used for the forces the propulsion may encounter, i.e., the forces acting upon the vessel due to wind and current.

5.2.2 Hull Interaction of Transverse Thrusters

The jet from a propeller installed in transverse direction under a hull is subjected to the Coanda effect. This phenomena describes the behavior of a jet in air or water in the vicinity of a convex surface. The jet tends to follow the curved surface and is deflected. The deflection increases with the ratio of surface radius to jet diameter or height. At higher ratios, the jet can be deflected up to 90 degrees. The Coanda effect increases with increasing jet velocity or with decreasing jet area. The jet of the transverse thruster flows along the bottom and is deflected at the bilge radius and follows the hull. The high velocity of the jet creates a low pressure field at the side of the hull. The vector of this low pressure is opposite to the direction of thrust; this causes a reduction of the available net side force.

The influence of the Coanda effect on thruster propulsion was discovered during the model tests for the DP drill vessel SEDCO 445. An extensive series of large scale (1:10) model tests were conducted for this project in order to predict the DP performance of the vessel as accurately as possible within the available technology.

The following results and observations were derived from these tests:

- Severe thrust deductions (up to 20%) resulted when the thruster installed at the bilge was subjected to Coanda effects while the propeller jet was directed under the bottom of the hull.

- Only marginal reductions occurred when operating the thruster in the opposite direction while the jet was directed away from the hull.

- The losses were reduced by half when the thruster was installed at the centerline of the vessel; however, the effect was present in either direction of operation. The total average net force available in both directions therefore remained the same as in the above installation.

- Tilting the propeller axis to deflect the jet downward away from the hull led to improvements. These improvements increased with increased tilt angle.

- The thrust deduction as a result of the Coanda effect is a function of the draft of the vessel. The low pressure field acting upon a large surface results in larger net side force losses. At shallow draft, the losses decreased approximately proportionally with the reduction of the submergence.

In full scale, tilting the propeller axis could be achieved either by installing a conventional thruster under an angle or by designing a right angle gear with an angle larger than 90 degrees. Both executions are feasible but certainly increase manufacturing costs. A recent thruster design employs a nozzle which is tilted several degrees downwards while keeping the propeller shaft axis in a horizontal position.

The above-discussed phenomena were investigated for transverse thrusters with bi-directional propellers and bi-directional nozzles installed under the bottom of a ship-shaped hull. The observations also apply to other types of propulsion devices installed or positioned in similar conditions.

5.2.3 Multiple Thruster Installations

Many DP vessels are equipped with multiple installations of rotatable thrusters. Reasons for the installation of a larger number of propellers include:

- Increase of redundancy
- Lower weights of individual thruster assemblies; fewer handling problems
- Availability of large thrusters (thrusters over 3500 HP have only been available since 1980)

5.2.4 Interaction Effects between Thrusters

To be effective for yaw maneuvers, the thrusters are often grouped at the bow and stern of the vessel (SEDCO 709, SEDCO 710). In response to certain vector commands, situations can occur in which the thrusters are positioned in such a way that the exit jet of one thruster is directly aimed into a second thruster. The thrust output of the second thruster is greatly reduced if the propeller ***axis coincides***. The second thruster operates in a condition of a higher advance coefficient. As discussed earlier, the thrust generated by a propeller is maximum at zero inflow velocity or at an advance coefficient of zero. Thrust decreases with increased inflow velocity. This applies even if it is possible to maintain the power load on the propeller by increasing the pitch of an CP propeller or the RPM of a fixed pitch propeller.

The quantity of the thrust decrease with increased inflow velocity is propeller-specific and can be calculated. The velocity of the propeller outflow jet as a function of the distance from the propeller must be known in order to analytically predict the thruster interaction. The approximate performance of the second thruster can be calculated if the inflow velocity is known.

5.3 Interaction of a Tunnel Thruster with the Hull

The tunnel thruster is an integral part of the vessel's hull. It is difficult to distinguish between considerations which involve designs which improve efficiency of the thruster itself or designs which reduce hull interference.

The previous section discussed recommendations for the installation of tunnel thrusters which took into consideration the influence of the hull. The reduction in efficiency of a tunnel thruster with increased vessel speed is a familiar problem which is caused by the interaction of the tunnel thruster with the hull. Often, a typical tunnel thruster generates only approximately 50% of its rated side force when the vessel's speed is around 4 knots. This effect is explained by the creation of a low pressure field at the hull by the deflection of the impeller jet emitting from the tunnel. The deflection of the jet is caused by the combined motions of the vessel during the operation of the thruster—forward velocity and simultaneous yaw maneuver, the latter caused by the action of the thruster. This phenomenon is less important for DP operation as it mainly affects vessels during maneuvering.

Countermeasures against the reduction of the side force during vessel speeds were developed in the early 1970s: The "Anti-Suction Tunnel," a small diameter tunnel, installed parallel and near the thruster tunnel, provides a connection between both sides of the hull in order to equalize the differences in pressure.

