Components and Elements of
Aircraft & Marine Propulsion

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Propeller

Rotating the Hamilton Standard 54H60 propeller on a US Navy EP-3E Orion's number four engine as part of pre-flight checks

A **propeller** is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and air or water is accelerated behind the blade. Propeller dynamics

can be modeled by both Bernoulli's principle and Newton's third law. A propeller is often colloquially known as **screw** both in aviation and maritime.

History

Ship propeller from 1843. Designed by C F Wahlgren based on one of John Ericsson propellers. It was fitted to the steam ship s/s *Flygfisken* built at the Motala dockyard.

The principle employed in using a screw propeller is used in sculling. It is part of the skill of propelling a Venetian gondola but was used in a less refined way in other parts of Europe and probably elsewhere. For example, propelling a canoe with a single paddle

using a "j-stroke" involves a related but not identical technique. In China, sculling, called "lu", was also used by the 3rd century AD.

In sculling, a single blade is moved through an arc, from side to side taking care to keep presenting the blade to the water at the effective angle. The innovation introduced with the screw propeller was the extension of that arc through more than 360° by attaching the blade to a rotating shaft. Propellers can have a single blade, but in practice there are nearly always more than one so as to balance the forces involved.

The origin of the actual screw propeller starts with Archimedes, who used a screw to lift water for irrigation and bailing boats, so famously that it became known as Archimedes' screw. It was probably an application of spiral movement in space (spirals were a special study of Archimedes) to a hollow segmented water-wheel used for irrigation by Egyptians for centuries. Leonardo da Vinci adopted the principle to drive his theoretical helicopter, sketches of which involved a large canvas screw overhead.

In 1784, J. P. Paucton proposed a gyrocopter-like aircraft using similar screws for both lift and propulsion. At about the same time, James Watt proposed using screws to propel boats, although he did not use them for his steam engines. This was not his own invention, though; Toogood and Hays had patented it a century earlier, and it had become an uncommon use as a means of propelling boats since that time.

By 1827, Czech constructor Josef Ressel had invented a screw propeller which had multiple blades fastened around a conical base; this new method of propulsion allowed steam ships to travel at much greater speeds without using sails thereby making ocean travel faster (first tests with the Austro-Hungarian Navy).

John Patch, a mariner in Yarmouth, Nova Scotia developed a two-bladed, fan-shaped propeller in 1832 and publicly demonstrated it in 1833, propelling a row boat across Yarmouth Harbour and a small coastal schooner at Saint John, New Brunswick, but his patent application in the United States was rejected until 1849 because he was not American citizen His efficient design drew praise in American scientific circles but by this time there were multiple competing versions of the marine propeller.

In 1835, when Francis Pettit Smith discovered a new way of building propellers. Up to that time, propellers were literally screws, of considerable length. But during the testing of a boat propelled by one, the screw snapped off, leaving a fragment shaped much like a modern boat propeller. The boat moved faster with the broken propeller. At about the same time, Frédéric Sauvage and John Ericsson applied for patents on vaguely similar, although less efficient shortened-screw propellers, leading to an apparently permanent controversy as to who the official inventor is among those three men. Ericsson became widely famous when he built the *Monitor*, an armoured battleship that in 1862 fought the Confederate States' *Virginia* in an American Civil War sea battle.

The first screw propeller to be powered by a gasoline engine, fitted to a small boat (now known as a powerboat) was installed by Frederick Lanchester, also from Birmingham.

This was tested in Oxford. The first 'real-world' use of a propeller was by David Bushnell, who used hand-powered screw propellers to navigate his submarine "Turtle" in 1776.

The superiority of screw against paddles was taken up by navies. Trials with Smith's SS *Archimedes*, the first steam driven screw, led to the famous tug-of-war competition in 1845 between the screw-driven HMS *Rattler* and the paddle steamer HMS *Alecto*; the former pulling the latter backward.

In the second half of the nineteenth century, several theories were developed. The momentum theory or Disk actuator theory—a theory describing a mathematical model of an ideal propeller—was developed by W.J.M. Rankine (1865), Alfred George Greenhill (1888) and R.E. Froude (1889). The propeller is modeled as an infinitely thin disc, inducing a constant velocity along the axis of rotation. This disc creates a flow around the propeller. Under certain mathematical premises of the fluid, there can be extracted a mathematical connection between power, radius of the propeller, torque and induced velocity. Friction is not included.

The blade element theory (BET) is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. It involves breaking an airfoil down into several small parts then determining the forces on them. These forces are then converted into accelerations, which can be integrated into velocities and positions.

A World War I wooden aircraft propeller on a workbench

Postage stamp, USA, 1923

The twisted airfoil (aerofoil) shape of modern aircraft propellers was pioneered by the Wright brothers. While both the blade element theory and the momentum theory had their supporters, the Wright brothers were able to combine both theories. They found that a propeller is essentially the same as a wing and so were able to use data collated from their earlier wind tunnel experiments on wings. They also found that the relative angle of attack from the forward movement of the aircraft was different for all points along the length of the blade, thus it was necessary to introduce a twist along its length. Their original propeller blades are only about 5% less efficient than the modern equivalent, some 100 years later.

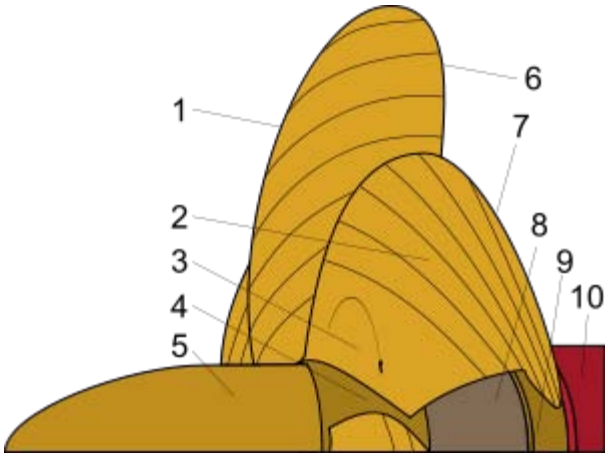
Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some of his designs used a bent aluminium sheet for blades, thus creating an airfoil shape. These are heavily undercambered because of this and combined with the lack of a lengthwise twist made them less efficient than the Wright propellers. Even so, this was perhaps the first use of aluminium in the construction of an airscrew.

Aviation

Aircraft propellers convert rotary motion from piston engines or turboprops to provide propulsive force. They may be fixed or variable pitch. Early aircraft propellers were carved by hand from solid or laminated wood with later propellers being constructed from metal. The most modern propeller designs use high-technology composite materials.

Marine

Marine propeller nomenclature



1) Trailing edge	6) Leading edge
2) Face	7) Back
3) Fillet area	8) Propeller shaft
4) Hub or Boss	9) Stern tube bearing
5) Hub or Boss Cap	10) Stern tube

A propeller is the most common propulsor on ships, imparting momentum to a fluid which causes a force to act on the ship.

The ideal efficiency of any size propeller (free-tip) is that of an actuator disc in an ideal fluid. An actual marine propeller is made up of sections of helicoidal surfaces which act together 'screwing' through the water (hence the common reference to marine propellers as "screws"). Three, four, or five blades are most common in marine propellers, although designs which are intended to operate at reduced noise will have more blades. The blades are attached to a *boss* (hub), which should be as small as the needs of strength allow - with fixed pitch propellers the blades and boss are usually a single casting.

An alternative design is the controllable pitch propeller (CPP, or CRP for controllable-reversible pitch), where the blades are rotated normal to the drive shaft by additional machinery - usually hydraulics - at the hub and control linkages running down the shaft. This allows the drive machinery to operate at a constant speed while the propeller loading is changed to match operating conditions. It also eliminates the need for a reversing gear

and allows for more rapid change to thrust, as the revolutions are constant. This type of propeller is most common on ships such as tugs where there can be enormous differences in propeller loading when towing compared to running free, a change which could cause conventional propellers to lock up as insufficient torque is generated. The downsides of a CPP/CRP include: the large hub which decreases the torque required to cause cavitation, the mechanical complexity which limits transmission power and the extra blade shaping requirements forced upon the propeller designer.

For smaller motors there are self-pitching propellers. The blades freely move through an entire circle on an axis at right angles to the shaft. This allows hydrodynamic and centrifugal forces to 'set' the angle the blades reach and so the pitch of the propeller.

A propeller that turns clockwise to produce forward thrust, when viewed from aft, is called right-handed. One that turns anticlockwise is said to be left-handed. Larger vessels often have twin screws to reduce *heeling torque*, counter-rotating propellers, the starboard screw is usually right-handed and the port left-handed, this is called outward turning. The opposite case is called inward turning. Another possibility is contra-rotating propellers, where two propellers rotate in opposing directions on a single shaft, or on separate shafts on nearly the same axis. One example of the latter is the CRP Azipod by the ABB Group. Contra-rotating propellers offer increased efficiency by capturing the energy lost in the tangential velocities imparted to the fluid by the forward propeller (known as "propeller swirl"). The flow field behind the aft propeller of a contra-rotating set has very little "swirl", and this reduction in energy loss is seen as an increased efficiency of the aft propeller.

Additional designs

An Azimuthing propeller is a vertical axis propeller.

The blade outline is defined either by a projection on a plane normal to the propeller shaft (*projected outline*) or by setting the circumferential chord across the blade at a given radius against radius (*developed outline*). The outline is usually symmetrical about a given radial line termed the *median*. If the median is curved back relative to the direction of rotation the propeller is said to have *skew back*. The skew is expressed in terms of circumferential displacement at the blade tips. If the blade face in profile is not normal to the axis it is termed *raked*, expressed as a percentage of total diameter.

Each blade's pitch and thickness varies with radius, early blades had a flat face and an arced back (sometimes called a circular back as the arc was part of a circle), modern propeller blades have aerofoil sections. The *camber line* is the line through the mid-thickness of a single blade. The *camber* is the maximum difference between the camber line and the *chord* joining the trailing and leading edges. The camber is expressed as a percentage of the chord.

The radius of maximum thickness is usually forward of the mid-chord point with the blades thinning to a minimum at the tips. The thickness is set by the demands of strength and the ratio of thickness to total diameter is called *blade thickness fraction.*

The ratio of pitch to diameter is called *pitch ratio*. Due to the complexities of modern propellers a nominal pitch is given, usually a radius of 70% of the total is used.

Blade area is given as a ratio of the total area of the propeller disc, either as *developed blade area ratio* or *projected blade area ratio*.

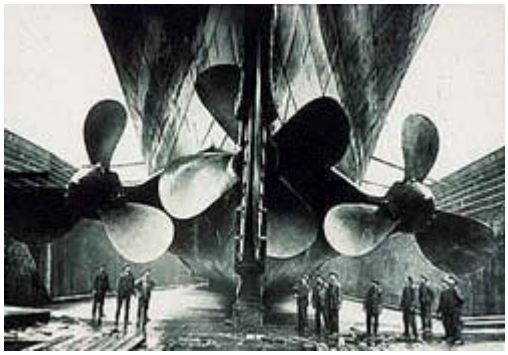
Transverse axis propellers

Most propellers have their axis of rotation parallel to the fluid flow. There have however been some attempts to power vehicles with the same principles behind vertical axis wind turbines, where the rotation is perpendicular to fluid flow. Most attempts have been unsuccessful. Blades that can vary their angle of attack during rotation have aerodynamics similar to flapping flight. Flapping flight is still poorly understood and almost never seriously used in engineering because of the strong coupling of lift, thrust and control forces.

The fanwing is one of the few types that has actually flown. It takes advantage of the trailing edge of an airfoil to help encourage the circulation necessary for lift.

The Voith-Schneider propeller pictured below is another successful example, operating in water.

History of ship and submarine screw propellers



Propellers of the *Titanic*: 2 triple-blade and 1 quadruple-blade at center

A propeller from the *Lusitania*

Propeller on a modern mid-sized merchant vessel

James Watt of Scotland is generally credited with applying the first screw propeller to an engine, an early steam engine, beginning the use of an hydrodynamic screw for propulsion.

Mechanical ship propulsion began with the steam ship. The first successful ship of this type is a matter of debate; candidate inventors of the 18th century include William Symington, the Marquis de Jouffroy, John Fitch and Robert Fulton, however William

Symington's ship the *Charlotte Dundas* is regarded as the world's "first practical steamboat". Paddlewheels as the main motive source became standard on these early vessels. Robert Fulton had tested, and rejected, the screw propeller.

Sketch of hand-cranked vertical and horizontal screws used in Bushnell's *Turtle*, 1775

The screw (as opposed to paddlewheels) was introduced in the latter half of the 18th century. David Bushnell's invention of the submarine (Turtle) in 1775 used hand-powered screws for vertical and horizontal propulsion. The Bohemian engineer Josef Ressel designed and patented the first practicable screw propeller in 1827. Francis Pettit Smith tested a similar one in 1836. In 1839, John Ericsson introduced practical screw propulsion into the United States. Mixed paddle and propeller designs were still being used at this time (*vide* the 1858 *SS Great Eastern*).

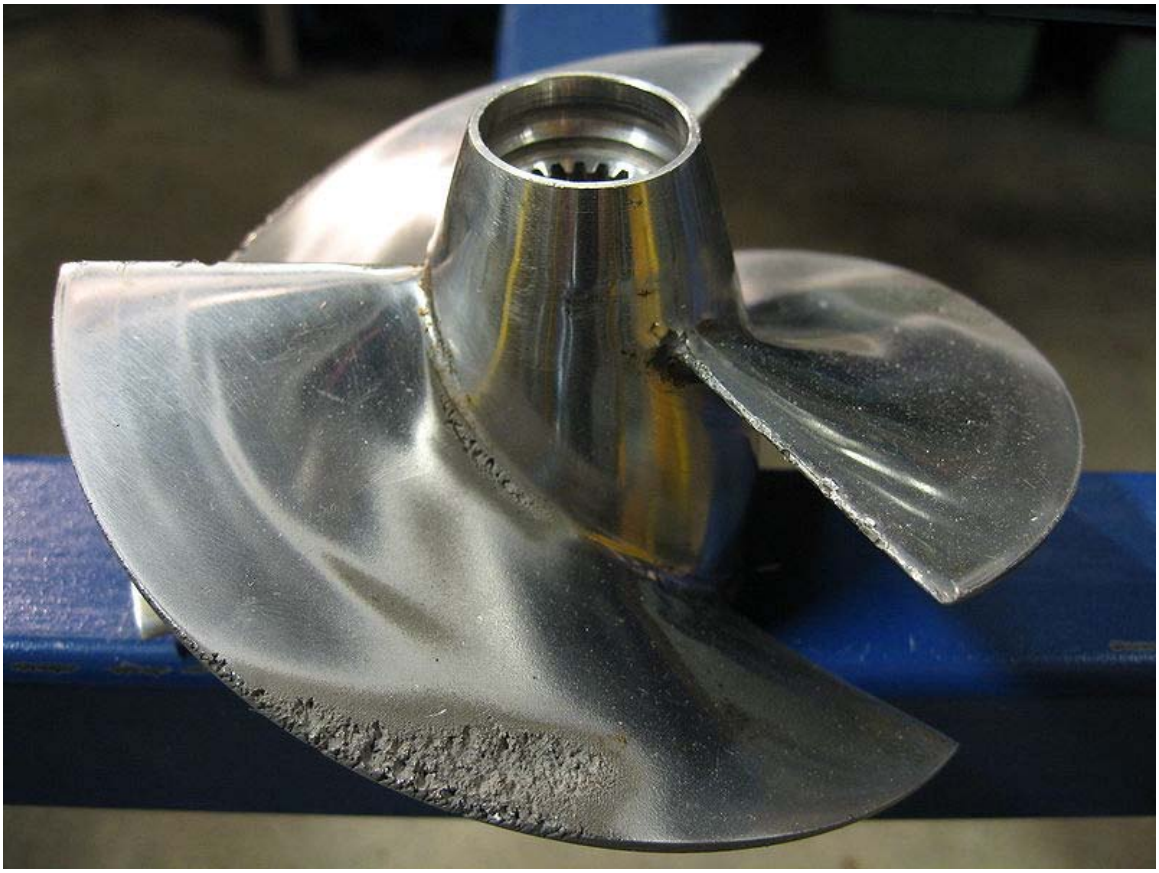
In 1848 the British Admiralty held a tug of war contest between a propeller driven ship, *Rattler*, and a paddle wheel ship, *Alecto*. *Rattler* won, towing *Alecto* astern at 2.5 knots (4.6 km/h), but it was not until the early 20th century that paddle propelled vessels were entirely superseded. The screw propeller replaced the paddles owing to its greater efficiency, compactness, less complex power transmission system, and reduced susceptibility to damage (especially in battle)

Voith-Schneider propeller

Initial designs owed much to the ordinary screw from which their name derived - early propellers consisted of only two blades and matched in profile the length of a single screw rotation. This design was common, but inventors endlessly experimented with different profiles and greater numbers of blades. The propeller screw design stabilized by the 1880s.

In the early days of steam power for ships, when both paddle wheels and screws were in use, ships were often characterized by their type of propellers, leading to terms like screw steamer or screw sloop.

Propellers are referred to as "lift" devices, while paddles are "drag" devices.



Cavitation damage evident on the propeller of a personal watercraft

Marine propeller cavitation

Cavitation can occur if an attempt is made to transmit too much power through the screw, or if the propeller is operating at a very high speed. Cavitation can occur in many ways on a propeller. The two most common types of propeller cavitation are suction side surface cavitation and tip vortex cavitation.

Suction side surface cavitation forms when the propeller is operating at high rotational speeds or under heavy load (high blade lift coefficient). The pressure on the upstream surface of the blade (the "suction side") can drop below the vapour pressure of the water, resulting in the formation of a pocket of vapour. Under such conditions, the change in pressure between the downstream surface of the blade (the "pressure side") and the suction side is limited, and eventually reduced as the extent of cavitation is increased. When most of the blade surface is covered by cavitation, the pressure difference between the pressure side and suction side of the blade drops considerably, and thrust produced by the propeller drops. This condition is called "thrust breakdown". This effect wastes energy, makes the propeller "noisy" as the vapour bubbles collapse, and most seriously, erodes the screw's surface due to localized shock waves against the blade surface.

Tip vortex cavitation is caused by the extremely low pressures formed at the core of the tip vortex. The tip vortex is caused by fluid wrapping around the tip of the propeller; from the pressure side to the suction side. This video demonstrates tip vortex cavitation well. Tip vortex cavitation typically occurs before suction side surface cavitation and is less damaging to the blade, since this type of cavitation doesn't collapse on the blade, but some distance downstream.

Cavitation can be used as an advantage in design of very high performance propellers, in form of the supercavitating propeller. In this case, the blade section is designed such that the pressure side stays wetted while the suction side is completely covered by cavitation vapor. Because the suction side is covered with vapor instead of water it encounters very low viscous friction, making the supercavitating (SC) propeller comparably efficient at high speed. The shaping of SC blade sections however, make it inefficient at low speeds, when the suction side of the blade is wetted.

A similar, but quite separate issue, is *ventilation,* which occurs when a propeller operating near the surface draws air into the blades, causing a similar loss of power and shaft vibration, but without the related potential blade surface damage caused by cavitation. Both effects can be mitigated by increasing the submerged depth of the propeller: cavitation is reduced because the hydrostatic pressure increases the margin to the vapor pressure, and ventilation because it is further from surface waves and other air pockets that might be drawn into the slipstream.

14-ton propeller from *Voroshilov* a Kirov class cruiser on display in Sevastopol

Forces acting on an aerofoil

The force (F) experienced by an aerofoil blade is determined by its area (A), chord (c), velocity (V) and the angle of the aerofoil to the flow, called *angle of attack* (α), where:

$$\frac{F}{\rho A V^2} = f(R_n, \alpha)$$

The force has two parts - that normal to the direction of flow is *lift* (L) and that in the direction of flow is *drag* (D). Both are expressed non-dimensionally as:

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \text{ and } C_D = \frac{D}{\frac{1}{2}\rho A V^2}$$

Each coefficient is a function of the angle of attack and Reynolds' number. As the angle of attack increases lift rises rapidly from the *no lift angle* before slowing its increase and then decreasing, with a sharp drop as the *stall angle* is reached and flow is disrupted. Drag rises slowly at first and as the rate of increase in lift falls and the angle of attack increases drag increases more sharply.

For a given strength of circulation (τ), Lift = $L = \rho V \tau$. The effect of the flow over and the circulation around the aerofoil is to reduce the velocity over the face and increase it over the back of the blade. If the reduction in pressure is too much in relation to the ambient pressure of the fluid, *cavitation* occurs, bubbles form in the low pressure area and are moved towards the blade's trailing edge where they collapse as the pressure increases, this reduces propeller efficiency and increases noise. The forces generated by the bubble collapse can cause permanent damage to the surfaces of the blade.

Propeller thrust

Single blade

Taking an arbitrary radial section of a blade at *r*, if revolutions are *N* then the rotational velocity is $2\pi Nr$. If the blade was a complete screw it would advance through a solid at the rate of *NP*, where *P* is the pitch of the blade. In water the advance speed is rather lower, V_a, the difference, or *slip ratio*, is:

$$\text{Slip} = \frac{NP - V_a}{NP} = 1 - \frac{J}{p}$$

where $J = \frac{V_a}{ND}$ is the *advance coefficient*, and $p = \frac{P}{D}$ is the *pitch ratio*.

The forces of lift and drag on the blade, *dA*, where force normal to the surface is *dL*:

$$\mathrm{d}L = \frac{1}{2}\rho V_1^2 C_L dA = \frac{1}{2}\rho C_L [V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2] b\mathrm{d}r$$

where:

$$V_1^2 = V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2$$

$$\mathrm{d}D = \frac{1}{2}\rho V_1^2 C_D \mathrm{d}A = \frac{1}{2}\rho C_D [V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2] b\mathrm{d}r$$

These forces contribute to thrust, *T*, on the blade:

$$\mathrm{d}T = \mathrm{d}L\cos\varphi - \mathrm{d}D\sin\varphi = \mathrm{d}L(\cos\varphi - \frac{\mathrm{d}D}{\mathrm{d}L}\sin\varphi)$$

where:

$$tan\beta = \frac{\mathrm{d}D}{\mathrm{d}L} = \frac{C_D}{C_L}$$

$$= \frac{1}{2}\rho V_1^2 C_L \frac{\cos(\varphi+\beta)}{\cos\beta} b\mathrm{d}r$$

As $V_1 = \frac{V_a(1+a)}{\sin\varphi}$,

$$\mathrm{d}T = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\cos(\varphi+\beta)}{\sin^2\varphi\cos\beta} b\mathrm{d}r$$

From this total thrust can be obtained by integrating this expression along the blade. The transverse force is found in a similar manner:

$$\mathrm{d}M = \mathrm{d}L\sin\varphi + \mathrm{d}D\cos\varphi$$

$$= \mathrm{d}L(\sin\varphi + \frac{\mathrm{d}D}{\mathrm{d}L}\cos\varphi)$$

$$= \frac{1}{2}\rho V_1^2 C_L \frac{\sin(\varphi+\beta)}{\cos\varphi} b\mathrm{d}r$$

Substituting for $V_1$and multiplying by *r*, gives torque as:

$$\mathrm{d}Q = r\mathrm{d}M = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\sin(\varphi+\beta)}{\sin^2\varphi\cos\beta} br\mathrm{d}r$$

which can be integrated as before.

The total thrust power of the propeller is proportional to TV_a and the shaft power to $2\pi NQ$. So efficiency is $\frac{TV_a}{2\pi NQ}$. The blade efficiency is in the ratio between thrust and torque:

$$\text{blade element efficiency} = \frac{V_a}{2\pi Nr} \cdot \frac{1}{\tan(\varphi + \beta)}$$

showing that the blade efficiency is determined by its momentum and its qualities in the form of angles φ and β, where β is the ratio of the drag and lift coefficients.

This analysis is simplified and ignores a number of significant factors including interference between the blades and the influence of tip vortices.

Thrust and torque

The thrust, *T*, and torque, *Q*, depend on the propeller's diameter, *D*, revolutions, *N*, and rate of advance, V_a, together with the character of the fluid in which the propeller is operating and gravity. These factors create the following non-dimensional relationship:

$$T = \rho V^2 D^2 [f_1(\frac{ND}{V_a}), f_2(\frac{v}{V_a D}), f_3(\frac{gD}{V_a^2})]$$

where f_1 is a function of the advance coefficient, f_2 is a function of the Reynolds' number, and f_3 is a function of the Froude number. Both f_2 and f_3 are likely to be small in comparison to f_1 under normal operating conditions, so the expression can be reduced to:

$$T = \rho V_a^2 D^2 \times f_r(\frac{ND}{V_a})$$

For two identical propellers the expression for both will be the same. So with the propellers T_1,T_2, and using the same subscripts to indicate each propeller:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{V_{a1}^2}{V_{a2}^2} \times \frac{D_1^2}{D_2^2}$$

For both Froude number and advance coefficient:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{D_1^3}{D_2^3} = \frac{\rho_1}{\rho_2} \lambda^3$$

where λ is the ratio of the linear dimensions.

Thrust and velocity, at the same Froude number, give thrust power:

$$\frac{P_{T1}}{P_{T2}} = \frac{\rho_1}{\rho_2}\lambda^{3.5}$$

For torque:

$$Q = \rho V_a^2 D^3 \times f_q\left(\frac{ND}{V_a}\right)$$

...

Actual performance

When a propeller is added to a ship its performance is altered; there is the mechanical losses in the transmission of power; a general increase in total resistance; and the hull also impedes and renders non-uniform the flow through the propeller. The ratio between a propeller's efficiency attached to a ship (P_D) and in open water (P'_D) is termed *relative rotative efficiency*.

The *overall propulsive efficiency* (an extension of *effective power* (P_E)) is developed from the *propulsive coefficient* (PC), which is derived from the installed shaft power (P_S) modified by the effective power for the hull with appendages (P'_E), the propeller's thrust power (P_T), and the relative rotative efficiency.

P'_E/P_T = hull efficiency = η_H
P_T/P'_D = propeller efficiency = η_O
P'_D/P_D = relative rotative efficiency = η_R
P_D/P_S = shaft transmission efficiency

Producing the following:

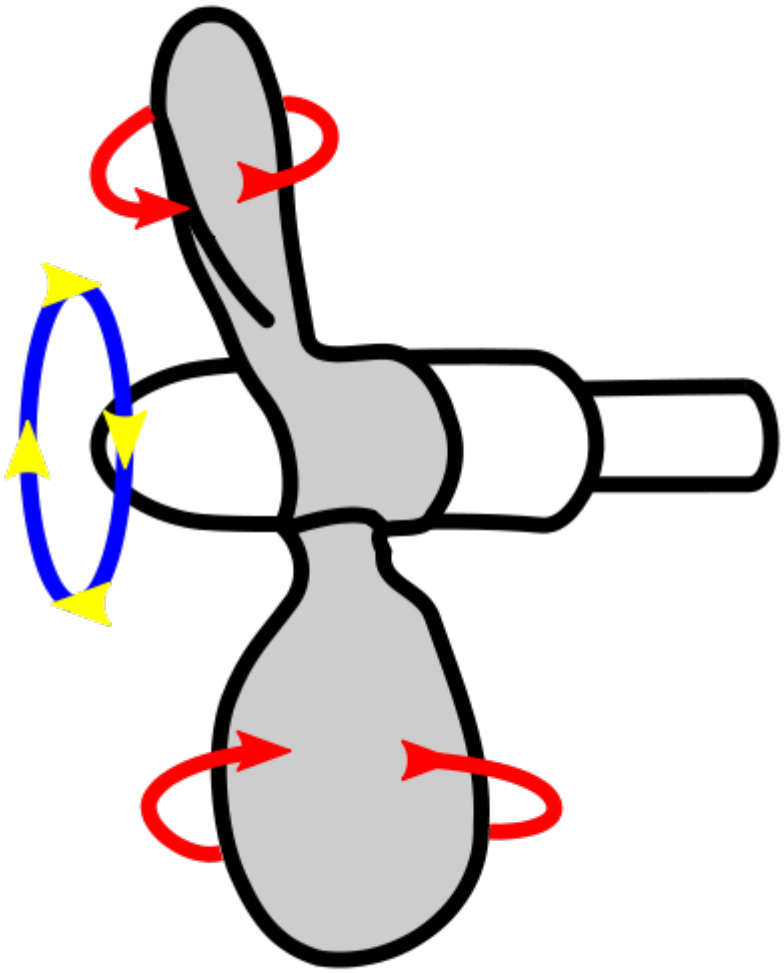
$$PC = \left(\frac{\eta_H \cdot \eta_O \cdot \eta_R}{\text{appendage coefficient}}\right) \cdot \text{transmission efficiency}$$

The terms contained within the brackets are commonly grouped as the *quasi-propulsive coefficient* (QPC, η_D). The QPC is produced from small-scale experiments and is modified with a load factor for full size ships.

Wake is the interaction between the ship and the water with its own velocity relative to the ship. The wake has three parts: the velocity of the water around the hull; the boundary layer between the water dragged by the hull and the surrounding flow; and the waves created by the movement of the ship. The first two parts will reduce the velocity of water into the propeller, the third will either increase or decrease the velocity depending on whether the waves create a crest or trough at the propeller.

Types of marine propellers

Controllable pitch propeller



A controllable pitch propeller

At present, one of the newest and best type of propeller is the controllable pitch propeller. This propeller has several advantages with ships. These advantages include: the least drag depending on the speed used, the ability to move the sea vessel backwards, and the ability to use the "vane"-stance, which gives the least water resistance when not using the propeller (e.g. when the sails are used instead).

Skewback propeller

An advanced type of propeller used on German Type 212 submarines is called a **skewback propeller**. As in the scimitar blades used on some aircraft, the blade tips of a skewback propeller are swept back against the direction of rotation. In addition, the blades are tilted rearward along the longitudinal axis, giving the propeller an overall cup-shaped appearance. This design preserves thrust efficiency while reducing cavitation, and thus makes for a quiet, stealthy design.

Modular propeller

A modular propeller provides more control over the boats performance. There is no need to change an entire prop, when there is an opportunity to only change the pitch or the damaged blades. Being able to adjust pitch will allow for boaters to have better performance while in different altitudes, water sports, and/or cruising.

Protection of small engines

A failed rubber bushing in an outboard's propeller

For smaller engines, such as outboards, where the propeller is exposed to the risk of collision with heavy objects, the propeller often includes a device which is designed to fail when over loaded; the device or the whole propeller is sacrificed so that the more expensive transmission and engine are not damaged.

Typically in smaller (less than 10 hp/7.5 kW) and older engines, a narrow shear pin through the drive shaft and propeller hub transmits the power of the engine at normal loads. The pin is designed to shear when the propeller is put under a load that could damage the engine. After the pin is sheared the engine is unable to provide propulsive power to the boat until an undamaged shear pin is fitted. Note that some shear pins used to have shear grooves machined into them. Nowadays the grooves tend to be omitted. The result of this oversight is that the torque required to shear the pin rises as the cutting edges of the propeller bushing and shaft become blunted. Eventually the gears will strip instead.

In larger and more modern engines, a rubber bushing transmits the torque of the drive shaft to the propeller's hub. Under a damaging load the friction of the bushing in the hub is overcome and the rotating propeller slips on the shaft preventing overloading of the engine's components. After such an event the rubber bushing itself may be damaged. If so, it may continue to transmit reduced power at low revolutions but may provide no power, due to reduced friction, at high revolutions. Also the rubber bushing may perish over time leading to its failure under loads below its designed failure load.

Whether a rubber bushing can be replaced or repaired depends upon the propeller; some cannot. Some can but need special equipment to insert the oversized bushing for an interference fit. Others can be replaced easily.

The "special equipment" usually consists of a tapered funnel, some kind of press and rubber lubricant (soap). Often the bushing can be drawn into place with nothing more complex than a couple of nuts, washers and "allscrew" (threaded bar). If one does not have access to a lathe an improvised funnel can be made from steel tube and car body filler! (as the filler is only subject to compressive forces it is able to do a good job) A more serious problem with this type of propeller is a "frozen-on" spline bushing which makes propeller removal impossible. In such cases the propeller has to be heated in order to deliberately destroy the rubber insert. Once the propeller proper is removed, the splined tube can be cut away with a grinder. A new spline bushing is of course required. To prevent the problem recurring the splines can be coated with anti-seize anti-corrosion compound.

In some modern propellers, a hard polymer insert called a *drive sleeve* replaces the rubber bushing. The splined or other non-circular cross section of the sleeve inserted between the shaft and propeller hub transmits the engine torque to the propeller, rather than friction. The polymer is weaker than the components of the propeller and engine so it fails before they do when the propeller is overloaded. This fails completely under excessive load but can easily be replaced.

Chapter- 2

Propeller (Aircraft)

The feathered propellers of an RAF Hercules C.4

Aircraft propellers convert rotary motion from piston engines or turboprops to provide propulsive force. They may be fixed or variable pitch. Early aircraft propellers were carved by hand from solid or laminated wood with later propellers being constructed from metal. The most modern propeller designs use high-technology composite materials.

The propeller is usually attached to the crankshaft of a piston engine, either directly or through a reduction unit. Light aircraft engines often do not require the complexity of gearing but on larger engines and turboprop aircraft it is essential.

History

The twisted airfoil (aerofoil) shape of modern aircraft propellers was pioneered by the Wright brothers. They found that a propeller is essentially the same as a wing and so were able to use data collated from their earlier wind tunnel experiments on wings. They also found that the relative angle of attack from the forward movement of the aircraft was different for all points along the length of the blade, thus it was necessary to introduce a twist along its length. Their original propeller blades were only about 5% less efficient than the modern equivalent, some 100 years later.

Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some of his designs used a bent aluminium sheet for blades, thus creating an airfoil shape. These are heavily undercambered because of this and combined with the lack of a lengthwise twist made them less efficient than the Wright propellers. Even so, this was perhaps the first use of aluminium in the construction of an airscrew.

Theory and design of aircraft propellers

A well-designed propeller typically has an efficiency of around 80% when operating in the best regime.Changes to a propeller's efficiency are produced by a number of factors, notably adjustments to the helix angle(θ), the angle between the resultant relative velocity and the blade rotation direction, and to blade pitch (where $\theta = \Phi + \alpha$) . Very small pitch and helix angles give a good performance against resistance but provide little thrust, while larger angles have the opposite effect. The best helix angle is when the blade is acting as a wing producing much more lift than drag.

A propeller's efficiency is determined by

$$\eta = \frac{\text{propulsive power out}}{\text{shaft power in}} = \frac{\text{thrust} \cdot \text{axial speed}}{\text{resistance torque} \cdot \text{rotational speed}}.$$

Propellers are similar in aerofoil section to a low drag wing and as such are poor in operation when at other than their optimum angle of attack. Control systems are required to counter the need for accurate matching of pitch to flight speed and engine speed.

The three-bladed propeller of a light aircraft: the Vans RV-7A

A further consideration is the number and the shape of the blades used. Increasing the aspect ratio of the blades reduces drag but the amount of thrust produced depends on blade area, so using high aspect blades can lead to the need for a propeller diameter which is unusable. A further balance is that using a smaller number of blades reduces interference effects between the blades, but to have sufficient blade area to transmit the available power within a set diameter means a compromise is needed. Increasing the number of blades also decreases the amount of work each blade is required to perform, limiting the local Mach number - a significant performance limit on propellers.

A propeller's performance suffers as the blade speed exceeds the speed of sound. As the relative air speed at the blade is rotation speed plus axial speed, a propeller blade tip will reach sonic speed sometime before the rest of the aircraft (with a theoretical blade the maximum aircraft speed is about 845 km/h (Mach 0.7) at sea-level, in reality it is rather lower). When a blade tip becomes supersonic, drag and torque resistance increase suddenly and shock waves form creating a sharp increase in noise. Aircraft with conventional propellers, therefore, do not usually fly faster than Mach 0.6. There are certain propeller-driven aircraft, usually military, which do operate at Mach 0.8 or higher, although there is considerable fall off in efficiency.

There have been efforts to develop propellers for aircraft at high subsonic speeds. The 'fix' is similar to that of transonic wing design. The maximum relative velocity is kept as low as possible by careful control of pitch to allow the blades to have large helix angles;

thin blade sections are used and the blades are swept back in a scimitar shape (Scimitar propeller); a large number of blades are used to reduce work per blade and so circulation strength; contra-rotation is used. The propellers designed are more efficient than turbo-fans and their cruising speed (Mach 0.7–0.85) is suitable for airliners, but the noise generated is tremendous.

Forces acting on a propeller

Five forces act on the blades of an aircraft propeller in motion, they are:

Thrust bending force
: Thrust loads on the blades act to bend them forwards, opposite to the direction of flight.

Centrifugal twisting force
: Acts to twist the blades to a low or fine pitch angle.

Aerodynamic twisting force
: As the centre of pressure of a propeller blade is forward of its centreline the blade is twisted towards a coarse pitch position.

Centrifugal force
: The force felt by the blades acting to pull them away from the hub when turning.

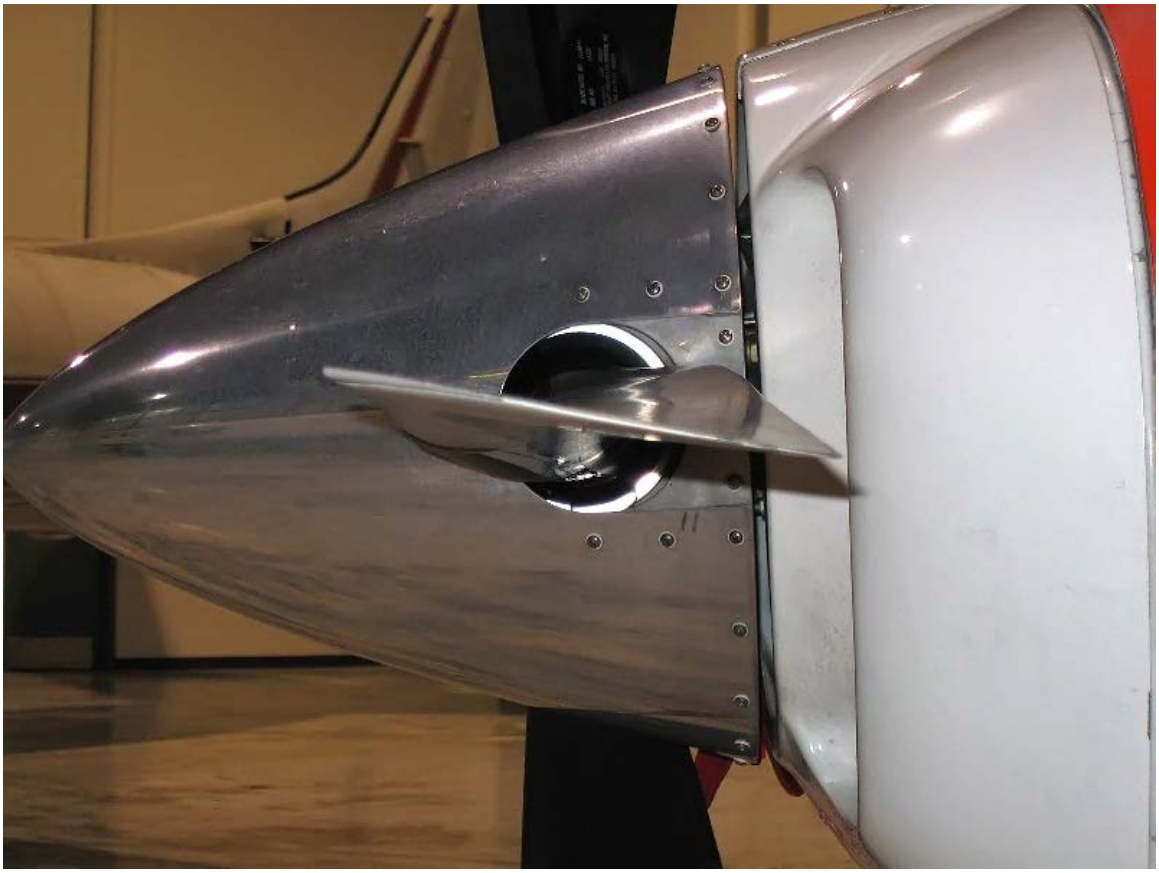
Torque bending force
: Air resistance acting against the blades, combined with inertial effects causes propeller blades to bend away from the direction of rotation.