5.4 Propeller Performance Under Oblique Inflow Angles

The analytical or empirical methods of predicting the performance of a propeller are based on the condition of an inflow into the propeller in the direction of the propeller axis. This assumption is satisfactory for conventional marine propulsion. Only during very short intervals of maneuvering may the propeller of a conventional vessel be subjected to inflow conditions other than those parallel to the propeller or vessel axis. Consequently, in the past, the performance of the propeller when operating under oblique inflow was of no concern to the naval architect. Only since the advent of offshore operations and the following demand for stationkeeping capabilities of vessels has this subject become increasingly important.

A fixed-direction propeller on a DP vessel (main propellers, retractable or bottom mounted transverse thrusters) may be operated under oblique inflow conditions for an extended period of time. To a lesser extent, similar conditions may occur with rotatable thrusters.

Under oblique inflow, the propeller characteristic is different from the characteristic at direct axial inflow. Changes affect torque and thrust of the propeller. A further parameter must be considered in the case of a ducted propeller: the cross-coupling force orthogonal to the propeller axis.

Although the effects pertaining to ducted thruster propellers could have been described in a previous section, this chapter was inserted into this section of the report since these propellers are not affected by the presence of the hull; in the case of a typical DP vessel with open propellers installed in the stern of the vessel, the oblique inflow is affected by the presence of the hull (in particular of the skeg).

5.4.1 Fixed Direction Thrusters with Nozzles

Intensive model tests on retractable transverse thrusters were performed for the development of the SEDCO 445. The results have been published in several papers. The measurements and observations of the cross-coupled forces were later used for the improvement of the DP system of Transocean Offshore Company's DISCOVERER SEVEN SEAS. Howard Shatto discusses the cross-coupled forces and presents an analytical explanation of them in the paper OTC 6962: "Dynamic Positioning Evaluation" He states that "*the cross force generated by a component of current perpendicular to the thruster axis is produced by the change in momentum. All of the water flowing axially through the thruster must have had its direction changed from that of the current to that of the thruster flow. A force is required to decelerate the cross flow component of current velocity to zero for that quantity of water flowing through the thruster. This is the cross force.*"

See ***Cross Forces*** by Howard Shatto in the Appendix.

The resistance of the nozzle/thruster itself under different angles of attack may amplify the magnitude of the effect. Unfortunately, no effort was made during the model tests to isolate the resistance of the thruster/nozzle assembly from the results.

The extent of the inflow under oblique angles into a propeller or thruster depends on a variety of parameters, including the geometry of the arrangement. This is a very complex problem; neither systematic model tests nor accurate analytical descriptions are available. If the development of a DP system requires an accurate prediction of these effects, custom model tests are the only available method today which produce useful and reliable results.

5.4.2 Main Propellers under Oblique Inflow

An inflow under oblique angles also affects the performance characteristics of open main propellers. A further problem is caused by the presence of the hull (skeg of the vessel), in this case. As a result, the inflow into one propeller can be very different from the inflow into the other propeller under some inflow angles. This results in different torque and thrust characteristics for each propeller.

6 MECHANICAL ASPECTS OF PROPULSION DEVICES

6.1 General

High standards of reliability, quality, serviceability, and efficiency are traditionally applied to marine propulsion. A failure of the vessel or its propulsion machinery may endanger human life or cause capital losses.

The design of the vessel and its machinery is greatly regulated by the rules and regulations of regulatory bodies and classification societies. Some of these regulations include rules for vessels in DP service. Unfortunately, these rules are not comprehensive enough to be used as general guidelines for the design. They also fail to distinguish different classes of DP service from one another. The requirements for capability and reliability of a DP system depend on the DP mission profile: a support vessel kept automatically on stand-by station close to a platform does not need the same degree of operational reliability and positioning accuracy as a DP vessel drilling in shallow water through a marine riser in an area of shifting currents.

The propulsion system has to be designed exactly according to the DP mission requirements and specifications for a particular vessel. DP vessels frequently operate for extended periods of time in remote areas, far away from shipyards or other support facilities which could assist in repairs and overhauls of equipment. It is mandatory for a successful DP operation that the equipment is designed for long endurance and easy serviceability. The components of the propulsion system which are underwater should be designed for ultra reliability and/or should be accessible or removable without drydocking the vessel or needing the assistance of outside heavy lift equipment.

The following chapter describes selected problem areas regarding the design, reliability, and operational efficiency.

6.2 Conventional Main Propulsion Systems

The typical conventional main propulsion arrangement of a DP vessel consists of an electric motor assembly driving a FP or CP propeller. The standard choice for electric propulsion in the past has been a direct drive, low speed electric motor, custom-designed and built. Although these motors were very reliable, a failure or a maintenance requirement of the motor disabled the power train to the propeller. Today, direct drive motors are seldom installed. High prices and long delivery times of the custom motors and the availability of high power industrial motors in all electric types of construction has led to a preference of the latter motors, which require the installation of a reduction gear since industrial higher speed motors cannot be applied directly to drive a propeller. This allows an economical

compound of several electric motors driving into one propeller shaft. The redundancy of the electric motor system is therefore increased, but the reduction gear remains the weak link in the power train. However, highly reliable reduction gears are available today and careful selection, sizing, and design of a gear should lead to satisfactory service. A conservative design/service factor which is at least as high as the factors used for reduction gears for tugs should be applied.

Multiple motor arrangements feature a number of benefits: availability of the motors, availability of spare parts, short delivery times, etc. In some cases, a total spare motor or major subassemblies may be stored on board.

Easy access or removal of the motor must be considered when designing the multiple motor arrangement. Couplings should be furnished with a spacer for easy separation or isolation of a motor shaft without the need of moving a motor horizontally on its foundation.

DC motors in DP service are subject to frequent stopping, reversal, acceleration, and deceleration maneuvers. Special attention has to be given to the design of the coupling assemblies. The requirements of the classification societies do not adequately cover this type of service.

Multi-motor arrangements are utilized by all DP drill vessels with conventional propulsion drives. The number of motors per propeller shaft ranges from two (PELICAN series) to six (SEDCO vessels). SEDCO uses standard locomotive DC motors of 800 hp each. In case of a failure, an easy exchange of a motor is ensured by the compact size and low weight of these motors.

6.3 Right-Angle Gear Thrusters

6.3.1 Installation Options

Tunnel Thrusters: Mechanical protection is provided by the installation of a right-angle gear thruster inside a tunnel. The inflow into the propeller is rather uniform, thus eliminating situations which occur with azimuthing thruster propellers, such as oblique inflow and rapidly changing inflow conditions. The tunnel thrusters are exposed to very low dynamic loads.

Tunnel thrusters may be damaged by floating debris trapped inside the tunnel. Severe secondary damage to the power train components can result in a failure of the propeller shaft seal.

The vessel is usually drydocked during maintenance to the power train, i.e., the propeller shaft seal. Only the vertical pinion assembly, including bearings and seals, can be removed

from the thruster without drydocking the vessel in most thruster designs.

For DP service, accessibility to the thrusters for maintenance (at least in emergency cases) is preferred while the vessel is afloat.

Two arrangements satisfy this requirement. Either method results in penalties in the initial investment or performance reduction, or requires additional installation space.

Maintenance to the tunnel thruster while the vessel is afloat requires the following:

> A watertight seal of the tunnel entries/exits or access to the thrusters either by access to the inside of the tunnel through a hatch in the tunnel top or a "trunk" installation of the thruster, which allows a vertical lift of the entire assembly. The second access method provides better working conditions and is preferred in spite of the larger space requirements.
>
> An operational risk is created by sealing the tunnel ends. A malfunction of the seal arrangement can cause the flooding of the section of the vessel where the tunnel is located (eventually the engine room for the stern thrusters).
>
> A previous section discussed the basic considerations of the tunnel thruster installation including hydrodynamic aspects.

Rotatable Thrusters: Rotatable thrusters are typically installed as follows:

- Through-hull, fixed-bottom mounted (this type requires drydocking of the vessel for maintenance.)
- Through-hull, bottom mounted, underwater detachable
- As above, but inside detachable (new method, developed by Aquamaster)
- Encapsulated (prime mover and auxiliary machinery is installed in a self-contained capsule which can be removed for maintenance.)

Maintainability of the thruster and access without drydocking are preferred requirements for

DP propulsion. Several manufacturers offer a bottom detachable thruster as a standard design, whereas an encapsulated thruster must often be custom-designed.

Encapsulated Thrusters: The encapsulated installation method is mainly applied for the deeply submerged thrusters on semisubmersible units; other installations include thrusters on jack-up-rigs (Rowan), and, in combination with a retracting feature, on DP drill vessels.

The capsule encloses the entire drive and auxiliary machinery including the cooling systems, steering drive, lubrication and pressure compensation systems, ventilation, and support systems such as bilge pumps and fire fighting systems.

The total assembly weight is one of the major disadvantages of the encapsulated system. A crane capacity which is normally not found on DP vessels is required in order to remove an encapsulated thruster and to position it on deck for maintenance.

An encapsulated thruster, including all internal piping and wiring which allows testing and no load trial runs of all systems at the factory, is completely built by the manufacturer. The shipyard interface is reduced to a minimum and can be accurately defined.

An encapsulated thruster employs a single, vertical prime mover due to the narrow cylindrical shape of the capsule. In some cases, a tandem arrangement of two motors in series is utilized (one motor on top of the other); this reduces the size of the motor but does not increase redundancy by 100 per cent.

In most installations, the capsule can be retracted into a shallow-water stowage position with the aid of the vessel's own lifting gear. This position provides a flush bottom without the protrusion of a thruster beyond the base line of the vessel, thus allowing the vessel to be towed into shallow water areas. This operation requires less time and effort than the removal and storage of removable bottom mounted thrusters.

Bottom Detachable Thrusters: Bottom detachable thruster technology was developed (originally by KaMeWa) to circumvent some of the inherent disadvantages of the encapsulated thrusters. It allows the underwater installation and removal of the lower part of the thruster. The need for support services such as divers, work boats, cranes, etc. during the installation or removal operation is the major disadvantage of this type of installation. Recently, a method which employs remote operated vehicles (ROVs) in lieu of divers has been introduced by KaMeWa .

A bottom detachable thruster is installed by the shipyard which usually manufactures a matching bottom structure according to the drawings provided by the thruster manufacturer.