Propeller control

Variable pitch

The purpose of varying pitch angle with a variable pitch propeller is to maintain an optimal angle of attack (maximum lift to drag ratio) on the propeller blades as aircraft speed varies. Early pitch control settings were pilot operated, either two-position or manually variable. Following World War II, automatic propellers were developed to maintain an optimum angle of attack. This was done by balancing the centripetal twisting moment on the blades and a set of counterweights against a spring and the aerodynamic forces on the blade. Automatic props had the advantage of being simple, lightweight, and requiring no external control, but a particular propeller's performance was difficult to match with that of the aircraft's powerplant. An improvement on the automatic type was the constant-speed propeller. Constant speed propellers allow the pilot to select a rotational speed for maximum engine power or maximum efficiency, and a propeller governor acts as a closed-loop controller to vary propeller pitch angle as required to maintain the RPM commanded by the pilot. In most aircraft this system is hydraulic, with engine oil serving as the hydraulic fluid. However, electrically controlled propellers were developed during World War II and saw extensive use on military aircraft, and have recently seen a revival in use on homebuilt aircraft.

Feathering



A propeller blade in feathered position

On some variable-pitch propellers, the blades can be rotated parallel to the airflow to reduce drag in case of an engine failure. This is called *feathering*. Feathering propellers were developed for military fighter aircraft prior to World War II, as a fighter is more likely to experience an engine failure due to the inherent danger of combat. On single-engined aircraft, whether a powered glider or turbine powered aircraft, the effect is to increase the gliding distance. On a multi-engine aircraft, feathering the propeller on a failed engine reduces drag.

Most feathering systems for reciprocating engines sense a drop in oil pressure and move the blades toward the feather position, and require the pilot to pull the propeller control back to disengage the high-pitch stop pins before the engine reaches idle RPM. Turboprop control systems usually utilize a *negative torque sensor* in the reduction gearbox which moves the blades toward feather when the engine is no longer providing power to the propeller. Depending on design, the pilot may have to push a button to override the high-pitch stops and complete the feathering process, or the feathering process may be totally automatic.

Reverse pitch

In some aircraft (e.g., the C-130 Hercules), the pilot can manually override the constant speed mechanism to reverse the blade pitch angle, and thus the thrust of the engine (although the rotation of the engine itself does not reverse). This is used to help slow the plane down after landing in order to save wear on the brakes and tires, but in some cases also allows the aircraft to back up on its own. This is known as "Beta Range" operation.

Contra-rotating propellers

Contra-rotating propellers use a second propeller rotating in the opposite direction immediately 'downstream' of the main propeller so as to recover energy lost in the swirling motion of the air in the propeller slipstream. Contra-rotation also increases power without increasing propeller diameter and provides a counter to the torque effect of high-power piston engine as well as the gyroscopic precession effects, and of the slipstream swirl. However on small aircraft the added cost, complexity, weight and noise of the system rarely make it worthwhile.

Counter-rotating propellers

Counter-rotating propellers, are found on twin-, and multi-engine, propeller-driven aircraft and have propellers that spin in opposite directions. Generally, the propellers on both engines of most conventional twin-engined aircraft spin clockwise (as viewed from the rear of the aircraft). Counter-rotating propellers generally spin clockwise on the left engine, and counter-clockwise on the right. The advantage of counter-rotating propellers is to balance out the effects of torque and p-factor, eliminating the problem of the critical engine.

Aircraft fans

A fan is a propeller with a large number of blades. A fan therefore produces a lot of thrust for a given diameter but the closeness of the blades means that each strongly affects the flow around the others. If the flow is supersonic, this interference can be beneficial if the flow can be compressed through a series of shock waves rather than one. By placing the fan within a shaped duct, specific flow patterns can be created depending on flight speed and engine performance. As air enters the duct, its speed is reduced while its pressure and temperature increases. If the aircraft is at a high subsonic speed this creates two advantages: the air enters the fan at a lower Mach speed; and the higher temperature increases the local speed of sound. While there is a loss in efficiency as the fan is drawing on a smaller area of the free stream and so using less air, this is balanced by the ducted fan retaining efficiency at higher speeds where conventional propeller efficiency would be poor. A ducted fan or propeller also has certain benefits at lower speeds but the duct needs to be shaped in a different manner than one for higher speed flight. More air is taken in and the fan therefore operates at an efficiency equivalent to a larger un-ducted propeller. Noise is also reduced by the ducting and should a blade become detached the

duct would contain the damage. However the duct adds weight, cost, complexity and (to a certain degree) drag.

Chapter- 3

Contra Rotating and Counter Rotating Propeller

Contra-rotating propellers

Contra-rotating propellers on a Rolls-Royce–Griffon–powered P-51 unlimited racer

Contra-rotating propellers, also referred to as *coaxial contra-rotating propellers*, apply the maximum power of usually a single piston or turboprop engine to drive two propellers in opposite rotation. Contra-rotating propellers are common in some marine transmission systems, in particular for medium to large size planing leisure craft. Two

propellers are arranged one behind the other, and power is transferred from the engine via a planetary gear or spur gear transmission. Contra-rotating propellers should not be confused with counter-rotating propellers—airscrews on different engines turning opposite directions.

When airspeed is low the mass of the air flowing through the propeller disk (thrust) causes a significant amount of tangential or rotational air flow to be created by the spinning blades. The energy of this tangential air flow is wasted in a single-propeller design. To use this wasted effort the placement of a second propeller behind the first takes advantage of the disturbed airflow. The tangential air flow also causes handling problems at low speed as the air strikes the vertical stabilizer, causing the aircraft to yaw left or right, depending of the direction of propeller rotation.

If it is well designed, a contra-rotating propeller will have no rotational air flow, pushing a maximum amount of air uniformly through the propeller disk, resulting in high performance and low induced energy loss. It also serves to counter the asymmetrical torque effect of a conventional propeller. Some contra-rotating systems were designed to be used at take off for maximum power and efficiency under such conditions, and allowing one of the propellers to be disabled during cruise to extend flight time.

Contra-rotating propellers have been found to be between 6% and 16% more efficient than normal propellers. However they can be very noisy, with increases in noise in the axial (forward and aft) direction of up to 30 dB, and tangentially 10 dB. Most of this extra noise can be found in the higher frequencies. These substantial noise problems will limit commercial applications unless solutions can be found. One possibility is to enclose the contra-rotating propellers in a shroud. It is also helpful if the two propellers have a different number of blades (e.g. four blades on the forward propeller and five on the aft).

The efficiency of a contra-rotating prop is somewhat offset by its mechanical complexity. Nonetheless, coaxial contra-rotating propellers and rotors are moderately common in military aircraft and naval applications, such as torpedoes.

Significant aircraft

While several nations experimented with contra-rotating propellers in aircraft, only the United Kingdom and Soviet Union produced them in large numbers. The first aircraft to be fitted with a contra-rotating propeller to fly though was in the US when two inventors from Ft Worth, Texas tested the concept on an aircraft.

United Kingdom

Fairey Gannet AS.6 at the Imperial War Museum Duxford

Some of the more successful British aircraft with contra-rotating propellers are the Avro Shackleton, powered by the Rolls-Royce Griffon engine, and the Fairey Gannet, which used the Double Mamba Mk.101 engine.

Later variants of the Supermarine Spitfire and Seafire used the Griffon with contra-rotating props as well. In the Spitfire/Seafire and Shackleton's case the primary reason for using contra-rotating propellers was so as to increase the propeller blade-area, and hence absorb greater engine power, within a propeller diameter limited by the height of the aircraft's undercarriage. Whilst this also applied to the Gannet, in addition this aircraft's engine had two separate power-sections, each driving one propeller. The Short Sturgeon used 2 Merlin 140s with contra-rotating propellers.

The Bristol Brabazon prototype airliner used eight Bristol Centaurus engines driving four pairs of contra-rotating propellers, each engine driving a single propeller.

USSR

In the 1950s, the Soviet Union developed the Kuznetsov NK-12 turboprop. It drives an 8-blade contra-rotating propeller and, at 15,000 shp, it is the most powerful turboprop in the world. Four NK-12 engines power the Tupolev Tu-95 *Bear*, the only turboprop bomber to enter service, as well as one of the fastest propeller-driven aircraft. The Tu-114, an airliner derivative of the Bear, holds the world speed record for propeller aircraft. The Bear was also the first Soviet bomber to have intercontinental range, allowing it to strike North American targets from Asia. The Tu-126 AEW aircraft and Tu-142 maritime patrol aircraft are two more NK-12 powered designs derived from the Bear.

The NK-12 engine powers another well-known Soviet aircraft, the Antonov An-22 Antheus, a heavy-lift cargo aircraft. At the time of its introduction, the An-22 was the largest aircraft in the world and is still by far the world's largest turboprop-powered aircraft. From the 1960s through the 1970s, it set several world records in the categories of maximum payload-to-height ratio and maximum payload lifted to altitude.

Of lesser note is the use of the NK-12 engine in the A-90 Orlyonok, a mid-size Soviet ekranoplan. The A-90 uses one NK-12 engine mounted atop its T-tail, along with two turbojets nestled in its nose.

In 1994, Antonov produced the An-70, a heavy transport aircraft. It is powered by four Progress D-27 propfan engines driving contra-rotating propellers. The characteristics of the D-27 engine and its propeller make it a propfan, a hybrid between a turbofan engine and a turboprop engine.

United States

The U.S. worked with several prototypes, including the A2J Super Savage, the Boeing XF8B, the XP-56 Black Bullet and the tail-sitting Convair XFY and Lockheed XFV "Pogo" VTOL fighters and the Hughes XF-11 reconnaissance plane, but jet engine technology was advancing rapidly and the designs were deemed unnecessary.

Counter-rotating propellers

Opposite propeller blade section can be clearly seen on this Piper PA-44 Seminole

Counter-rotating propellers, found on twin- and multi-engine propeller-driven aircraft, spin in directions opposite one another.

The propellers on both engines of most conventional twin-engined aircraft spin clockwise (as viewed from the rear of the aircraft). Counter-rotating propellers generally spin clockwise on the left engine and counter-clockwise on the right. The advantage of such designs is that counter-rotating propellers balance the effects of torque and p-factor, eliminating the problem of the critical engine.

In designing the Lockheed P-38, the decision was made to reverse the counter-rotation such that the "tops" of the propeller arcs move outwards, away from each other. Tests on the initial XP-38 prototype demonstrated greater accuracy in gunnery with the unusual configuration. The German World War II Henschel Hs 129 ground attack aircraft, Heinkel He 177 heavy bomber and Messerschmitt Me 323 transport's counter-rotating powerplants used the same rotational "sense" as the production P-38 did.

Drawbacks of counter-rotating propellers come from the fact that, in order to reverse sense of rotation of one propeller, a gearbox needs to be used or the engine or engine installation must be different. This may increase weight (gearbox), or maintenance and spare parts costs for the engines and propellers, as different spare parts need to be produced in lower numbers, compared to a conventional installation.

Counter-rotating propellers should not be confused with contra-rotating propellers that share common axes.

The following aircraft have counter-rotating propellers:

(Twin-engine, 1 engine per wing)

- The Wright Flyer
- de Havilland Hornet
- Lockheed P-38 Lightning
- Heinkel He 177 *Greif* (fourth prototype onwards)
- Piper PA-31 Navajo
- Piper PA-34 Seneca
- Piper PA-39 Twin Comanche
- Piper PA-40 Arapaho
- Piper PA-44 Seminole
- Cessna T303 Crusader
- Beech BE-76 Duchess

At least four engines, two or more on each wing :

- Messerschmitt Me 323 *Gigant* transport
- Airbus A400M - first plane with propellers that counter-rotate on each wing

Chapter- 4

Types of Propellers

Chopper (propeller)

A **Chopper** is a propeller design especially used for fast boats or boat racing. It can cope with breaking through the water surface without losing its thrust. This provides the facility to mount the motor higher, which commonly increases speed. Besides this, it has a high progressive rake which leads to a good bow lift.

Cleaver (propeller)

A **Cleaver** is a type of propeller design especially used for boat racing. Its leading edge is formed round, while the trailing edge is cut straight. It provides little bow lift, so that it can be used on boats that don't need much bow lift, for instance Hydroplanes, that naturally have enough hydrodynamic bow lift. To compensate for the lack of bow lift, a hydrofoil may be installed on the lower unit. Hydrofoils reduce bow lift and help to get a boat out of the hole and onto plane.

Composite propeller

Composite propellers are made of an extremely strong, high-tech material. These propellers are produced using an injection molding process, which guarantees a high quality propeller every time. The composite propeller is a lightweight and environmentally friendly boat propeller. When a composite propeller hits debris, the propeller absorbs the impact energy, instead of transferring it to the lower unit; therefore, providing more protection for the drive train. Corrosion from salt water, and electrolysis are nonexistent with composite material.

Advantages

Lower unit protection is the primary advantage of composite materials. While the initial cost of a composite propeller is usually comparable to aluminum, it is significantly less than a stainless steel propeller. Additionally, replacement blades offer significant savings

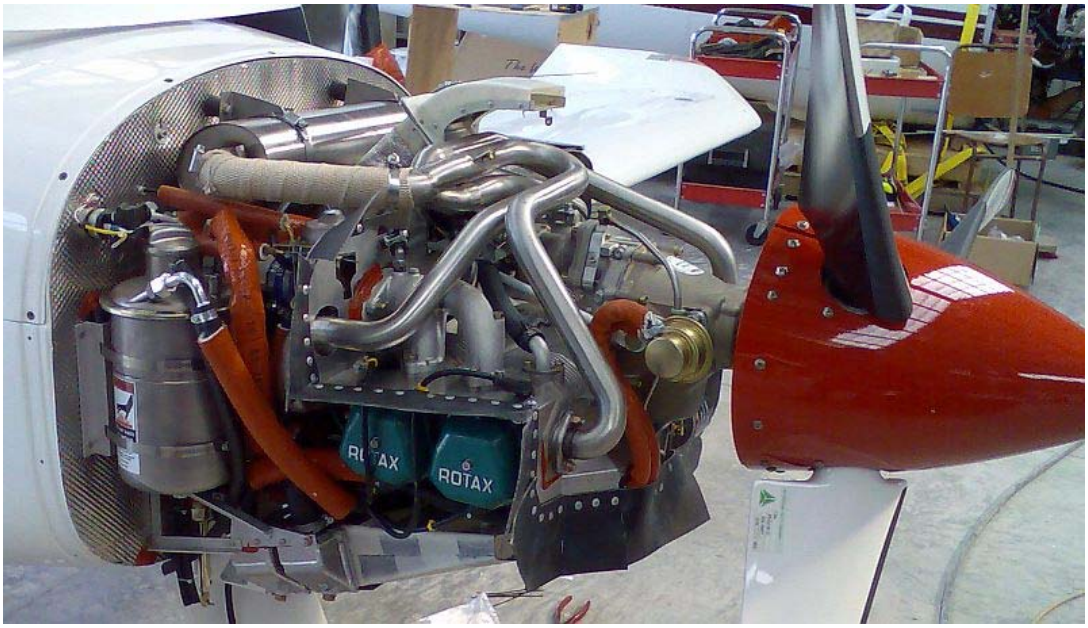
over metal propeller repairs. Another advantage to using composite propellers is that it is a lightweight material. Composite material is about half the weight of aluminum and 1/6 the weight of stainless steel propeller. A lightweight propeller will reduce the amount of wear and tear on the entire boat.

Effect on the Environment

Composite propellers are 100% recyclable and can help preserve the environment. Recycled propellers reduce material and energy costs for manufacturers allowing for lower costs for consumers.

Constant speed propeller

A constant speed propeller on a 1943 model Stinson V77 Reliant



A hydraulic Constant Speed Propeller (CSU) on a Rotax 912S engine in a Dyn'Aéro MCR01 Microlight aircraft. The thin tube visible between the front exhaust pipes carries the oil from the speed governor to the propeller hub to actuate the pitch change.

A **constant speed propeller** is a type of propeller that can change its blade pitch to take better advantage of the power supplied by an engine in much the same way that a transmission in a car takes better advantage of its power source. The mechanism varies depending on the aircraft, but the desired effect is to change the angle of attack of the propeller blades to take a smaller or larger "bite" of air as it rotates.

Operation

An airplane propeller operates as the source of thrust that moves the plane forward.

When an airplane is stationary with the propeller spinning (in calm air), air flows past the narrow leading edge of the propeller. This is the most efficient configuration as the drag forces on the propeller are the lowest. As the airplane starts moving forward, the airflow begins to push against the front, wider cross section of the propeller, creating greater drag.

A constant-speed propeller is able to rotate along the longest axis of the blade to take a sharper bite of air with respect to the airplane, allowing the propeller to maintain the most efficient orientation to the airflow around it. This balances the tradeoff that fixed-pitch propellers must make between high take-off performance and high cruise performance.

A shallower angle of attack requires the least horsepower, but the highest RPM because the propeller is not moving very much air with each revolution. This is similar to a car operating in low gear: when you get up to speed you want to slow down the engine while

still putting out enough energy to keep the vehicle moving. This is accomplished in an airplane by increasing the angle of attack of the propeller. This means that the propeller moves more air per revolution and allows the engine to spin slower while moving an equivalent volume of air, thus maintaining velocity.

The first attempts at constant-speed propellers were called counterweight propellers which were driven by mechanisms which operated on centrifugal force. A counterbalance was set up near or in the spinner, held in by a spring. When the propeller reached a certain RPM, centrifugal force would cause these counterbalances to swing outwards, which would drive a mechanism that twisted the propeller into a steeper pitch. When the airplane slowed down, the RPM would decrease enough for the spring to push the counterweights back in, realigning the propeller to the shallower pitch.

In newer models of constant-speed propellers, oil is pumped through the propeller shaft to push on a piston which drives the mechanism to change pitch. The flow of oil and the pitch is controlled by a governor. The constant-speed propeller also has a speeder spring, fly weights, and a pilot valve. The tension of the speeder spring is set by the prop control lever, which sets the RPMs. The governor will maintain that RPM setting until an overspeed or underspeed condition exists. When an overspeed condition occurs, the propeller begins to rotate faster than the desired RPM setting. This would occur as the plane descends and airspeed increases. The flyweights begin to pull outward due to centrifugal force which further compresses the speeder spring. As that happens, the piston moves forward allowing the pilot valve to open and oil to flow from the oil sump into the hub. This increase in oil pressure will increase the pitch of the propeller angle causing it to slow back down to the desired RPM setting. When an underspeed condition occurs, as in a climb with loss of airspeed, just the opposite takes place. The airspeed decreases causing the propeller to slow down. This will cause the flyweights to move inward due to a lack in centrifugal force and tension will be released from the speeder spring. As this happens, the piston will move in the opposite direction causing pilot valve to allow oil to flow from the hub back to the oil sump. The propeller blade angle will now decrease to a lower pitch allowing the propeller to speed back up to the desired RPM setting. This process usually takes place frequently throughout flight.

All high-performance aircraft have constant-speed propellers as they vastly improve fuel efficiency and performance, especially at high altitude.

Constant speed units

A **constant speed unit** (CSU) or **propeller governor**, is the device fitted to one of these propellers to automatically change its pitch so as to attempt to keep engine speed constant. Most engines produce their maximum power in a narrow speed band. The CSU can be said to be to an aircraft what the automatic gearbox is to the motor car: The engine can be kept running at its optimum speed no matter what speed the aircraft is flying through the air. The advent of the CSU had another benefit: It allowed the designers of aircraft engines to keep ignition systems simple - the automatic spark advance seen in motor vehicle engines is much simplified in aircraft engines.

Three methods are used to vary the pitch: Engine oil pressure is the usual mechanism used in commercial aircraft and the Continental and Lycoming engines fitted to light aircraft. Alternatively or additionally centrifugal weights may be attached directly to the propeller as in the Yak-52. Small modern engines such as the Rotax 912 which have a CSU may use either the traditional hydraulic method or an electrical pitch control mechanism. A pilot requires some additional training and, in most jurisdictions, a formal signoff before being allowed to fly aircraft fitted with a CSU. CSU's are not allowed to be fitted to aircraft certified under the USA Light-sport Aircraft regulations.

Controllable pitch propeller

A **controllable pitch propeller** (CPP) or **variable pitch propeller** is a special type of propeller with blades that can be rotated around their long axis to change their pitch. If the pitch can be set to negative values, the **reversible propeller** can also create reverse thrust for braking or going backwards without the need of changing the direction of shaft revolutions.