The thruster manufacturer supplies the direct support systems such as hydraulic systems for pitch control and steering which are then installed by the shipyard. Other subsystems such as ventilation, cooling, etc. are furnished by the yard. The final assembly can only be tested at the shipyard.

A bottom detachable thruster installation is not typically associated with severe space limitation problems. It is feasible to use two drive motors per thruster for this type of installation. The motors are horizontally mounted and drive the thruster through a top right-angle gear. This arrangement provides full redundancy for the thruster drives. It reduces the size of the motor and, thus, reduces the costs for the starting equipment and eases maintenance.

Underwater Handling Methods: The methods applied by several thruster manufacturers utilize an arrangement of wire ropes for the support of the lower thrust units. The winches for the ropes are either located inside the lower hull or on the upper deck of the vessel.

The systems vary in their mechanical details such as the methods of sealing the openings in the hull, the mating structures in the hull, the type of guidance of the thrust unit into its seating, the type of remote faster handling, and the location of the mechanical separation with regard to the steering gear.

The following points should be considered when evaluating the quality of the design of a particular system:

- All maintenance-prone parts, e.g., azimuth seals, steering gear, etc., should be accessible after removing the thrust unit.
- The weight of the thrust unit should be low enough to be handled by the onboard lifting devices.
- The amount of clearance which is required between the bottom of the hull and the sea floor for the installation/removal procedure should be sufficient.
- The number of divers required to assist the procedure should be known.
- Required support services, such as crane barges, supply vessels etc., should be known.
- The average duration of a removal/installation should be known.

In conclusion, it may be stated that the available underwater handling methods are cumbersome but safe, as are other methods, e.g., retracting an encapsulated thruster. Improvements in design continuously being made.

Retractable Thrusters: The installation of a thruster which extends under the hull during normal stationkeeping operation and which is retracted during transit to decrease the resistance and the draft of the vessel is often the only solution to an otherwise difficult operational problem.

Retractable thrusters are very expensive and mechanically complex. Therefore, they should be considered only if other installation options are unfeasible. In particular, this applies to installations involving high power and high thrust propulsion devices. Smaller retractable thrusters have been successfully installed on DP vessels, such as on the WIMPEY SEALAB. The weight of the assembly, the moment produced by the propeller thrust acting on the long extension arm, and the transfer of the forces into the hull create a variety of problems for larger thrusters. A feasible compromise can be achieved by using an encapsulated thruster and retracting the entire capsule. This approach eliminates the separate retracting mechanism of the power train. The design of a retractable capsule was applied to the (fixed direction, transverse) thrusters on the SEDCO and Transocean drillships. The retraction is actuated by hydraulic cylinders (SEDCO) or simply by lifting and lowering the units with onboard cranes (Transocean).

6.3.2 Basic Considerations for the Design of Right Angle Gear Thrusters

The following chapter addresses some design aspects and problem areas relating to the reliability of the thrusters.

Design of the Gear Housing: A right angle gear thruster is an "open gear" design, i.e., the right angle gear components (ring gear and pinion gear) are calculated and manufactured by a specialized company and installed by the thruster manufacturer. The thruster manufacturer is responsible for the design of the housing, shafting, bearing arrangements, etc. No standards or regulations guide the design of the gear housings. The thruster gear housing is affected by exterior forces such as the propeller thrust and the weight of the nozzle which is usually supported in part by the gear housing. The primary requirements for the right angle gear are rigidity of the gear housing and freedom of deflection. Any deflections directly affect the action of the gear mesh.

A stress analysis applying finite element techniques should be performed during the design for large thrusters (1500 to 8000 hp) . The results should prove that the reflections are within acceptable limits and should be approved by the gear manufacturer.

Design, Manufacturing, and Testing of Right Angle Gears: Gears for thrusters over 2000 hp are addressed in particular in the following. Only a few gear companies are equipped and qualified to manufacture large size, high power right angle gears. In recent years, practically every large thruster gear was manufactured by Klingelnberg in Germany or manufactured on Kligelnberg gear cutters. This includes gears installed in thrusters of European or Japanese manufacture. Klingelnberg and gear manufacturers utilizing Klinelnberg machinery have dominated the thruster market worldwide since the advent of demand for larger thrusters in the early 1970s. Klingelnberg has since then accumulated a great deal of experience via the feedback of field reports with thrusters from the various manufacturers.

For critical applications, Klingelnberg's engineering department may be consulted and asked for advice regarding the rating of a particular proposed gear design.

Gear Testing: It is recommended that a full torque test be conducted in order to ensure the appropriate installation and adjustment of a large right angle gear. This test should be done after completion of the final settings and adjustments of bearings and gears and after a satisfactory no load check of the gear. Although it is neither a standard procedure nor a mandatory requirement of the manufacturers of the right angle gears, a full torque test is the only assurance that the gear contact under actual operating conditions complies with the gear design criteria.

A workshop test should attempt to simulate the actual operating conditions as closely as possible. It is not feasible to simulate the dynamic loads acting upon the propeller blades. Furthermore, it is very difficult to simulate the deflection of the gear housing caused by the propeller thrust. However, the static torque of the gear train can be simulated while simultaneously applying an axial force equivalent to the propeller thrust to the propeller shaft. This thrust causes the propeller shaft to move into its final position by the plastic deformation of housing walls, bearing supports, and by eliminating internal bearing clearances.