Aircraft

One of a C-130 Hercules' four controllable and reversible pitch propellers

The earliest known attempt towards creating a variable pitch propeller of any type for an aircraft, though only adjustable on the ground before or after flight, was on the *IdFlieg*-numbered "R.30/16" example of the Zeppelin-Staaken R.VI four engined World War I-era *Riesenflugzeug* heavy bomber in 1918.

The French aircraft firm Levasseur displayed a variable pitch propeller at the 1921 Paris Airshow which they claimed had been tested by the French government in a ten hour run and could change pitch at any engine rpm. But nothing was ever heard anymore about the Levasseur development after 1921.

The first practical controllable pitch propeller for aircraft was introduced in 1932.

Such propellers are used in propeller aircraft to adapt the propeller to different thrust levels and air speeds so that the propeller blades don't stall, hence degrading the propulsion system's efficiency. Especially for cruising, the engine can operate in its most economical range of rotational speeds. With the exception of going into reverse for braking after touch-down, the pitch is usually controlled automatically without the pilot's intervention. A propeller with a controller that adjusts the blades' pitch so that the rotational speed always stays the same is called a *constant speed propeller*.

The most common type of controllable pitch propeller is hydraulically actuated; it was originally developed by Frank W. Caldwell of the Hamilton Standard Division of the United Aircraft Company. This design led to the award of the Collier Trophy of 1933.

A propeller with controllable pitch can have a nearly constant effeciency over a range of airspeeds.

Ships

A ship's controllable pitch propeller

Controllable pitch propellers (CPP) for marine propulsion systems have been designed to give the highest propulsive efficiency over a broad range of speeds and load conditions. When the vessel is fully loaded with cargo the propulsion required at a given ship speed is much higher than when the vessel is empty. By adjusting the blade pitch, the optimum efficiency can be obtained and fuel can be saved. Also, the controllable pitch propeller has a "vane"-stance, which is useful with combined sailing / motor vessels as this stance gives the least water resistance when not using the propeller (e.g. when the sails are used instead).

A fixed pitch propeller (FPP) is more efficient than a controllable pitch propeller under a *specific* rotational speed and load condition. At that particular rotational speed and load, a FPP can transmit power more efficiently than a CPP. At any other rotational speed, or any other vessel loading, the FPP will not be more efficient, either being over pitched or under pitched. A correctly sized controllable pitch propeller can be efficient for a wide range of rotational speeds, since pitch can be adjusted to absorb all the power that the engine is capable of producing at nearly any rotational speed.

The CPP also improves maneuverability of a vessel. When maneuvering the vessel the advantage of the CPP is the fast change of propulsion direction. The direction of thrust can be changed without slowing down the propeller and depending on the size of the CPP can be changed in approximately 15 to 40 seconds. The increased maneuverability can eliminate the need for docking tugs while berthing.

A reversing gear or a reversible engine is not necessary for ships utilizing CPP, saving money to install and service these components. Depending on the main engine rotational speed and the size of the CPP, a reduction gear may still be required. A CPP does require a hydraulic system to control the position of the blades. A CPP does not produce more or less wear or stress on the propeller shaft or propulsion engine than an FPP. Therefore this will not be an argument to choose between an FPP or a CPP.

Large vessels that make long trips at a constant service speed, for example crude oil tankers or the largest container ships, do not utilize a CPP, since the amount of power generated exceeds the current CPP design capabilities. A CPP is usually found on harbor or ocean-going tugs, dredgers, cruise ships, ferries, cargo vessels and larger fishing vessels that sail to ports with limited or no tug assistance.

Current CPP designs can tolerate a maximum output of 44000 kW (60,000 hp).

Ducted propeller

Kort nozzle

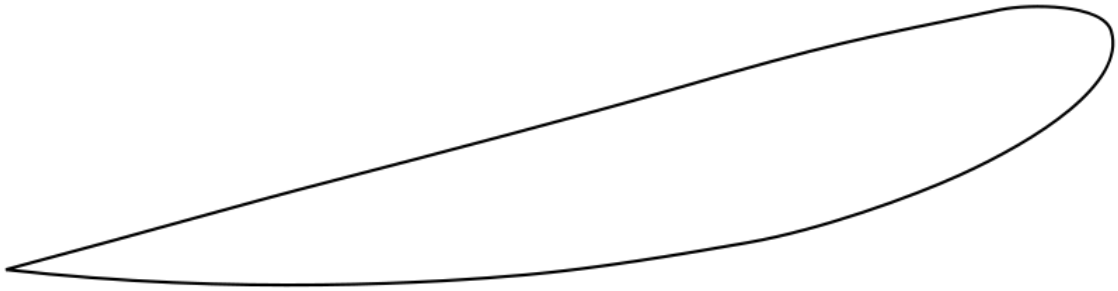
A **ducted propeller** is a propeller fitted with a non-rotating nozzle. It is used to improve the efficiency of the propeller and are especially used on heavily loaded propellers or propellers with limited diameter. It was developed by Luigi Stipa (1931) and Ludwig Kort (1934).

Advantages are increased efficiency, better course stability and less vulnerability to debris. Downsides are reduced efficiency and course stability when sailing astern and increase of cavitation. Ducted propellers are also used to replace rudders.

Types

There are two types of ducts; accelerating and decelerating. With accelerating ducts, the inflow velocity and efficiency of the propeller is increased. This is the type that is used on heavily loaded propellers or propellers with limited diameter. As Ludwig Kort performed extensive research on this type, it is often called Kort nozzle.

With the second type, the inflow velocity is reduced, whereby pressure is increased, reducing cavitation. This is called a pump-jet, especially in combination with fixed blades or stators.

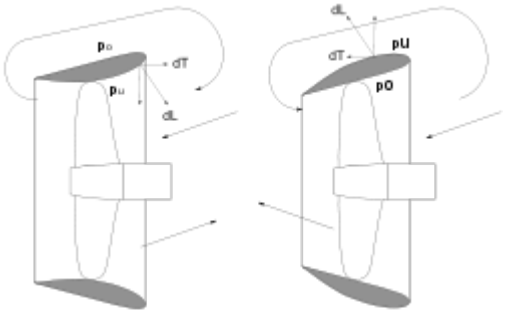


NACA 4415.

MARIN has done extensive research on ducted propellers. Many of the used profiles are based on the NACA airfoils of which the NACA 4415 has very good characteristics. Most commonly used are nozzle 19A and 37 of the MARIN series. Thes have a rounded trailing edge to ease fabrication and increase efficiency sailing astern. Initially, the propellers of the Wageningen B-series were used, later the Kaplan-type with a wider blade tip.

Physics

Circulation around accelerating and decelerating nozzle



dT = Thrust
dL = Lift

p_u: Negative pressure
p_o: Positive pressure

In a Kort nozzle, the inflow velocity is increased, reducing pressure. This lowers thrust and torque of the propeller. At the same time, a circulation occurs, resulting in an inward aimed force, that has a forward component. The duct therefore has a positive thrust. This is normally larger than the thrust reduction of the propeller. The small clearance between the propeller and duct reduces tip vortex, increasing efficiency.

As drag increases with increasing speed, eventually this will become larger than the added thrust. Vessels that normally operate above this speed are therefore normally not fitted with ducts. When towing, tugboats sail with low speed and heavily loaded propellers, and are often fitted with ducts. Bollard pull can increase up to 30% with ducts.

With decelerating ducts, the circulation opposite of the Kort nozzle, resulting in a negative thrust of the duct. This type is used for high speed vessels with increased exposure to cavitation and vessels that want to reduce noise levels, such as warships.

Folding propeller

A **folding propeller** is a type of propeller where the propeller blades fold in when the propeller is not in use, and out when the propeller is in use. This type of propeller is often used on sailing yachts to reduce drag while under sail. It is also used on microfilm model aircraft. Pros and cons of folding compared with fixed propellers are:

Pros	Cons
Folding propellers reduce drag while not in use. Less fluid resistance allows for more speed through the water or air.	Non self feathering folding propellers have poor performance when used in reverse.
Less noise and vibration than fixed blades when not in use since the propeller will not rotate when forced through water.	They cost more than fixed propellers.
Self feathering propellers may increase efficiency because the blades are always pitched at the optimal angle.	For marine propellers, vegetation growth can stop the propeller from folding in/out.

Modular propeller

The purpose of a **modular propeller** is to provide more control over a boats performance. The most common modular propeller has three main parts: the center hub with an integrated front cap, a set of replaceable blades, and a rear cap. Assembly of the propeller is completed by sliding the base of the blades into the corresponding slots of the

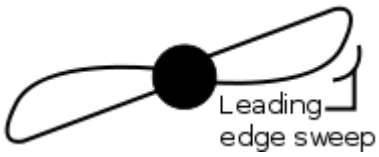
center hub, and then placing the rear cap onto the assembly. A nylock nut, prop nut, and cotter pin of another prop nut will be added to keep the assembly together.

Modular propellers offer boaters several advantages a fixed pitch propeller. The ability to change blades allows boaters to make adjustments in pitch for various performance needs or a change in altitude. Carrying spare blades for this purpose takes up considerably less space then carrying a complete spare propeller. The ability to replace blades also offers the advantage of replacing damaged blades while still on the water, and saves long term repair costs. Other options include adjusting pitch for altitue, watersports, cruising, and quick turnover time.

An applicable way to view blade pitch is through car gears. A pitch of 13 is similar to 1st gear: less speed, more power and acceleration. The third gear of a car would be in comparison to a propeller with a pitch of 17. Good acceleration and top end speed is offered with a 17 pitch. A higher pitch of 21 is similar to fifth gear, which is more speed for given rpm, but has less acceleration capabilities.

When changing a props pitch, it is important to know the specified range of diameter and pitch options from the boat manufacturer. If RPMs are too low, the engine can “over rev.” In contrast, if the RPMs are too high, the engine may lug at wide open throttle. The best estimate is that for every 2 inch pitch change will result in approximately 400 RPM change at wide-open throttle. An increase in pitch will cause the RPM to drop, and a decrease in pitch will increase the RPM

Scimitar propeller



Scimitar propeller on a 1926 Alexander Eaglerock

A **scimitar propeller** is shaped like a scimitar sword, with increasing sweep along the leading edge. Typically scimitar propellers are constructed of lightweight or composite materials. In the early 1900s they were made of laminated wood. The combination of light weight and efficient aerodynamics results in more power and reduced noise.

Eight-blade scimitar propellers on the A400M.

Propfan engines use contra-rotating scimitar propellers to achieve turboprop efficiency levels at high subsonic air speeds comparable to that of turbofans.

Turboprops have a fairly narrow sweet spot at speeds below about 450 mph. All propellers lose efficiency at high speed, due to an effect known as wave drag which occurs just below supersonic speeds. This powerful form of drag exhibits sudden onset, and it led to the concept of a sound barrier when it was first encountered in the 1940s. In the case of a propeller, this effect can happen when the prop is spun fast enough that the tips of the prop start traveling near the speed of sound, even if the plane itself is not moving forward.

This can be controlled to some degree by adding more blades to the prop, absorbing more power at a lower rotational speed. This is why some WWII fighters started with two-blade props and were using five-blade designs by the end of the war. The only downside to this approach is that adding blades makes the propeller harder to balance and maintain. At some point, though, the forward speed of the plane combined with the rotational speed of the propeller will once again result in wave drag problems. For most aircraft, this will occur at speeds over about 450 mph.

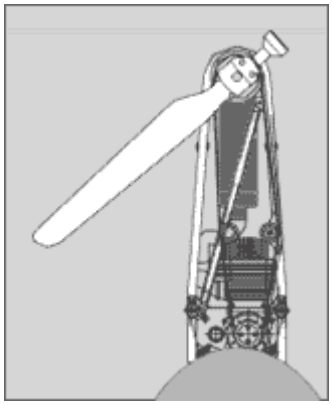
A method of decreasing wave drag was discovered by German researchers in WWII: sweeping the wing backward. Today, almost all aircraft designed to fly much above 450 mph (700 km/h) use a swept wing. In the 1940s, NACA started researching propellers with similar sweep. Since the inside of the prop is moving more slowly than the outside, the blade becomes progressively more swept toward the outside, leading to a curved shape similar to that of a scimitar.

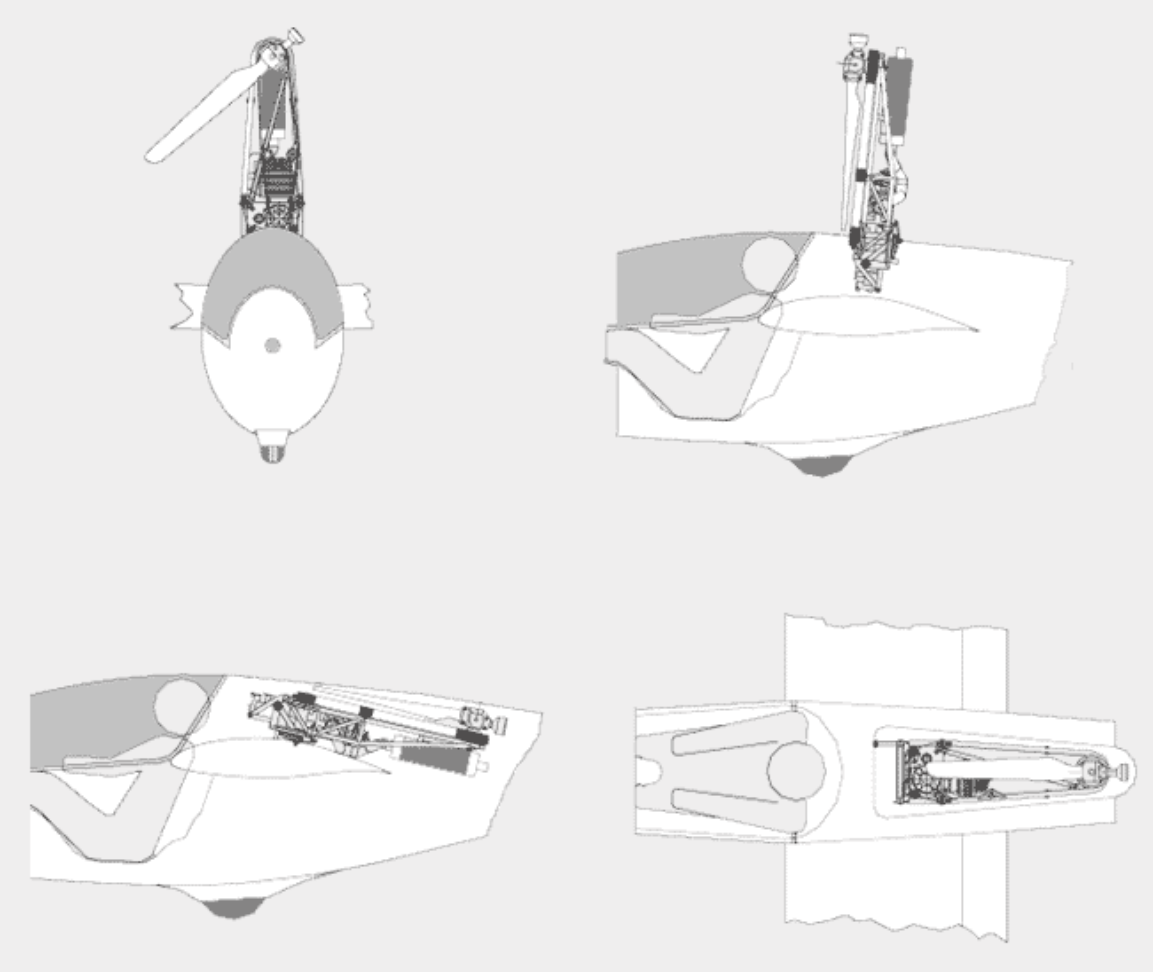
Progress propfan on the Antonov An-70.

The propfan concept was intended to deliver 35% better fuel efficiency than contemporary turbofans, and in this they succeeded. In static and air tests on a modified DC-9, propfans reached a 30% improvement. This efficiency comes at a price, as one of the major problems with the propfan is noise, particularly in an era where aircraft are required to comply with increasingly strict FAA noise requirements for certification.

Single-blade propeller

A **single-blade propeller** may be used on aerodynes to generate thrust. Normally propellers are multiblades but the simplicity of a single-blade propeller fits well on motorized gliders, because it permits the design of a smaller aperture of the glider fuselage for retraction of the powerplant. The counter-balanced teetering mono-blade propeller generates fewer vibrations than conventional multiblade configurations. Everel Propeller Corporation in the 1940s produced the counter-balance single-blade propeller.Everel Propeller





Supercavitating propeller

Artist rendering of a supercavitating propeller in function

The **supercavitating propeller** is a variant of a propeller for propulsion in water, where supercavitation is actively employed to gain increased speed by reduced friction.

The supercavitating propeller is being used for military purposes and for high performance boat racing vessels as well as model boat racing.

The supercavitating propeller operates in the conventional submerged mode, with the entire diameter of the blade below the water line. The blades of a supercavitating propeller are wedge shaped to force cavitation at the leading edge and avoid water skin friction along the whole forward face. The cavity collapses well behind the blade, which is the reason the supercavitating propeller avoids the erosion damage due to cavitation that is a problem with conventional propellers.

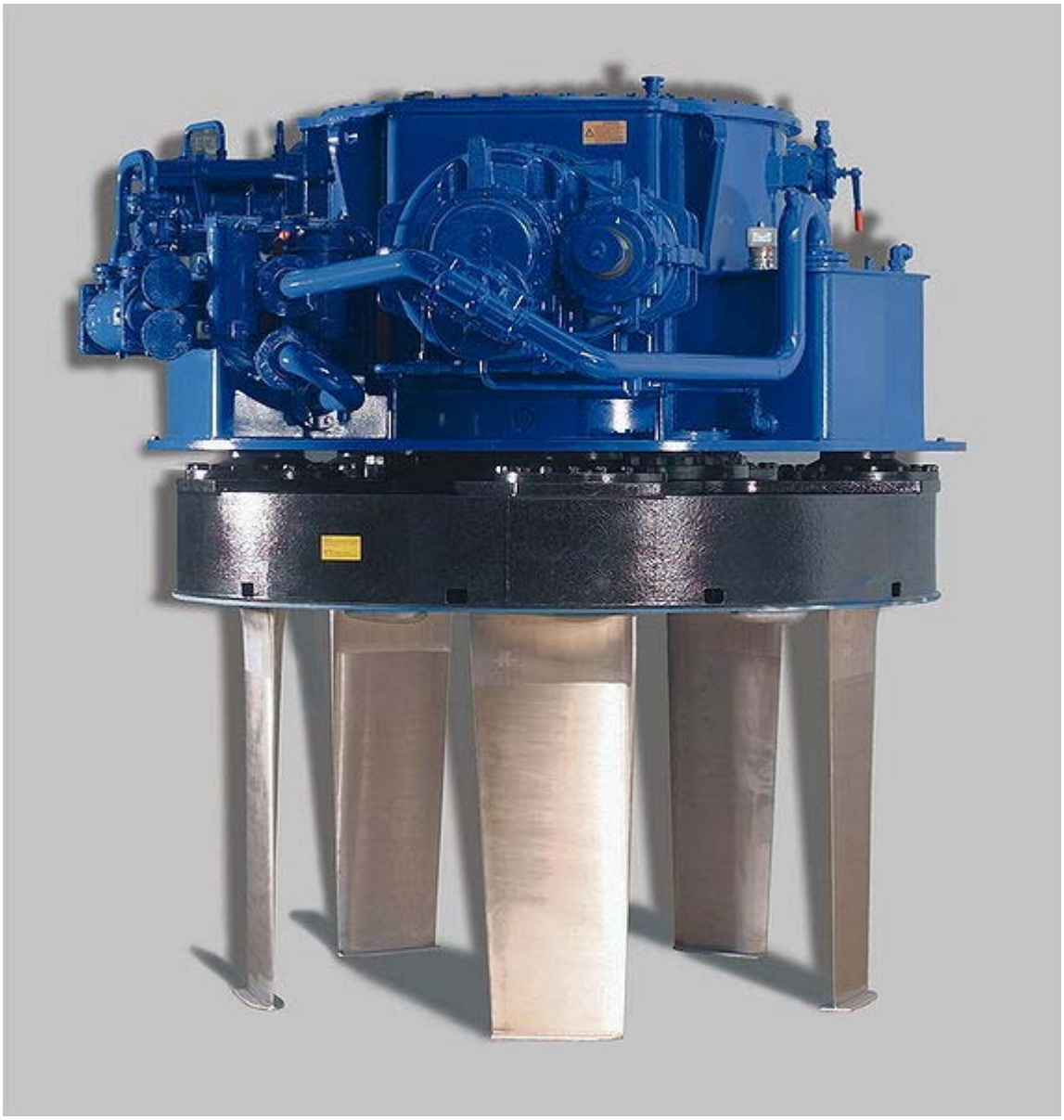
An alternative to the supercavitating propeller is the surface piercing, or *ventilated* propeller. These propellers are designed to intentionally cleave the water and entrain atmospheric air to fill the void, which means that the resulting gas layer surrounding the propeller blade consists of air instead of water vapour. Less energy is thus used, and the surface piercing propeller generally enjoys lower drag than the supercavitating principle. The surface piercing propeller also has wedge shaped blades, and propellers may be designed that can operate in both supercavitating and surface piercing mode.

The pioneer of this technology and other high speed offshore boating technologies was Albert Hickman (1877-1957), early in the 20th century. His *Sea Sled* designs used a surface piercing propeller.

Surface piercing propeller

The **surface piercing** or **ventilated propeller** (image) is a propeller that is designed to intentionally cleave the water and entrain atmospheric air to fill the void, which means that the resulting gas layer surrounding the propeller blade consists of air instead of water vapour. Less energy is thus used, and the surface piercing propeller generally enjoys lower drag than the supercavitating propeller. The surface piercing propeller also has wedge shaped blades, and propellers may be designed that can operate in both supercavitating and surface piercing mode.

Voith Schneider Propeller



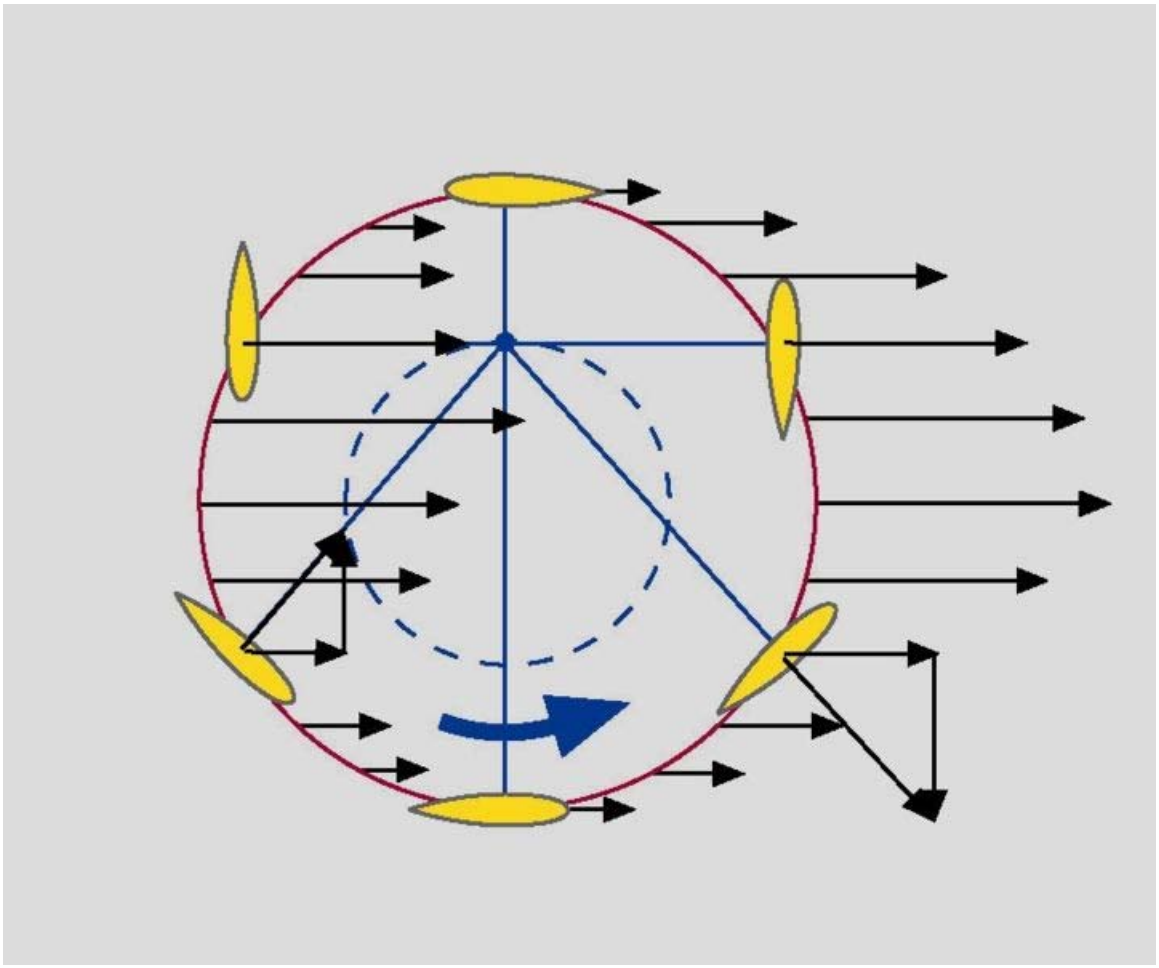
Voith Schneider Propeller

Twin Voith Schneider Propeller on a tug's hull.

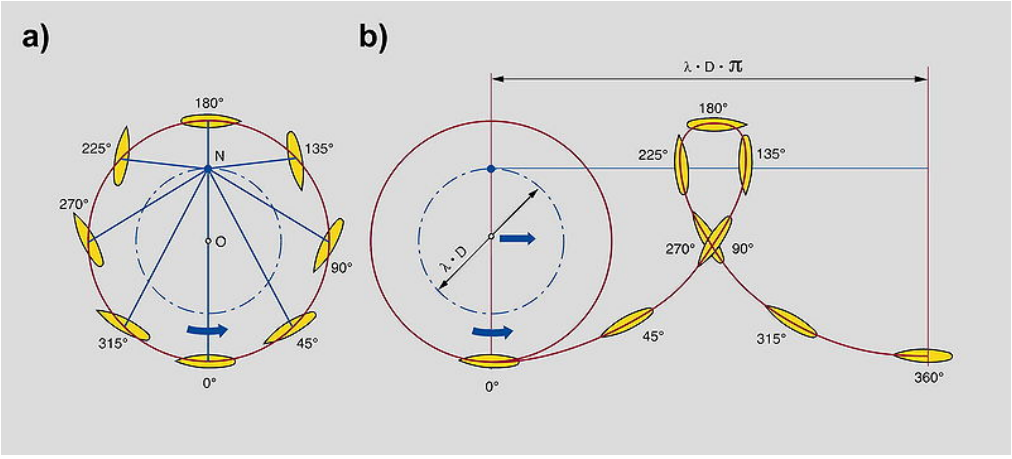
The **Voith Schneider** propeller (VSP), also known as a **cycloidal drive** (CD) is a specialized marine propulsion system (MPS). It is highly manoeuvrable, being able to change the direction of its thrust almost instantaneously. It is widely used on tugs and ferries.

From a circular plate, rotating around a vertical axis, a circular array of vertical blades (in the shape of hydrofoils) protrude out of the bottom of the ship. Each blade can rotate itself around a vertical axis. The internal gear changes the angle of attack of the blades in sync with the rotation of the plate, so that each blade can provide thrust in any direction, very similar to the *collective pitch control* and *cyclic* in a helicopter.

Unlike a Z-drive (where a conventional propeller is tilted on a vertical rudder axis) changing the direction of thrust with a Voith-Schneider drive merely requires changing the pattern of orientation of the vertical blades. In a marine situation this provides for a drive which can be directed in any direction and thus does away with the need for a rudder. It is highly efficient and provides for an almost instantaneous change of direction. These drives are becoming increasingly common in work boats such as fireboats and tugboats where extreme manoeuvrability is needed.



Lift forces of the VSP on the water body



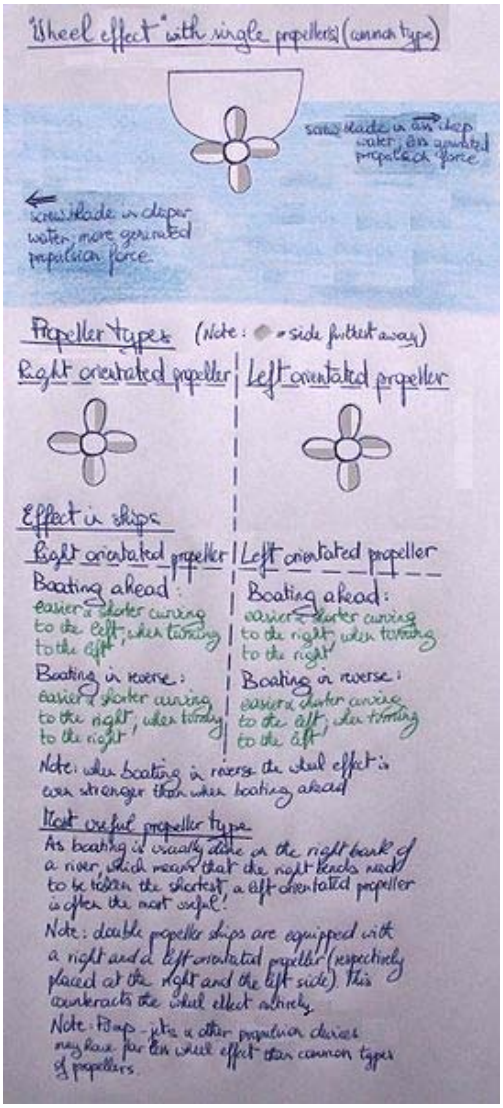
Path of a blade in the water

Z-drives (and Kort nozzles) have both advantages and disadvantages when compared to cycloidal drives. The Z-drive is less efficient and slower to manoeuvre, but is likely to be cheaper in the short term. Life cycle costs favour the Voith solution, something reflected in the residual value of a Voith water tractor. A choice is made on the basis of perceived performance requirements. Also, the blades of the drive protrude from the bottom of the hull making shallow water operation a problem.

Chapter- 5

Propeller Phenomena

Propeller walk



The propeller walk

Propeller walk is the term for a propeller's tendency to rotate a boat as well as accelerating it forwards or backwards.

A right-handed propeller (which rotates clockwise [as viewed from the stern] when in forward gear) will tend to push the stern of the boat to starboard. When in reverse gear, the effect will be much greater and opposite. A right-handed propeller will now push the aft of the boat to port.

Knowing of and understanding **propeller walk** is important when maneuvering in small spaces. It can be used to one's advantage while mooring off, or it can complicate a maneuver if the effect works against the pilot.

Propeller walk is a complicated effect which depends on ship geometry, direction of travel, propeller direction, vessel speed and depth of water. Three causes are identified for a vessel in deep water:-

1. Upward oblique flow at the propeller location.
2. Vertical wake distribution at the propeller.
3. Unbalanced lateral forces on the rudder (when set amidships) arising from the propeller slipstream impinging on the rudder blade.

The first of these results from there being a measurable difference in speed of water flowing close to the hull and that at lower depths which has not been affected by the vessel's motion. At low speeds the last effect is most pronounced and when going astern has even more influence.

In shallow water the upwards flow from under the vessel becomes much less strong and ultimately disappears. Model tests carried out show that, at a very small underkeel clearance, screw bias caused a ship to sheer to starboard (rather than port) when moving ahead and that there is an intermediate depth where the sheer from bias is neither one thing nor the other.

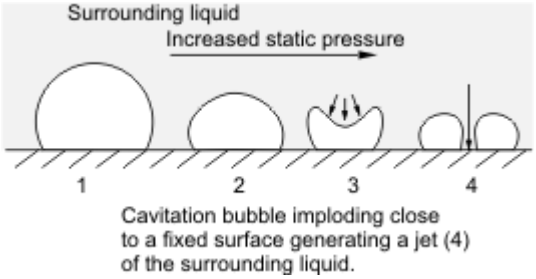
Finally, when moving ahead with the propeller moving astern, flow into and around the propeller is very confused. Generally the overall result for a single screw ship when stopping is a sheer to starboard, but this is not always guaranteed; sometimes it may go the other way, depending often on any yaw rate on the vessel when the propeller starts to turn astern.

Other terms for **propeller walk** are:-

- **propeller effect**
- **paddle wheel effect**
- **asymmetric thrust**
- **asymmetric blade effect**
- or simply **prop walk**.

Cavitation

Cavitating propeller model in a water tunnel experiment.



High speed jet of fluid impact on a fixed surface.

Cavitation damages on a valve plate for an axial piston hydraulic pump.

Cavitation is the formation of gas bubbles of a flowing liquid in a region where the pressure of the liquid falls below its vapor pressure. Cavitation is usually divided into two classes of behavior: inertial (or transient) cavitation, and noninertial cavitation.

Inertial cavitation is the process where a void or bubble in a liquid rapidly collapses, producing a shock wave. Inertial cavitation occurs in nature in the strikes of mantis shrimps and pistol shrimps, as well as in the vascular tissues of plants. In artifacts, it can occur in control valves, pumps, propellers and impellers.

Noninertial cavitation is the process in which a bubble in a fluid is forced to oscillate in size or shape due to some form of energy input, such as an acoustic field. Such cavitation is often employed in ultrasonic cleaning baths and can also be observed in pumps, propellers, etc.

Since the shock waves formed by cavitation are strong enough to significantly damage moving parts, cavitation is usually an undesirable phenomenon. It is specifically avoided in the design of machines such as turbines or propellers, and eliminating cavitation is a major field in the study of fluid dynamics.

Inertial cavitation

Inertial cavitation was first studied by Lord Rayleigh in the late 19th century, when he considered the collapse of a spherical void within a liquid. When a volume of liquid is subjected to a sufficiently low pressure, it may rupture and form a cavity. This phenomenon is termed *cavitation inception* and may occur behind the blade of a rapidly

rotating propeller or on any surface vibrating in the liquid with sufficient amplitude and acceleration. A fast-flowing river can cause cavitation on rock surfaces, particularly when there is a drop-off, such as on a waterfall.

Other ways of generating cavitation voids involve the local deposition of energy, such as an intense focused laser pulse (optic cavitation) or with an electrical discharge through a spark. Vapor gases evaporate into the cavity from the surrounding medium; thus, the cavity is not a perfect vacuum, but has a relatively low gas pressure. Such a low-pressure cavitation bubble in a liquid begins to collapse due to the higher pressure of the surrounding medium. As the bubble collapses, the pressure and temperature of the vapor within increases. The bubble eventually collapses to a minute fraction of its original size, at which point the gas within dissipates into the surrounding liquid via a rather violent mechanism, which releases a significant amount of energy in the form of an acoustic shock wave and as visible light. At the point of total collapse, the temperature of the vapor within the bubble may be several thousand kelvin, and the pressure several hundred atmospheres.

Inertial cavitation can also occur in the presence of an acoustic field. Microscopic gas bubbles that are generally present in a liquid will be forced to oscillate due to an applied acoustic field. If the acoustic intensity is sufficiently high, the bubbles will first grow in size and then rapidly collapse. Hence, inertial cavitation can occur even if the rarefaction in the liquid is insufficient for a Rayleigh like void to occur. High-power ultrasonics usually utilize the inertial cavitation of microscopic vacuum bubbles for treatment of surfaces, liquids, and slurries.

The physical process of cavitation inception is similar to boiling. The major difference between the two is the thermodynamic paths that precede the formation of the vapor. Boiling occurs when the local vapor pressure of the liquid rises above its local ambient pressure and sufficient energy is present to cause the phase change to a gas. Cavitation inception occurs when the local pressure falls sufficiently far below the saturated vapor pressure, a value given by the tensile strength of the liquid.

In order for cavitation inception to occur, the cavitation "bubbles" generally need a surface on which they can nucleate. This surface can be provided by the sides of a container, by impurities in the liquid, or by small undissolved microbubbles within the liquid. It is generally accepted that hydrophobic surfaces stabilize small bubbles. These pre-existing bubbles start to grow unbounded when they are exposed to a pressure below the threshold pressure, termed Blake's threshold.

The vapor pressure here differs from the meteorological definition of vapor pressure, which describes the partial pressure of water in the atmosphere at some value less than 100% saturation. Vapor pressure as relating to cavitation refers to the vapor pressure in equilibrium conditions and can therefore be more accurately defined as the equilibrium (or saturated) vapor pressure.

Noninertial cavitation

Noninertial cavitation is the process in which small bubbles in a liquid are forced to oscillate in the presence of an acoustic field, when the intensity of the acoustic field is insufficient to cause total bubble collapse. This form of cavitation causes significantly less erosion than inertial cavitation, and is often used for the cleaning of delicate materials, such as silicon wafers.

Cavitation damage

Cavitation damage to a Francis turbine.

Cavitation is, in many cases, an undesirable occurrence. In devices such as propellers and pumps, cavitation causes a great deal of noise, damage to components, vibrations, and a loss of efficiency.

When the cavitation bubbles collapse, they force energetic liquid into very small volumes, thereby creating spots of high temperature and emitting shock waves, the latter of which are a source of noise. The noise created by cavitation is a particular problem for military submarines, as it increases the chances of being detected by passive sonar.

Although the collapse of a cavity is a relatively low-energy event, highly localized collapses can erode metals, such as steel, over time. The pitting caused by the collapse of cavities produces great wear on components and can dramatically shorten a propeller or pump's lifetime.

After a surface is initially affected by cavitation, it tends to erode at an accelerating pace. The cavitation pits increase the turbulence of the fluid flow and create crevasses that act as nucleation sites for additional cavitation bubbles. The pits also increase the components' surface area and leave behind residual stresses. This makes the surface more prone to stress corrosion.

Hydrodynamic cavitation

Hydrodynamic cavitation describes the process of vaporisation, bubble generation and bubble implosion which occurs in a flowing liquid as a result of a decrease and subsequent increase in pressure. Cavitation will only occur if the pressure declines to some point below the saturated vapor pressure of the liquid. In pipe systems, cavitation typically occurs either as the result of an increase in the kinetic energy (through an area constriction) or an increase in the pipe elevation.

Hydrodynamic cavitation can be produced by passing a liquid through a constricted channel at a specific velocity or by mechanical rotation through a liquid. In the case of the constricted channel and based on the specific (or unique) geometry of the system, the combination of pressure and kinetic energy can be created when the hydrodynamic cavitation cavern downstream of the local constriction generating high energy cavitation bubbles.

The process of bubble generation, subsequent growth and collapse of the cavitation bubbles results in very high energy densities, resulting in very high temperatures and pressures at the surface of the bubbles for a very short time. The overall liquid medium environment, therefore, remains at ambient conditions. When uncontrolled, cavitation is damaging; however, by controlling the flow of the cavitation the power is harnessed and non-destructive. Controlled cavitation can be used to enhance chemical reactions or propagate certain unexpected reactions because free radicals are generated in the process due to disassociation of vapors trapped in the cavitating bubbles.

Orifices and venturi are reported to be widely used for generating cavitation. A venturi, because of its smooth converging and diverging sections, has an inherent advantage, over the orifice, that it can generate a higher velocity at the throat for a given pressure drop across it. On the other hand, an orifice has an advantage that it can accommodate more number of holes (larger perimeter of holes) in a given cross sectional area of the pipe.

Hydrodynamic cavitation can improve industrial processes. For instance, cavitated corn slurry show higher yields in ethanol production compared to uncavitated corn slurry in dry milling facilities.

This is also used in the mineralization of bio-refractory compounds which otherwise would need extremely high temperature and pressure conditions since free radicals are generated in the process due to the dissociation of vapours trapped in the cavitating bubbles, which results in either the intensification of the chemical reaction or may even result in the propagation of certain reactions not possible under otherwise ambient conditions.

Chemical engineering applications

In industry, cavitation is often used to homogenize, or mix and break down, suspended particles in a colloidal liquid compound such as paint mixtures or milk. Many industrial mixing machines are based upon this design principle. It is usually achieved through impeller design or by forcing the mixture through an annular opening that has a narrow entrance orifice with a much larger exit orifice. In the latter case, the drastic decrease in pressure as the liquid accelerates into a larger volume induces cavitation. This method can be controlled with hydraulic devices that control inlet orifice size, allowing for dynamic adjustment during the process, or modification for different substances. The surface of this type of mixing valve, against which surface the cavitation bubbles are driven causing their implosion, undergoes tremendous mechanical and thermal localized stress; they are therefore often constructed of super-hard or tough materials such as stainless steel, Stellite, or even polycrystalline diamond (PCD).