This test can be performed at very low costs; only a few revolutions of the ring gear are required. The size, location, and shape of the contact pattern on the gear teeth under the simulated loads can be evaluated regarding its compliance with the manufacturer's recommendations.

Gear Standards: The following standards are widely used for the calculation of right angle gears:

- DIN 3990 Rating of Spur and Bevel Gears
- ISO Standard for Gears
- ANSI/AGMA/American Gear Manufacturers Association Standard 2003-A 86 Rating of Spiral Bevel Gear Teeth

Rules of the Classification Societies for DP Propulsion Machinery:

Det Norske Veritas DnV addresses propulsion machinery in their ***Rules for Classification of Steel Ships , Part 6 Chapter 7: Dynamic Positioning Systems*** . The rules for gears refer to DnV standard rules for spur and helical marine reduction gears.

A thorough discussion of rules for right angle gears for thrusters in DP service is found in ***American Bureau of Shipping: Guide for Thrusters and Dynamic Positioning Systems***

This guide addresses bevel gears and refers to the above AGMA standards. It indicates service factors for contact stress and bending stress. The guidelines distinguish between thrusters for athwartship service (transverse tunnel thrusters used for maneuvering only) and thrusters for main propulsion, propulsion assist, and dynamic positioning. The selection of the service factors by ABS is very realistic. The application of these rules in conjunction with the AGMA standard delivers conservatively rated gears.

Azimuthing Gear: A hydraulically actuated gear assembly which utilizes either high-torque or geared high-speed hydraulic motors became standard for azimuth gear drives in recent years**.**. Large thrusters use a bull gear driven by several pinions, each actuated by a separate hydraulic motor. The gear should be designed to meet the hydrodynamic steering moments which occur during stationkeeping.
A response time of 10 to 12 degrees per second is required for DP service. The rules of the classifications society must be applied if the same gear is used for steering during transit. A gear sized for DP service is usually good for transit steering, provided the hydraulic circuit is equipped with a power limitation. This feature prevents overload of the system by reducing the flow and subsequently reducing the steering response. But even this reduced response should satisfy the requirements for transit steering.

The steering moments are a function of the physical size and geometry of the rotatable thruster, the speed of advance, and the angular position.

Seals: Seals are critical problem areas, in particular for deep submerged thrusters.

Propeller shaft seal: This is the most critical seal in a thruster assembly. Leakage in this seal allows sea water to penetrate into the gear housing and to contaminate the lubrication oil for gear and bearings. Major damage to gears and bearings can result from a breakdown of lubrication. Several different types of seals are successfully applied as propeller shaft seals: low pressure lips seals and high pressure radial seals. As a low pressure lip seal, the HDW Simplex Compact Seal is widely used. This seal, which was developed for commercial propeller shaft applications, consists of several lip seals running on a replaceable wear sleeve. The life of the seal can be extended by using seal rings of Viton running on a sleeve with a surface coated with chromium oxide. This seal is a low pressure seal, it requires a maximum pressure differential between inside oil and outside sea water of approximately 3 to 5 psi. In case of a leakage, oil would leak out. The pressure inside the gear housing must be controlled when using this type of seal for a deep and variable draft application. Thrusters for semisubmersibles accomplish this pressure control either by an automatic control system or by connecting the gear housing oil space to header tanks of different elevation, depending on the submergence of the thruster. The latter method is simple but rather crude. The automatic pressure control raises the oil level of a stand pipe according to the outside sea water pressure. This method continuously provides the appropriate pressure differential for the lip seals, even during the lowering and raising operations of the semisubmersible.

Another approach utilizes radial seal assemblies (face seals or mechanical seals). The gear housing can be pressurized with a constant pressure independent of the submergence with these seals.

Azimuth seal: The azimuth seal is a further critical component. No commercial seal assemblies are developed for the required size and application. The oscillating rotation, the frequent reversal in direction, and the large diameter make this seal application very difficult.

Design features of this seal should include multiple (four) seal rings, separated by lantern rings and installed so that an equal amount of compression for each seal ring is allowed. The cavity between seal rings should be connected with small diameter tubing to the inside of the thruster compartment. This feature allows a check on the condition of the seals and allows grease or other compounds to be pumped into the seal assembly in case of a leakage.

A rigid thruster support design with a minimum of deflection is a prerequisite for the satisfactory function of the azimuth seals.

Bearing Life: The ABS Guide for Thrusters and Dynamic Positioning Systems (1994) determines the following minimum L10 life for continuous duty thrusters:

Propulsion service	20,000 hours
Dynamic positioning service	20,000 hours

Balancing of the bearing life is the major task in the design of a thruster gear drive. It is difficult to install a long life bearing at the lower pinion shaft due to the specific geometry for nearly every thruster design. However, a minimum L10 life of 30,000 hours should be achieved for the lower pinion bearing, whereas all other bearings in DP service should be rated for 50,000 to 100,000 hours.