Cavitating water purification devices have also been designed, in which the extreme conditions of cavitation can break down pollutants and organic molecules. Spectral analysis of light emitted in sonochemical reactions reveal chemical and plasma-based mechanisms of energy transfer. The light emitted from cavitation bubbles is termed sonoluminesence.

Hydrophobic chemicals are attracted underwater by cavitation as the pressure difference between the bubbles and the liquid water forces them to join together. This effect may assist in protein folding.

Biomedical application

Cavitation plays an important role for the destruction of kidney stones in shock wave lithotripsy. Currently, tests are being conducted as to whether cavitation can be used to transfer large molecules into biological cells (sonoporation). Nitrogen cavitation is a method used in research to lyse cell membranes while leaving organelles intact. Cavitation plays a key role in non-thermal noninvasive fractionation of tissue for treatment of a variety of diseases. Cavitation also probably plays a role in HIFU, a thermal noninvasive treatment methodology for cancer.

Ultrasound is sometimes used to increase bone formation, for instance post-surgical applications. Ultrasound treatments and/or exposure can create cavitation that can

potentially "result in a syndrome involving manifestations of nausea, headache, tinnitus, pain, dizziness, and fatigue.".

Cleaning application

In industrial cleaning applications, cavitation has sufficient power to overcome the particle-to-substrate adhesion forces, loosening contaminants. The threshold pressure required to initiate cavitation is a strong function of the pulse width and the power input. This method works by generating controlled acoustic cavitation in the cleaning fluid, picking up and carrying contaminant particles away so that they do not reattach to the material being cleaned.

Pumps and propellers

Major places where cavitation occurs are in pumps, on propellers, or at restrictions in a flowing liquid.

As an impeller's (in a pump) or propeller's (as in the case of a ship or submarine) blades move through a fluid, low-pressure areas are formed as the fluid accelerates around and moves past the blades. The faster the blades move, the lower the pressure around it can become. As it reaches vapor pressure, the fluid vaporizes and forms small bubbles of gas. This is cavitation. When the bubbles collapse later, they typically cause very strong local shock waves in the fluid, which may be audible and may even damage the blades.

Cavitation in pumps may occur in two different forms:

Suction cavitation

Suction cavitation occurs when the pump suction is under a low-pressure/high-vacuum condition where the liquid turns into a vapor at the eye of the pump impeller. This vapor is carried over to the discharge side of the pump, where it no longer sees vacuum and is compressed back into a liquid by the discharge pressure. This imploding action occurs violently and attacks the face of the impeller. An impeller that has been operating under a suction cavitation condition can have large chunks of material removed from its face or very small bits of material removed, causing the impeller to look spongelike. Both cases will cause premature failure of the pump, often due to bearing failure. Suction cavitation is often identified by a sound like gravel or marbles in the pump casing.

In automotive applications, a clogged filter in a hydraulic system (power steering, power brakes) can cause suction cavitation making a noise that rises and falls in synch with engine RPM. It is fairly often a high pitched whine, like set of nylon gears not quite meshing correctly.

Discharge cavitation

Discharge cavitation occurs when the pump discharge pressure is extremely high, normally occurring in a pump that is running at less than 10% of its best efficiency point. The high discharge pressure causes the majority of the fluid to circulate inside the pump instead of being allowed to flow out the discharge. As the liquid flows around the impeller, it must pass through the small clearance between the impeller and the pump housing at extremely high velocity. This velocity causes a vacuum to develop at the housing wall (similar to what occurs in a venturi), which turns the liquid into a vapor. A pump that has been operating under these conditions shows premature wear of the impeller vane tips and the pump housing. In addition, due to the high pressure conditions, premature failure of the pump's mechanical seal and bearings can be expected. Under extreme conditions, this can break the impeller shaft.

Discharge cavitation in joint fluid is thought to cause the popping sound produced by bone joint cracking, for example by deliberately cracking one's knuckles.

Control valves

Cavitation can occur in control valves. If the upstream pressure is just above the vapor pressure, then it is possible that the pressure will drop below the vapor pressure as the fluid flows through the valve. If the pressure recovers after the valve to a pressure that is once again above the vapor pressure, then cavitation will occur.

Cavitation on spillways

When water flows over a dam spillway, the irregularities on the spillway surface will cause small areas of flow separation in a high speed flow, and, in these regions, the pressure will be lowered. If the velocities are high enough the pressure may fall to below the local vapor pressure of the water and vapor bubbles will form. When these are carried downstream into high pressure region the bubble collapses giving rise to high pressures and possible cavitation damage.

Experimental investigations show that the damage on concrete chute and tunnel spillways can start at clear water velocities of between 12 to 15 m/s, and, up to velocities of 20 m/s, it may be possible to protect the surface by streamlining the boundaries, improving the surface finishes or using resistant materials.

When some air is present in the water the resulting mixture is compressible and this damps the high pressure caused by the bubble collapses. If the velocities near the spillway invert are sufficiently high, aerators (or aeration devices) must be introduced to prevent cavitation. Although these have been installed for some years, the mechanisms of air entrainment at the aerators and the slow movement of the air away from the spillway surface are still challenging.

The spillway aeration device design is based upon a small deflection of the spilway bed (or sidewall) such as a ramp and offset to deflect the high velocity flow away from the spillway surface. In the cavity formed below the nappe, a local subpressure beneath the nappe is produced by which air is sucked into the flow. The complete design includes the deflection device (ramp, offset) and the air supply system.

Cavitation in engines

Some larger diesel engines suffer from cavitation due to high compression and undersized cylinder walls. Vibrations of the cylinder wall induce alternating low and high pressure in the coolant against the cylinder wall. The result is pitting of the cylinder wall, which will eventually let cooling fluid leak into the cylinder and combustion gases to leak into the coolant.

It is possible to prevent this from happening with the use of chemical additives in the cooling fluid that form a protective layer on the cylinder wall. This layer will be exposed to the same cavitation, but rebuilds itself. Additionally a regulated overpressure in the cooling system (regulated and maintained by the coolant filler cap spring pressure) prevents the forming of cavitation.

From about the 1980s, new designs of smaller petrol (gasoline) engines also displayed cavitation phenomenon. One answer to the need for smaller and lighter engines was a smaller coolant volume and a correspondingly higher coolant velocity. This gave rise to rapid changes in flow velocity and therefore rapid changes of static pressure in areas of high heat transfer. Where resulting vapor bubbles collapsed against a surface, they had the effect of first disrupting protective oxide layers (of cast aluminum materials) and then repeatedly damaging the newly formed surface, preventing the action of some types of corrosion inhibitor (such as silicate based inhibitors). A final problem was the effect that increased material temperature had on the relative electrochemical reactivity of the base metal and its alloying constituents. The result was deep pits that could form and penetrate the engine head in a matter of hours when the engine was running at high load and high speed. These effects could largely be avoided by the use of organic corrosion inhibitors or (preferably) by designing the engine head in such a way as to avoid certain cavitation inducing conditions.

Vascular plants

Cavitation occurs in the xylem of vascular plants when the tension of water within the xylem becomes so great that dissolved air within the water expands to fill either the vessel elements or tracheids. Plants are generally able to repair cavitated xylem in a number of ways. For plants less than 50 cm tall, root pressure can be sufficient to redissolve air. For larger plants, they must repair cavitation by importing solutes into the xylem; this causes water to enter as well, which can then redissolve the air. In some trees, the sound of the cavitation is clearly audible, particularly in summer, when the rate of

evapotranspiration is highest. Deciduous trees shed leaves in the autumn partly because cavitation increases as temperatures decrease.

Marine life

Just as cavitation bubbles form on a fast-spinning boat propeller, they may also form on the tails and fins of aquatic animals. The effects of cavitation are especially important near the surface of the ocean, where the ambient water pressure is relatively low and cavitation is more likely to occur.

For powerful swimming animals like dolphins and tuna, cavitation may be detrimental, because it limits their maximum swimming speed. Even if they have the power to swim faster, dolphins may have to restrict their speed because collapsing cavitation bubbles on their tail are too painful. Cavitation also slows tuna, but for a different reason. Unlike dolphins, these fish do not feel the painful bubbles, because they have bony fins without nerve endings. Nevertheless, they cannot swim faster because the cavitation bubbles create an air film around their fins that limits their speed. Lesions have been found on tuna that are consistent with cavitation damage.

Cavitation is not always a limitation for sea life; some animals have found ways to use it to their advantage when hunting prey. The pistol shrimp snaps a specialized claw to create cavitation, which can kill small fish. The mantis shrimp (of the *smasher* variety) uses cavitation as well in order to stun, smash open, or kill the shellfish that it feasts upon.

Coastal erosion

In the last half-decade, coastal erosion in the form of inertial cavitation has been generally accepted. Air pockets in an incoming wave are forced into cracks in the cliff being eroded, then the force of the wave compresses the air pockets until the bubble implodes, becoming liquid, giving off various forms of energy that blast apart the rock.

List of cavitation tunnels

Canada

- National Research Council—Institute for Ocean Technology Cavitation Tunnel, St. Johns, Newfoundland.

France

- "Tunnel de Cavitation" Ecole Navale, Lanveoc.
- "Grand Tunnel Hydrodynamique" Bassin d'Essais des Carènes, Val de Reuil.

Germany

- Multiple cavitation tunnels at the Versuchsanstalt für Wasserbau und Schiffbau, Berlin.
- Large Cavitation tunnel at Hamburg Ship Model Basin, Hamburg.
- Cavitation tunnel at the Schiffbau-Versuchsanstalt, Potsdam.

India

- Fluid Control Research Institute, Palakkad,Kerala.
- Cavitation Tunnel of the Naval Science and Technology Labs at Visakhapatnam.

Iran

- Applied Hydrodynamics Laboratory, Iran University of Science and Technology, Narmak, Tehran.
- Marine Engineering Laboratory, Sharif University of Technology, Azadi Av., Tehran.

Netherlands

- Large Cavitation Tunnel and High Speed Cavitation Tunnel at the Maritime Research Institute, Wageningen.

Norway

- "Cavitation Lab" NTNU, The Norwegian University of Science and Technology, Trondheim.

Poland

- Ship Design and Research Centre (CTO S.A.) Centrum Techniki Okrętowej S.A., Gdansk.

South Korea

- Samsung Ship Model Basin (SSMB), Samsung Heavy Industries, Daejeon.

Spain

- CEHIPAR (Canal de Experiencias Hidrodinámicas de El Pardo), El Pardo (Madrid).

Sweden

- SSPA

Switzerland

- Tunnel de Cavitation au Laboratoire des Machines Hydrauliques (LMH), Ecole Polytechnique Federale de Lausanne (EPFL)

Taiwan

- The Large Cavitation Tunnel at National Taiwan Ocean University, Keelung.

Ukraine

- The Cavitation Tunnel at Institute of Hydromechanics of National Academy of Sciences, Kiev

United Kingdom

- Emerson Cavitation Tunnel, University of Newcastle upon Tyne.

United States

- The Garfield Thomas Water Tunnel, The Pennsylvania State University, State College, PA.
- Naval Surface Warfare Center, Carderock Division 24" Variable Pressure Water Tunnel West Bethesda, MD
- Naval Surface Warfare Center, Carderock Division 36" Variable Pressure Water Tunnel West Bethesda, MD
- The William B. Morgan Large Cavitation Channel, part of NSWCCD Memphis, TN.
- MIT's variable pressure water tunnel.
- University of Minnesota's St. Anthony Falls Laboratory cavitation facilities.

Chapter- 6

Paddle Steamer

A paddle steamer from the 1850s

The *Music City Queen* on the Cumberland in Nashville is a stern-wheeler showboat.

A **paddle steamer** is a steamship or boat driven by a steam engine that uses one or more paddle wheels to develop thrust for propulsion. Paddle Steamers are also classified as a type of steamboat. Although generally associated with steam power from obvious historical factors, modern working **paddle wheelers** have also been driven by diesel engines.

After the pole and oar, the paddle wheel was the first practical form of cyclical mechanical propulsion applied to watercraft, and the first pragmatic means lending itself to using an engine as prime mover. Save for tourism designs and small pleasure boats (Paddle boats) paddle propulsion has been superseded by the screw propeller and other, more modern, forms of marine propulsion.

Paddle wheels

The paddle wheel is a large wheel, generally built of a steel framework, upon the outer edge of which are fitted numerous paddle blades (called *floats* or *buckets*). The bottom

quarter or so of the wheel travels underwater. Rotation of the paddle wheel produces thrust, forward or backward as required. More advanced paddle wheel designs have featured *feathering* methods that keep each paddle blade oriented closer to vertical while it is in the water; this increases efficiency. The upper part of a paddle wheel is normally enclosed in a paddlebox to minimise splashing.

Types of paddle steamer

Left: Riveted steel paddle wheel from a paddle steamer on the lake of Lucerne.
Right: detail of a steamer.

There are two basic ways to mount paddle wheels on a ship; either a single wheel on the rear, known as a *stern-wheeler*, or a paddle wheel on each side, known as a *side-wheeler*.

Stern-wheelers have generally been used as riverboats in the United States where they still operate for tourist use on the Mississippi River.

Side-wheelers are used as riverboats and as coastal craft. While wider than a stern-wheeler, due to the extra width of the paddle wheels and their enclosing *sponsons*, a side-wheeler has extra manoeuvrability since they are usually rigged so the paddles can move at different rates, and even in differing directions (one forward, one reversed giving rapid turning capabilities). Due to this extra manoeuvrability side-wheelers were more popular on the narrower, windy rivers of the Murray-Darling system in Australia where a number are still in operation today.

European side-wheelers such as the PS *Waverley* have solid drive shafts that require both wheels to turn ahead or astern together, which limits manoeuvrability and gives a wide turning circle. Some were built with paddle clutches to disengage one or both paddles and allow them to turn independently. However early experience with side-wheelers requires them to be operated with clutches out, or as solid shaft vessels. It was noticeable that as ships approached their piers for docking, passengers would move to the side of the ship ready to disembark. The shift in weight when added to independent movements of the paddles could lead to imbalance and potential for capsize.

Paddle tugs were frequently operated with clutches in, as the lack of passengers aboard meant that independent paddle movement could be used safely and the added manoeuvrability exploited to the full.

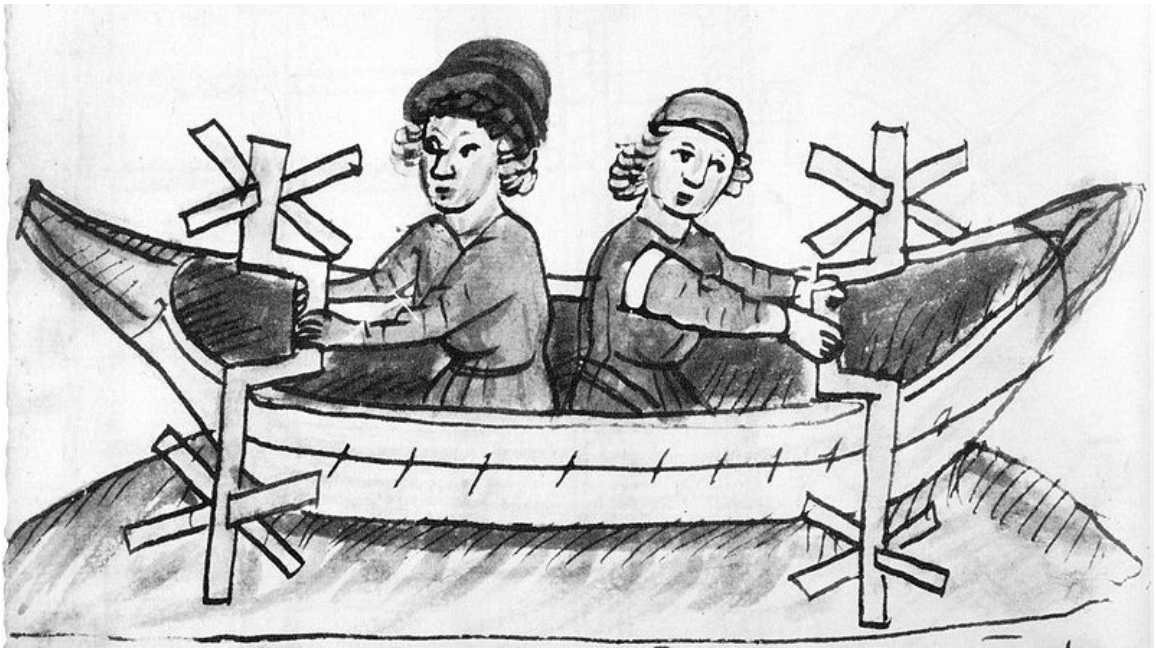
Western world

Ox-powered Roman paddle wheel boat from a 15th century copy of *De Rebus Bellicis*

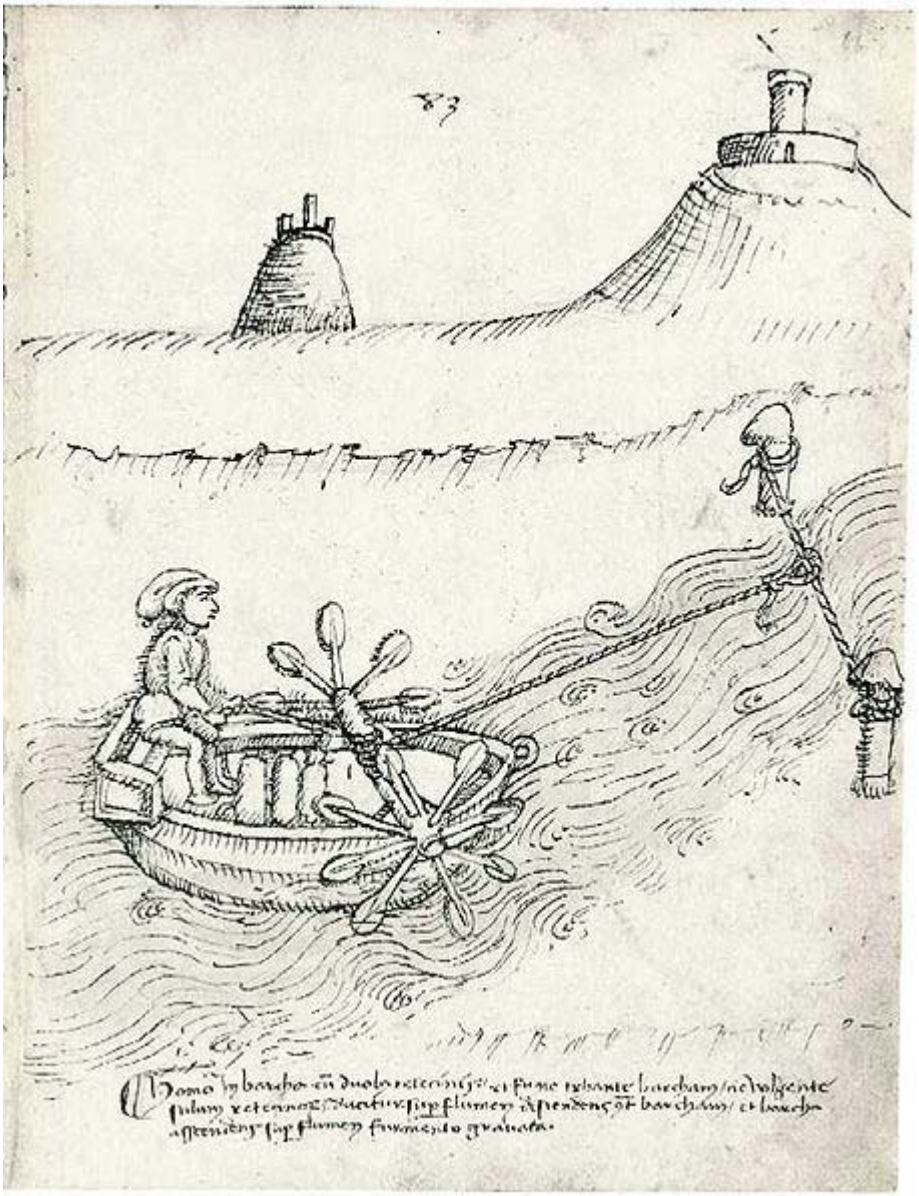
The use of a paddle wheel in navigation appears for the first time in the mechanical treatise of the Roman engineer Vitruvius (*De architectura*, X 9.5-7), where he describes multi-geared paddle wheels working as a ship odometer. The first mention of paddle wheels as a means of propulsion comes from the 4th–5th century military treatise *De Rebus Bellicis* (chapter XVII), where the anonymous Roman author describes an ox-driven paddle-wheel warship:

> “Animal power, directed by the resources on ingenuity, drives with ease and swiftness, wherever utility summons it, a warship suitable for naval combats, which, because of its enormous size, human frailty as it were prevented from being operated by the hands of men. In its hull, or hollow interior, oxen, yoked in pairs to capstans, turns wheels attached to the sides of the ship; paddles, projecting above the circumference or curved surface of the wheels, beating the water with their strokes like oar-blades as the wheels revolve, work with an amazing and ingenious effect, their action producing rapid motion. This warship, moreover, because of its own bulk and because of the machinery working inside it, joins battle with such pounding force that it easily wrecks and destroys all enemy warships coming at close quarters.”

The Italian physician Guido da Vigevano (c. 1280−1349), planning for a new crusade, made illustrations for a paddle boat that was propelled by manually turned compound cranks.



15th century paddle-wheel boat powered by crankshafts (Anonymous of the Hussite Wars)



Paddle boat, by the Italian artist-engineer Taccola, *De machinis* (1449)

One of the drawings of the Anonymous Author of the Hussite Wars shows a boat with a pair of paddle-wheels at each end turned by men operating compound cranks (see above). The concept was much improved by the Italian Roberto Valturio in 1463, who devised a boat with five sets, where the parallel cranks are all joined to a single power source by one connecting-rod, an idea also taken up by his compatriot Francesco di Giorgio.

In 1543 the Spanish engineer Blasco de Garay in Barcelona made an experimental vessel propelled by a paddle-wheel on each side, worked by forty men. In the same year he showed Carlos I of Spain (also known as Charles V, the Holy Roman Emperor), a new idea - a ship propelled by a giant wheel powered by steam. Carlos was not interested in it.

In 1787 Patrick Miller of Dalswinton invented a double-hulled boat, which was propelled on the Firth of Forth by men working a capstan which drove paddles on each side.

The first paddle steamer was the *Pyroscaphe* built by Marquis Claude de Jouffroy of Lyon in France, in 1783. It had a horizontal double-acting steam engine driving two 13.1-ft (4 m) paddle wheels on the sides of the craft. On July 15, 1783 it steamed successfully up the Saône for fifteen minutes before the engine failed. Political events interrupted further development.

The next successful attempt at a paddle-driven steam ship was by the Scottish engineer William Symington who suggested steam power to Patrick Miller of Dalswinton. Experimental boats built in 1788 and 1789 worked successfully on Lochmaben Loch. In 1802, Symington built a barge-hauler, *Charlotte Dundas*, for the Forth and Clyde Canal Company. It successfully hauled two 70-ton barges almost 20 miles (30 km) in 6 hours against a strong headwind on test in 1802. There was much enthusiasm, but some directors of the company were concerned about the banks of the canal being damaged by the wash from a powered vessel, and no more were ordered.

While *Charlotte Dundas* was the first commercial paddle-steamer and steamboat, the first commercial *success* was possibly Robert Fulton's *Clermont* in New York, which went into commercial service in 1807 between New York City and Albany. Many other paddle-equipped river boats followed all around the world.

East Asia

A Chinese paddle-wheel ship from a Qing Dynasty encyclopedia published in 1726

It is asserted that the first mention of a paddle-wheel ship from China is described in the *History of the Southern Dynasties*, compiled in the 7th century but describing the naval ships of the Liu Song Dynasty (420–479) used by admiral Wang Zhene in his campaign against the Qiang people in 418 AD. The mathematician and astronomer Zu Chongzhi (429–500) had a paddle-wheel ship built on the Xinting River (south of Nanjing) known as the "thousand league boat". When campaigning against Hou Jing in 552, the Liang Dynasty (502–557) admiral Xu Shipu employed paddle-wheel boats called "water-wheel boats". At the siege of Liyang in 573, the admiral Huang Faqiu employed foot-treadle powered paddle-wheel boats. A successful paddle-wheel warship design was made in

China by Prince Li Gao in 784 AD, during an imperial examination of the provinces by the Tang Dynasty (618–907) emperor. The Chinese Song Dynasty (960–1279) issued the construction of many paddle-wheel ships for its standing navy, and according to historian Joseph Needham:

"...between 1132 and 1183 (AD) a great number of treadmill-operated paddle-wheel craft, large and small, were built, including stern-wheelers and ships with as many as 11 paddle-wheels a side,".

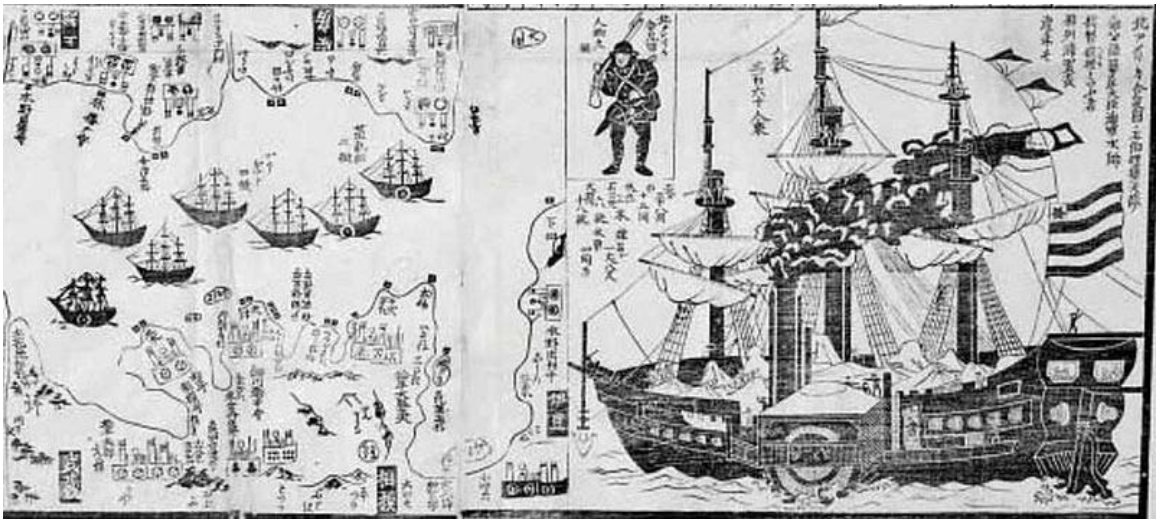
It is asserted that the standard Chinese term "wheel ship" was used by the Song period, whereas a litany of colorful terms were used to describe it beforehand. In the 12th century, the Song government used paddle-wheel ships *en masse* to defeat opposing armies of pirates armed with their own paddle-wheel ships. At the Battle of Caishi in 1161, paddle-wheelers were also used with great success against the Jin Dynasty (1115–1234) navy. The Chinese used the paddle-wheel ship even during the First Opium War (1839–1842) and for transport around the Pearl River during the early 20th century.

Seagoing paddle steamers

PS *Waverley*, the last sea-going paddle steamer

The first seagoing trip of a paddle steamer was that in 1808 of the *Albany'*, which steamed from the Hudson River along the coast to the Delaware River. This was purely for the purpose of moving a river-boat to a new market, but the use of paddle-steamers for short coastal trips began soon after that.

The first paddle-steamer to make a long ocean voyage was SS *Savannah*, built in 1819 expressly for this service. *Savannah* set out for Liverpool on May 22, 1819, sighting Ireland after 23 days at sea. This was the first powered crossing of the Atlantic, although *Savannah* also carried a full rig of sail to assist the engines when winds were favorable. In 1822, Charles Napier's *Aaron Manby*, the world's first iron ship, made the first direct steam crossing from London to Paris and the first seagoing voyage by an iron ship anywhere.



One of Commodore Perry's fleet: either the *Mississippi* or the *Susquehanna*.

In 1838, *Sirius*, a fairly small steam packet built for the Cork to London route, became the first vessel to cross the Atlantic under sustained steam power, beating Isambard Kingdom Brunel's much larger *Great Western* by a day. *Great Western*, however, was actually built for the transatlantic trade, and so had sufficient coal for the passage; *Sirius* had to burn furniture and other items after running out of coal. The *Great Western*'s more successful crossing began the regular sailing of powered vessels across the Atlantic. *Beaver* was the first coastal steamship to operate in the Pacific Northwest of North America. Paddle steamers helped open Japan to the Western World in the mid-19th century.

The largest paddle-steamer ever built was Brunel's *Great Eastern*, but it also had screw propulsion and sail rigging. It was 692 ft (211 m) long and weighed 32,000 tons, its paddle-wheels being 56 ft (17 m) in diameter.

In oceangoing service, paddle steamers became obsolete rather quickly with the invention of the screw propeller, but they remained in use in coastal service and as river tugboats, thanks to their shallow draught and good maneuverability.

Modern paddle steamers

Sternwheel paddleboat *Natchez* in Louisiana

The phrase *'Modern paddle steamers'* is a *double oxymoron* as there are no good reasons, save museum replication, to power a ship sized vessel by steam and no good reason, save showmanship and ambiance in tourism, to use inefficient paddle wheel propulsion. Consequently no recent (since 1947) paddle wheel steamers have been laid down and there are only a few original paddle steamers remaining in existence, and those that do are mainly preserved for tourists or as museums.

Quite a few paddle steamers serve niche tourism needs as cruise boats on lakes and others, such as the *Delta Queen*, still operate on the Mississippi River and in the Pacific Northwest along the Willamette River, as do a few in the United Kingdom and elsewhere in Europe.

PS *Skibladner* is the oldest steamship in regular operation. Built in 1856, she still operates on lake Mjøsa in Norway.

PS *Washington Irving*, built in 1912 by the New York Shipbuilding Company, was the biggest passenger-carrying riverboat ever built with a capacity for 6,000 passengers. It was operated on the Hudson River from 1913 until it was sunk in an accident in 1926. One of the last paddle steamers built in the U.S. was the dredge *William M. Black*, built in 1934 and now a National Historic Landmark.

PS *Waverley*, built in 1947, is the last seagoing paddle steamer in the world. This ship sails a full season of cruises every year from ports around Britain, and has sailed across the English Channel to commemorate the sinking of her predecessor of 1899 at the 1940 Battle of Dunkirk.

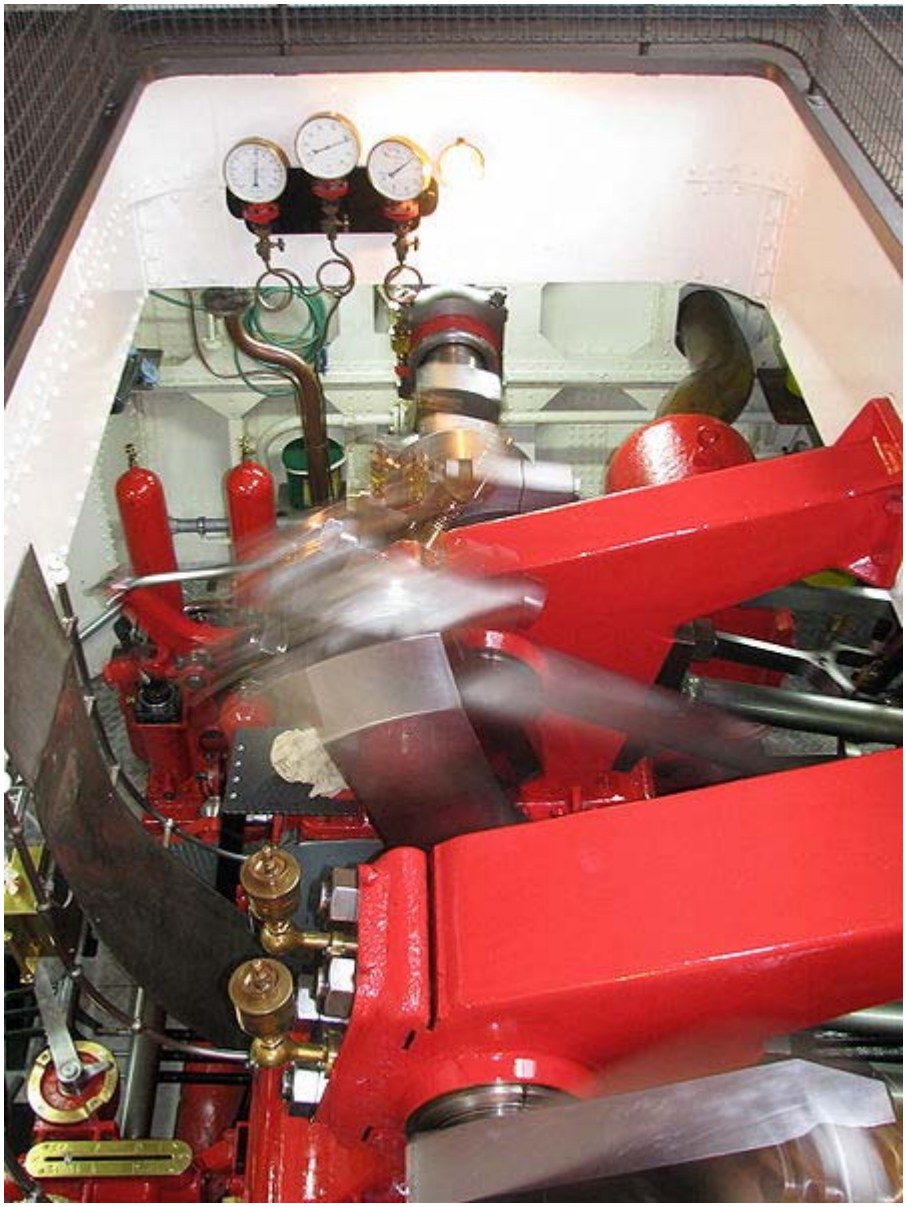
CGN paddle steamer *Montreux* leaving Evian-les-Bains in July 2002

PS *Adelaide* is the oldest wooden-hulled paddle steamer in the world. Built in 1866, she operates from the Port of Echuca, on Australia's Murray River, which has the largest fleet of paddle steamers in the world. The replica paddle steamer *Curlip* was constructed in Gippsland, Australia, and launched in November 2008.

Also in Australia, the PS *Kookaburra Queen* services the Brisbane River, operating as a floating restaurant or venue for hire.

PS *Kookaburra Queen* and a CityCat

The Elbe river Saxon Paddle Steamer Fleet in Dresden (known as "White Fleet"), Germany, is said to be the oldest and biggest in the world, with around 700.000 passengers per year. The 1913-built *Goethe* was the last paddle steamer on the River Rhine. Previously the world's greatest sidewheeler with a 2-cylinder steam engine of 700 hp (520 kW), a length of 83 m and a height above water of 9.2 m, the Goethe was converted to Diesel-Hydraulic power during the winter of 2008/09.



Steam ship engine ZSG *Stadt Rapperswil*, built in 1914 by Escher & Wyss at Zurich

Stadt Zürich (to the left) and *Stadt Rapperswil* in Zurich-Wollishofen

MPV *Constitution* in Vancouver, Canada

Switzerland has a large paddle steamer fleet, most of the "Salon Steamer-type" built by Sulzer in Winterthur or Escher-Wyss in Zurich. There are five active and one inactive on Lake Lucerne, two on Lake Zurich, and one each on Lake Brienz, Lake Thun and Lake Constance. Swiss company CGN operates a number of paddle steamers on Lake Geneva. Their fleet includes three converted to diesel electric power in the 1960s and five retaining steam. One, *Montreux*, was reconverted in 2000 from diesel to an all-new steam engine. It is the world's first electronically remote-controlled steam engine and has operating costs similar to state-of-the-art diesels, while producing up to 90 percent less air pollution.

In the USSR, river paddle steamers of the type *Iosif Stalin* (project 373), later renamed *Ryazan*-class steamships, were built until 1951. Between 1952 and 1959, ships of this type were build for the Soviet Union by Obuda Hajogyar Budapest factory in Hungary. In total, 75 type *Iosif Stalin/Ryazan* side-wheelers were built. They are 70 m long and can carry up to 360 passengers. Few of them still remain in active service.

In Italy, a small paddle steamer fleet operates on Lake Como and Lake Garda, primarily for the benefit of tourists.

On the Isle of Wight, PS *Monarch* (one of the smallest passenger-carrying vessels of her type) takes trips on the River Medina. *Monarch* is a side wheeler built at Chatham Historic Dockyard in Kent.

The restored paddle steamer *Waimarie* is based in Wanganui, New Zealand. The *Waimarie* was built in kitset form in Poplar, London in 1899, and originally operated on the Whanganui River under the name *Aotea*. Later renamed, she remained in service until 1949. She sank at her moorings in 1952, and remained in the mud until raised by volunteers and restored to begin operations again in 2000.

Paddle tugs

The British Admiralty used diesel-electric paddle tugs in recent times. Each paddle wheel was driven by an individual electric motor, giving outstanding maneuverability. Paddle tugs were able to more easily make use of the inherent advantage of side wheel paddle propulsion, having the option to disconnect the clutches that connected the paddle drive shafts as one. This enabled them to turn one paddle ahead and one astern to turn and manuvre quickly.

Chapter- 7

Propeller Variations

Azimuth thruster

Siemens *Schottel* azimuth thrusters

An **azimuth thruster** is a configuration of ship propellers placed in pods that can be rotated in any horizontal direction, making a rudder unnecessary. These give ships better maneuverability than a fixed propeller and rudder system.

Types of azimuth thrusters

There are two major variants, based on the location of the motor:

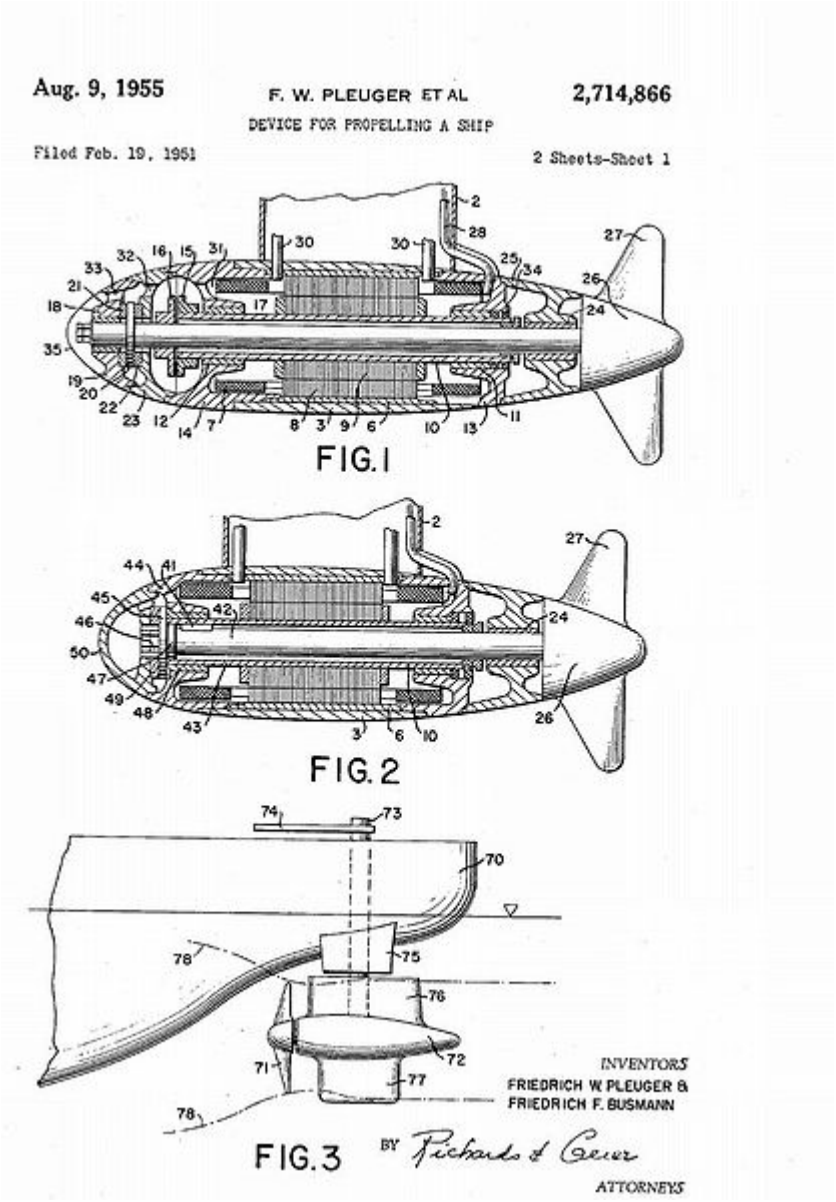
1. Mechanical transmission, where a motor inside the ship is connected to the pod by gearing. The motor may be diesel or diesel-electric. Depending on the shaft arrangement the mechanical azimuth thruster are divided into L-drive and Z-drive. An L-drive thruster has a vertical input shaft and a horizontal output shaft with one right-angle gear. A Z-drive thruster has an horizontal input shaft, vertical shaft in the rotating column and a horizontal output shaft with two right-angle gears.
2. Electrical transmission, where an electric motor is in the pod itself, connected directly to the propeller without gears. The electricity is produced by an onboard engine, usually diesel or gas turbine. Invented in 1955 by Mr. F.W. Pleuger and Mr. F. Busmann (*Pleuger Unterwasserpumpen GmbH*), ABB *Azipod* was the first product using this technology.