7 PROPULSION DRIVE SYSTEMS

7.1 General

To a large extent, the performance of a propulsion system is governed by the characteristic of the drive machinery. Although widely applied, some types of prime movers are very poor matches for the propellers on vessels which have to operate frequently and for extended periods of time in different modes of operation. The DP vessel is a typical example of a vessel with multi-mode propulsion requirements. Operations with high thrust requirements at bollard pull or zero inflow velocity and cruising at full speed and full power are extremely different conditions, and a match of the characteristics of the propeller and the prime mover for both conditions is restricted to only a few propeller/machinery arrangements. The utilization of a controllable pitch propeller with its capability of adjusting the pitch to the required power or thrust command allows the application of prime movers which are not qualified for fixed propeller applications because of the incompatibility of their characteristics or the lack of reversibility of the rotation direction.

The following chapter describes the available prime mover options and comments on their feasibility as candidate drive machinery for DP applications.

7.2 Diesel Engine Drives

The majority of the commercial vessels are driven by Diesel engines. Low-speed, two-stroke Diesel engines are predominantly used to directly drive the propeller on medium and large vessels. Many smaller vessels utilize medium or high-speed Diesel engines with reduction gears between the engine and propeller.

A Diesel engine driving a fixed-pitch propeller is not a qualified candidate for a DP propulsion system.

- A stepless control between zero RPM and full RPM is not feasible. A Diesel engine must always maintain a minimum (idling) RPM or it must be stopped.

- Reversing maneuvers are slow; they include either shifting a reverse gear or direct reversing, which includes stopping and starting the engine in the opposite direction.

- Engine control consists of controlling the fuel rack position of the engine; it is not possible to integrate this control into a close loop/feedback-type control system.

In cases of existing, converted systems, a Diesel engine driving a controllable pitch propeller could be utilized. The engine control has to be modified for constant RPM operation, and the DP control system can only interface with the pitch control system. The selected engine and controls must be able to respond to rapid load changes; the engine must be able to operate continuously at the expected low power levels. The engine manufacturer must be consulted for recommendations. The feasibility of low load operation varies between engine designs. Special fuel injectors can be installed on some engines in order to allow low load operation. However, in this case full load can no longer be achieved.

In conclusion, it can be stated that some engine plans may be utilized after modifications for conversions of vessels for DP service. The direct or geared Diesel engine drive is not a desirable candidate for newly constructed vessels.

7.3 Steam Turbines

Although it matches the FP propeller characteristics better than a Diesel engine, the geared steam turbine drive is also does not qualify for DP propulsion. It is a propulsion drive which is fading out of the technology. A steam turbine plant may be utilized for conversions. The turbine needs to be modified for constant RPM control and low load operation, the reverse turbine must be deactivated, and the boiler and steam circuit have to be modified or prepared for continuous low load operation. The propeller must be exchanged with a CP propeller. The DP control only interfaces with the CP propeller. The capability of the boiler/turbine system to respond to sudden load changes must be checked, and improvements, if required, must be implemented.

7.4 Electric Drives

The predominant type of prime movers for DP propulsion plants is the electric drive. Practically every DP propulsion device installed in newly constructed vessels as well as in most of the conversions is driven by an electric motor.

In the beginning of DP technology (which coincided with the advent of the DC/SCR technology), either AC motors were utilized driving CP propellers at constant RPM or SCR-controlled DC motors were utilized driving fixed-pitch propellers at variable RPM.

In recent years, variable speed AC drives have become available and have been used in some applications for DP propulsion.

The following chapter describes the various electric drive options and comments on their feasibility for DP application.

7.4.1 AC Systems with Controllable Pitch Propeller

System Description: A traditional AC system consists of several generators which feed AC of constant frequency and voltage (4160 - 6000 VAC) into a common bus. Either one or several induction or synchronous motors drive the propeller. Its inability to continuously vary the speed of the propulsion motors from zero to maximum is the major disadvantage of this system.

The control of propeller thrust in magnitude and direction has to be accomplished by a controllable pitch propeller. The propeller and its drive machinery operate continuously in one sense of direction. No frequent start/stop maneuvers are required. The absence of high power electronic switching devices increases the reliability of the electric system.

History and Applications: The AC-CP propulsion system is quite popular due to its high efficiency and electrical simplicity. The PELICAN series of dynamically positioned drill vessels is a prominent example of this propulsion drive. It consists of 6000 VAC generators which power two induction-type propulsion motors per shaft. The propeller shaft is driven through a reduction gear by the two motors.

AC-CP drives are utilized for propulsion of dynamically positioned semisubmersible drilling rigs. Both SEDCO 709 and SEDCO 710 are propelled by eight 3000 hp rotatable propulsion units with CP propellers. Each propeller is driven by a 4160 VAC synchronous motor through a right angle gear. Synchronous motors were selected to stabilize the power factor of the AC system for this application.
The PELICAN class drill vessels have been in operation since the early 1970s. SEDCO 709 was commissioned in 1976 and SEDCO 710 was commissioned in 1982. No major problems have been reported regarding the electrical systems or the CP propeller systems. The relatively low efficiency during low load operations caused by the propeller turning constantly at full rated speed is the major drawback of these systems.

Recent system designs attempt to reduce these inherent disadvantages of the AC-CP systems:

The (no DP) Readings & Bates semisubmersible ZANE BARNES (1987) is equipped with 2 x 7000 hp rotatable propeller drives for cruising and mooring assist. During low load operations, the frequency of the generators is reduced from 60 cycles to 40 cycles, subsequently proportionally reducing the RPM of the propulsion motors.

The Coflexip DP pipe laying vessel SUNRISE (1994) is equipped with ***CPP*** thrusters driven by AC constant speed motors. The DP SEDCO 707 was also upgraded with 8x3000 hp azimuthing thrusters.

Efficiency: The system efficiency at design point (maximum load) of an AC-CP system is the highest of the electric drive systems.

The CP propeller driven by a constant RPM prime mover is comparable in efficiency with a variable speed fixed-pitch propeller only at full load condition. (Even at this condition, the efficiency of the fixed-pitch propeller is marginally higher.) The CP propeller is less efficient than a fixed pitch propeller in partial load conditions and, in particular, during neutral operation (zero thrust).

While idling at full RPM in neutral blade position, a typical CP propeller consumes approximately 20% (and, in some cases, up to 30%) of its rated power, i.e., two 7000 hp CP propellers on a DP drill vessel during stand-by mode, producing zero thrust, consume 2800 hp.

Subsequently, a reduction of the propeller RPM during low speed and maneuvering operations lowers these parasitic propeller loads. Varying the system frequency from 60 Hertz to 40 Hertz reduces the above-mentioned power requirements from 20% at 60 Hertz to 6-10% at 40 Hertz.

Since the mission profile of a DP vessel includes frequent maneuvering and stand-by operations and relatively short time periods of operation at full speed, a variable or two-step propeller speed control through operating the Diesel generators between 60 and 40 Hertz would provide an effective arrangement.

CP Propeller System Reliability: Although the electrical part of an AC-CP system is a simple and reliable arrangement, a CP propeller is considerably more complex than a fixed-pitch propeller. This problem is amplified by the fact that the major portion of the mechanical parts (the pitch mechanism) is unaccessible for routine maintenance and requires drydocking of the vessel to gain access to or removal of the thruster.

A CP propeller, however, is considered to be a reliable propulsion device worldwide. Its disadvantages are outweighed by the benefits in specific installations. One of the major advantages of a CP propeller installation for DP propulsion is the constant operation of the propeller, thus eliminating frequent start/stop/reversing maneuvers of the propulsion power train.

7.4.2 AC/DC System with SCR Controlled Fixed Pitch Propeller

System Description: In a typical AC/DC propulsion system, AC current is produced by several Diesel generators at constant voltage (600 VDC max.) and frequency. This AC current is converted by silicon controlled rectifiers into variable voltage (0-750 VDC) direct current. The propulsion motor is a DC motor or a combination of several motors. The speed of the DC motor is a function of the armature voltage and the strength of the excitation. Controlling the output voltage of the SCRs from zero to full voltage provides stepless speed control of the DC motor from zero to rated RPM.

A fixed pitch propeller is driven by the propulsion motors. Varying the propeller RPM and reversing the rotation direction of the propeller shaft allow the thrust to be controlled in magnitude and direction.

The AC/DC propulsion combines the highly efficient and reliable generation of AC current with the characteristic of the DC motor. This characteristic includes the capability of producing high torque at low speed, the feasibility of varying the characteristic by adjusting the excitation, and easy reversing of the direction of rotation.

Disadvantages of this system include:

- The limitation of voltage. Common maximum voltages are 600 VAC/750 VDC. This leads to heavy, expensive motors and cable runs.
- The higher maintenance requirements of the DC motors due to commutator wear.
- The installation of high power electronic equipment requiring a clean and cool environment.
- The need of personnel capable of operating and maintaining electronic equipment.
- The presence of electromagnetic interference (EMI)—unwanted voltage or current produced by the SCRs—which causes an undesirable response in electronic equipment (such as engine and generator controls, instrumentation, navigation equipment, engine room automation, computers, etc.)

History and Applications: Since the introduction of the high current SCR in the late

1960s, the AC/DC electric propulsion drive has become quite popular. Vessels with this type of propulsion system include fishing trawlers and factory vessels, research vessels, icebreakers, offshore supply vessels, conventionally moored and dynamically positioned drill vessels, and semisubmersibles.

DP drill vessels with SCR controlled AC/DC propulsion systems include the following:

SEDCO 445
SEDCO 471
SEDCO 472
GLOMAR EXPLORER
GLOMAR CHALLENGER
Transocean 534
Transocean SEVEN SEAS
HENRY GOODRICH

Efficiency: The efficiency of the electrical system can be determined as follows:

AC generators	97%
SCRs	98%
Propulsion DC motors	94%
Total system efficiency	89%

In the case of a multiple high speed DC motor arrangement, the efficiency of the reduction gear must be considered (98%).

System Performance: Regeneration: in order to regenerate, the SCR system must have a reversing field supply contactor or back-to-back SCR bridges. The same control can be achieved by reversing the armature, but the high power components which are required make this option are very expensive.

Generally, DC motors are available in two basic designs, either with series field excitation or shunt field excitation. The characteristics of a DC motor is determined by the type of excitation. The characteristics of a shunt motor are very different from those of a series motor. The shunt field motor is exclusively applied for propulsion drives.

Operation of a DC Shunt Motor: varying the SCR output voltage from 0 to 720 volts controls the range between zero and the nominal (base) speed of the motor. Over this entire speed range, the full torque of the motor is available at rated field current. Independent of the control command, a current-limiting circuit in the SCR control system prevents the motor from overloading. This current limitation protects the mechanical components of the

propulsion system, such as reduction gears, couplings, and shafting, against overload in torque.

By lowering the field current under rated value, the torque/speed characteristic of the shunt motor can be varied to a high degree. The motor can produce constant power output at reduced torque and increased speed in this field-weakened condition. The range of field weakening is limited by the design of the commutator. A weakened field leads to increased armature current which increases the problems of commutation.

Reversing the direction of field current reverses the shunt motor.

The shunt motor is adaptable to a wide range of propeller operations due to its performance flexibility. It is one of the optimum prime movers for a fixed pitch propeller drive system.

DC systems are still competitive in the power range up to approximately 4000 hp per propeller. The upgrade of the GLOMAR EXPLORER (1996, 4x3000 hp) as well as the conversion of the crane barge HERCULES (1996, 8x3000 hp) utilized SCR - DC systems for the thruster drives.

7.4.3 AC/AC System with Variable Frequency Drive and Fixed Pitch Propeller

System Description: This type of AC system usually generates medium voltage AC (4160 to 6000 VAC) at constant frequency and voltage. It controls the RPM of the drive motor—induction or synchronous motors, depending on the type of system—by varying the frequency of the system.

Three basic system configurations are available for the variable frequency control:

Cyclo Converter: The cyclo converter converts a three-phase AC voltage of constant frequency into a variable three-phase AC voltage with variable frequency. This system is large and expensive, and its major advantage (high torque at zero rpm) is not required for DP propulsion. These drives are typically applied as direct propeller drives on modern icebreakers.

Synchro Converter: The synchro converter is typically a six step Load Commutated Inverter (LCI). In conjunction with a synchronous motor it allows load commutation of the inverter and the use of far simpler firing schemes with high power SCRs. The greater simplicity of the control system is the main advantage of this system. Until recently, these systems were only able to control the speed to approximately 10% of synchronous speed.

Synchro converter drives were applied to provide quiet propulsion for passenger vessels; the required range of control of thrust was accomplished by controlling the pitch of a controllable pitch propeller in conjunction with the (limited) speed control of the synchronous propulsion motors (Queen Elizabeth II repowering).

Advances in the design of the synchro converter now allow speed control over the full operating range, from zero to full speed.

ALLSEA’s new DP pipe laying vessel SOLITAIRE applies a synchro converter for the propulsion system.

PWM Drive: The PWM drive is pulse width modulated voltage source inverter which controls standard induction motors. To this date, this is the only variable AC system in DP service (ALLSEA's LORELEY Pipelaying Vessel, 1985). Two dynamically positioned cable ships are equipped with PWM electric propulsion. ABB has equipped 15 vessels with PWM drives for propulsion and thrusters.

The following features qualify this type of drive for DP applications:

- The drive provides a very flexible system. It is not necessary to start the engines for thruster starts. All thrusters can stay connected to one or two generators without rotation and any of them can supply thrust within seconds.
- The converter uses Gate-Turn-Off (GTO) thyristors; no commutation circuits are required. Switching losses are minimal. The efficiency at rated load is as high as 99%.
- The Neutral Point Clamped (NPC) connection of the thyristors means fewer harmonics in the output voltage, which in turn results in lower losses in the drive motor. Motor efficiencies may exceed 96%.
- The system utilizes induction motors, which are the simplest and most robust type of electric motors available. Very little maintenance is required for the induction motor.
- The PWM allows a smooth start. No starting inrush occurs when starting the

motor (soft-start). Full torque is available immediately when accelerating. Acceleration time and the mechanical stresses are limited to the rated values and are controlled by appropriate programming of the starting sequence. The power factor is close to unity over the entire speed range. Consequently, generators, transformers, and cables can be selected for a power factor of .95, instead of .8 or .7 as with conventional conversion systems.

- Frequency converters allow field weakening similar to DC shunt motors. The characteristic of the drive can be tuned to the varying propeller characteristics at different inflow velocities.

- The propeller thrust/motor rpm control is completely digital; it has no mechanical or hydraulic components

Unfavorable features include:

- Higher costs than other drives

- Complex electronic equipment which requires qualified and trained personnel. Since digital technology is applied in other systems of a DP drillship (DP controls, power management system, etc.) this factor should not create any problems.

- The PWM converter which generates harmonics in the main power lines; this must be taken into account when planning of the system and cabling. However, the harmonic content is substantially smaller than that of other types of frequency converters, since rectification takes place in a diode bridge and the current fundamental is directly proportional to the kW output of the motor.

Cost, Space and Maintenance Requirements: The variable frequency drive system is by far the most expensive propulsion system alternative. The great amount of solid state power switching devices demands far more installation space than any other system. A system of a high degree of complexity requires personnel educated in maintaining sophisticated electronic equipment.

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