Mechanical azimuth thrusters can be fixed installed, retractable and underwater-mountable. They may have fixed pitch propellers (FPP) or controllable pitch propellers (CPP). Fixed installed thrusters are used for tugs, ferries and supply-boats. Retractable thrusters are used as auxiliary propulsion for dynamically positioned (DP) vessels and take-home propulsion for military vessels. Underwater-mountable thrusters are used as dynamic positioning propulsion for very large vessels such as semi-submersible drilling rigs.

Advantages

Primary advantages are electrical efficiency, better use of ship space, and lower maintenance costs. Ships with azimuth thrusters do not need tugs to dock, though they still require tugs to maneuver in difficult places.

History



U.S. Patent 2,714,866 from 1955

The first azimuth thrusters, using the mechanical Z-drive transmission, were built by Hollming in Finland in the 1960s under the *Aquamaster* brand name. The business was later sold to Rolls-Royce, after the merger of Finnish shipyards into Finnyards.

Later, subsidiaries of ABB, also based in Finland, developed the *Azipod* thruster, with the motor located in the pod itself. This kind of propulsion was first patented in 1955 by Pleuger of Germany.

Azipod

Closeup of one of USCGC *Mackinaw*'s azipods

Azipod is the registered brand name of the ABB Group for their azimuth thruster. Originally developed in Finland jointly by Kvaerner Masa-Yards dockyards and ABB, these are marine propulsion units consisting of electrically driven propellers mounted on a steerable pod.

The pod's propeller usually faces forward because in this puller (or tractor) configuration the propeller is more efficient. Because it can rotate around its mount axis, the pod can apply its thrust in any direction. Azimuth thrusters allow ships to be more maneuverable and enable them to travel backward nearly as efficiently as they can travel forward.

The new CRP (Contra Rotating Propellers) Azipod places a counter rotating azipod propeller behind a fixed propeller achieving improved fuel efficiency.

Azipod concept

In the traditional azimuth propulsion system the motor is inside the ship's hull and the propeller is driven through shafts and gearboxes. In the Azipod system the electric motor is inside the pod, and the propeller is connected directly to the motor shaft. By not using a

traditional propeller shaft, the propeller can be farther below the stern of the ship in a clear flow of water providing greater hydrodynamic and mechanical efficiency.

Electric power for the Azipod motor is conducted through slip rings that allow the Azipod to rotate through 360 degrees. Because fixed pitch propellers are used in Azipods, power for an Azipod system is always fed through a variable-frequency drive or cycloconverter that allows speed and direction control of the propulsion motors.

Impeller

An **impeller** *(or impellar)* is a rotor inside a tube or conduit used to increase the pressure and flow of a fluid.

An impeller for a dam turbine generator.

Impellers in pumps

Several different types of pump impellers.

Rotor of the impeller pump (cooling system) of an outboard engine.

An impeller is a rotating component of a centrifugal pump, usually made of iron, steel, bronze, brass, aluminum or plastic, which transfers energy from the motor that drives the

pump to the fluid being pumped by accelerating the fluid outwards from the center of rotation. The velocity achieved by the impeller transfers into pressure when the outward movement of the fluid is confined by the pump casing. Impellers are usually short cylinders with an open inlet (called an eye) to accept incoming fluid, vanes to push the fluid radially, and a splined, keyed or threaded bore to accept a drive-shaft.

The impeller made out of cast material in many cases may be called *rotor*, also. It is cheaper to cast the radial impeller right in the support it is fitted on, which is put in motion by the gearbox from an electric engine or by steam driven turbine. The *rotor* usually names both the *spindle* and the impeller when they are mounted by bolts.

Impellers in water jets

Some impellers are similar to small propellers but without the large blades. Among other uses, they are used in water jets to power high speed boats.

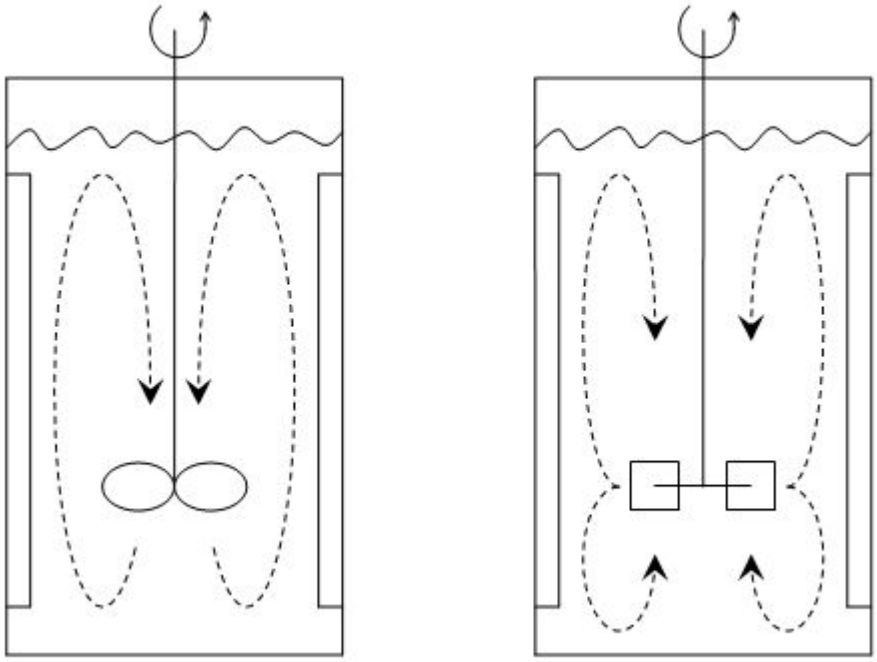
Since impellers have no large blades to turn, they can spin at much higher speeds than propellers. The water forced through the impeller is channelled by the housing, creating a water jet that propels the vessel forward. The housing is normally tapered into a nozzle to increase the speed of the water, which also creates a Venturi effect in which low pressure behind the impeller pulls more water towards the blades, tending to increase the speed.

To work efficiently, there must be a close fit between the impeller and the housing. The housing is normally fitted with a replaceable *wear ring* which tends to wear as sand or other particles are thrown against the housing side by the impeller.

Vessels using impellers are normally steered by changing the direction of the water jet.

Compare to propeller and jet aircraft engines.

Impellers in agitated tanks



Axial flow impeller (left) and radial flow impeller (right).

Impellers in agitated tanks are used to mix fluids or slurry in the tank. This can be used to combine materials; solids, liquids, gas. Mixing the fluids in a tank is very important if there are gradients in conditions such as temperature or concentration.

There are two types of impellers, depending on the flow regime created (see figure):

- **axial flow impeller**
- **radial flow impeller**.

Radial flow impellers impose essentially shear stress to the fluid, and are used, for example, when we need to mix immiscible liquids or in general when there is a deformable interface to break. Another application of radial flow impellers are the mixing of very viscous fluids.

Axial flow impellers impose essentially bulk motion, and are used on homogenization processes, in which is important to increase fluid volumetric flow rate.

Impellers can be further classified principally into three sub-types

- **Propellers**
- **Paddles**
- **Turbines**

All these can be discussed immediately after example.

Example

If one heats a pot of soup on the stove the pot will develop a temperature gradient, (warmest on the bottom and cooler at the surface). Mild agitation will increase the rate of heating by dissipating the heat through the entire pot. See: Law of cooling (which also applies to heating). Even more significant, agitation disturbs the soup directly in contact with the hotter pot surface. Highly turbulent flow at the warming surface is important to good heat transfer. This is the same effect as the "wind chill" factor where moving air and turbulent action on surfaces (like those on people) result in significantly enhanced heat transfer. In unusual circumstances, overly-severe agitation may decrease the rate of heating which defeats the purpose.

Propellers

They are axial thrust giving elements. These elements give very high degree of swirling in the vessel. The flow pattern generated in the fluid resembles helix.

Impellers in washing machines

Agitator for a laundromat washing machine.

Some constructions of top loading washing machines use impellers to agitate the laundry during washing.

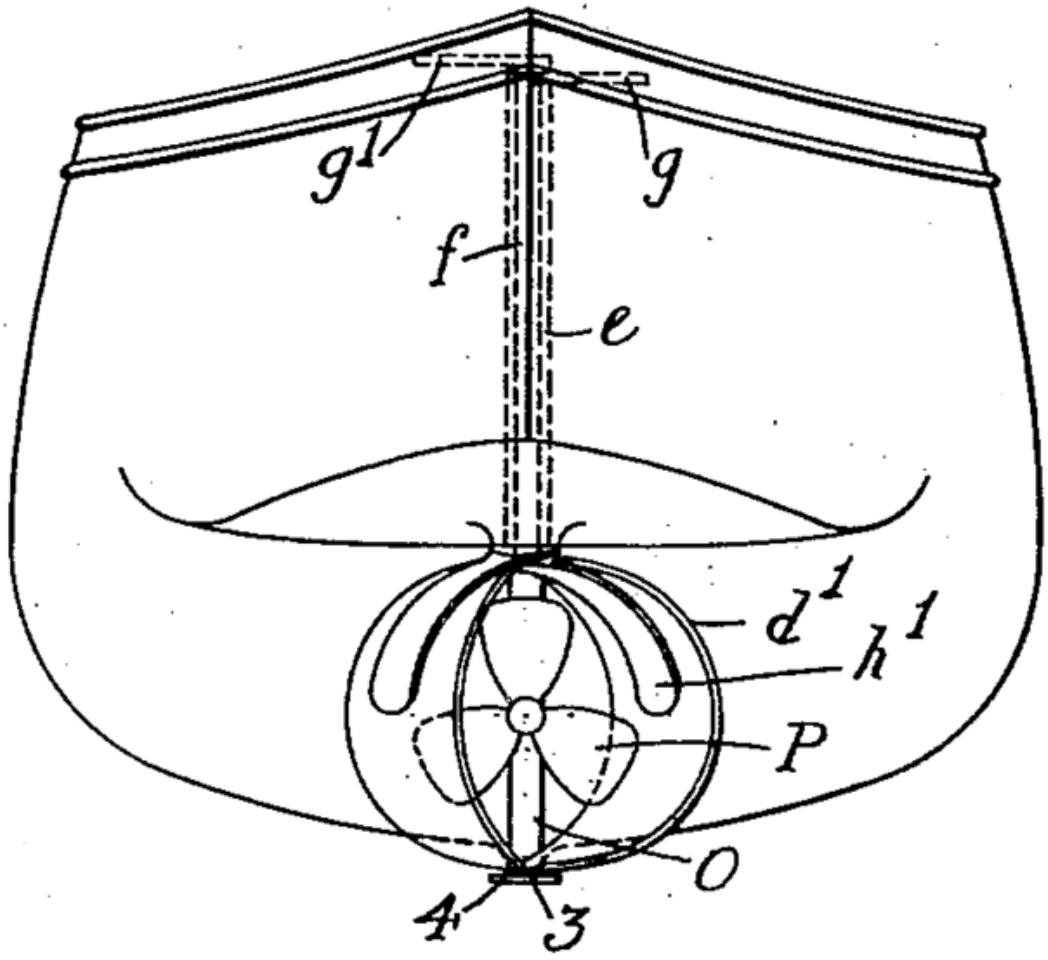
Firefighting rank badge

Fire services in the United Kingdom and many countries of the Commonwealth use a stylized depiction of an impeller as a rank badge. Officers wear one or more on their epaulettes or the collar of their firefighting uniform as an equivalent to the "pips" worn by the army and police.

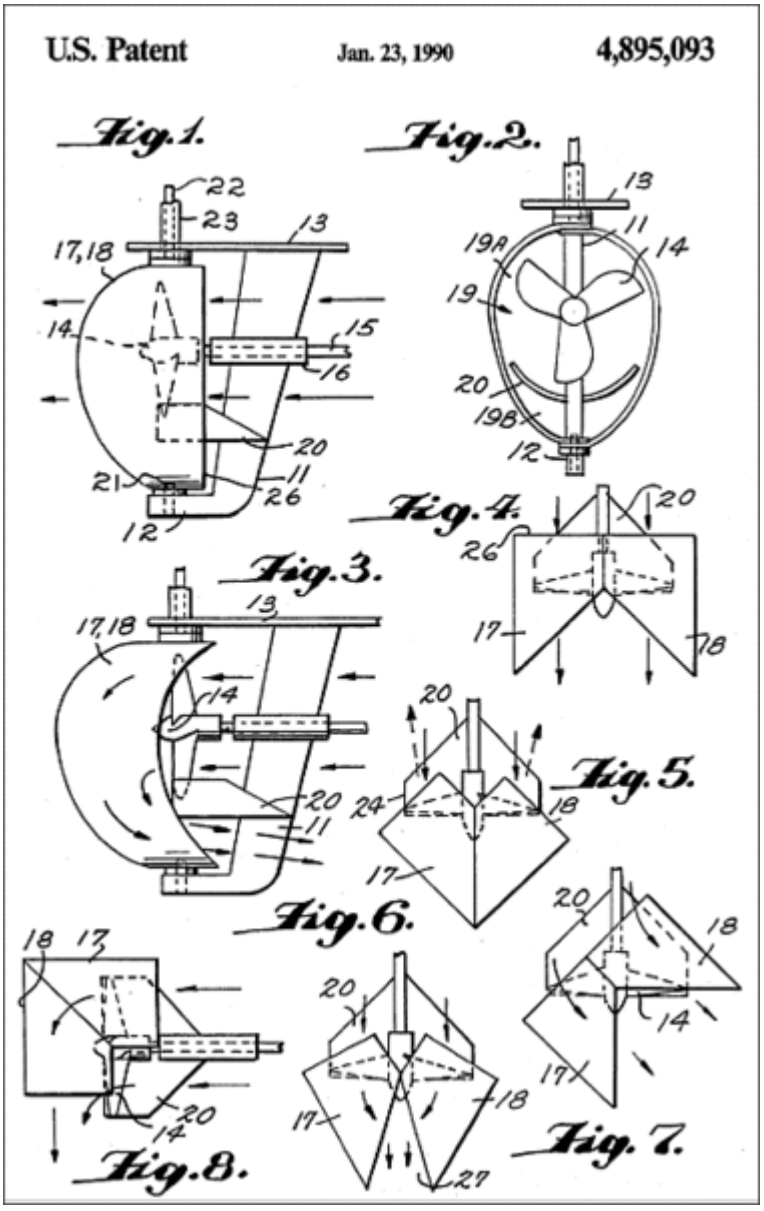
Impellers in gas turbine (turboprop) engines

Some turboprop engines use an impeller instead of an axial compressor. For example the Pratt & Whitney Canada PW100 uses a two-stage compressor with a low power impeller discharging air pressure on the high power impeller which compresses the air again into the combustion chamber. The fuel is mixed in at over 200 psi (1,400 kPa) and the mixture burns in the combustion chamber. The reason for using an impeller instead of an axial compressor is that the engine's length can be reduced.

Kitchen rudder



Kitchen Rudder. Image from the 1916 U.S. patent.



Enhanced design to the Kitchen Rudder. Image from the 1990 U.S. patent.

KLM Fokker 70 with reverse thrust applied. The two surfaces behind the engine can be seen in the deployed position, diverting the engine exhaust gases (hence thrust) forward. This is similar to the Kitchen rudder in "Full astern" position

The **Kitchen Rudder** is the familiar name for "Kitchen's Patent Reversing Rudders", a combination rudder and directional propulsion delivery system for relatively slow speed displacement boats which was invented in the early 20th century by John G.A.Kitchen of Lancashire, England. It turns the rudder into a directional thruster, and allows the engine to maintain constant revolutions and direction of drive shaft rotation while altering thrust by use of a control which directs thrust forward or aft. Only the rudder pivots; the propeller itself is on a fixed shaft and does not.

"Kitchener gear" or "Kitchener rudder" have been common misnomers for the Kitchen rudder.

It is held under British Provisional Patent No. 3249/1914 and US Patent No. 1186210 (1916) and has been improved with the design in US Patent 4895093 (1990)

Description

The rudder consists of a pair of slightly conical (usually but not always - designs vary), semi-cones mounted on a pivot either side of the propeller with the long axis of the cone running fore and aft when the helm is midships. They are pivoted about a vertical axis

such that the cone may close off the propeller thrust aft of the propeller, directing the thrust forwards and thus creating motion astern.

In addition to the "jaws" of the cone being controlled the direction of thrust is also controlled by rudder direction (compare this with an outdrive or an outboard motor for direction of thrust of an unenclosed propeller where the propeller itself pivots).

Modern equivalent include certain types of pump jets or the jet drive.

While not strictly Kitchen rudder technology, the "clamshell" thrust reverser on some aircraft jet engines is an aeronautical derivative of the device. The picture of the aircraft shows the clamshells deployed directing thrust forwards. This is equivalent to the Kitchen rudder in the "full astern" position.

Operation

The operation of the Kitchen Rudder is performed with the propellor engaged, even when the boat is stationary. The rudder is controlled by a small wheel on the tiller.

Neutral

The engine is brought up to speed with the drive to the propeller engaged and with the Kitchen rudder in the "neutral" position. This is a position where an equal quantity of thrust is aimed forward and aft. Each vessel will have a unique "neutral" position.

Moving ahead

The Kitchen gear is opened up to direct an increasing proportion of thrust aft. As the balance changes the vessel will move ahead.

Moving astern

The Kitchen gear is closed to direct an increasing proportion of thrust forward. As the balance changes the vessel will move astern.

Kort nozzle

The towboat *Dolphin I* in a floating drydock on the Mississippi River in Algiers, Louisiana.

The **Kort nozzle** is a shrouded, ducted propeller assembly for marine propulsion. The hydrodynamic design of the shroud, which is shaped like a foil, offers advantages for certain conditions over bare propellers.

Kort nozzles or ducted propellers can be significantly more efficient than unducted propellers at low speeds, producing greater thrust in a smaller package. Tugboats are the most common application for Kort nozzles as highly loaded propellers on slow moving vessels benefit the most.

The additional shrouding adds drag, however, and Kort nozzles lose their advantage over propellers at about ten knots (18.5 km/h).

Kort nozzles may be fixed, with directional control coming from a rudder set in the water flow, or pivoting, where their flow controls the vessel's steering.

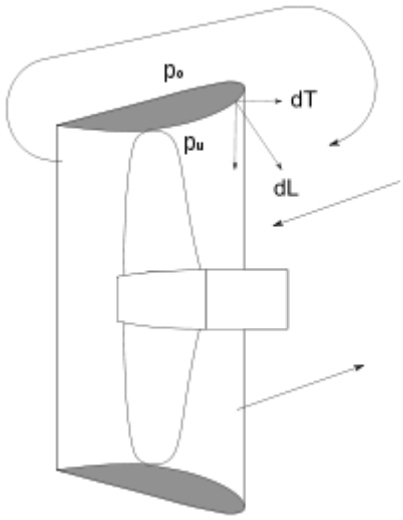
Shrouding of this type is also beneficial to navigation in ice fields since it protects the propeller tips to some extent.

Origins

Luigi Stipa and later Ludwig Kort (1934) demonstrated that an increase in propulsive efficiency could be achieved by surrounding the propeller with a foil-shaped shroud in the case of heavily loaded propellers. A "Kort Nozzle" is referred to as an accelerating nozzle and is generally a MARIN 19A profile or a MARIN 37 profile.

Physics

Circulation around Kort nozzle

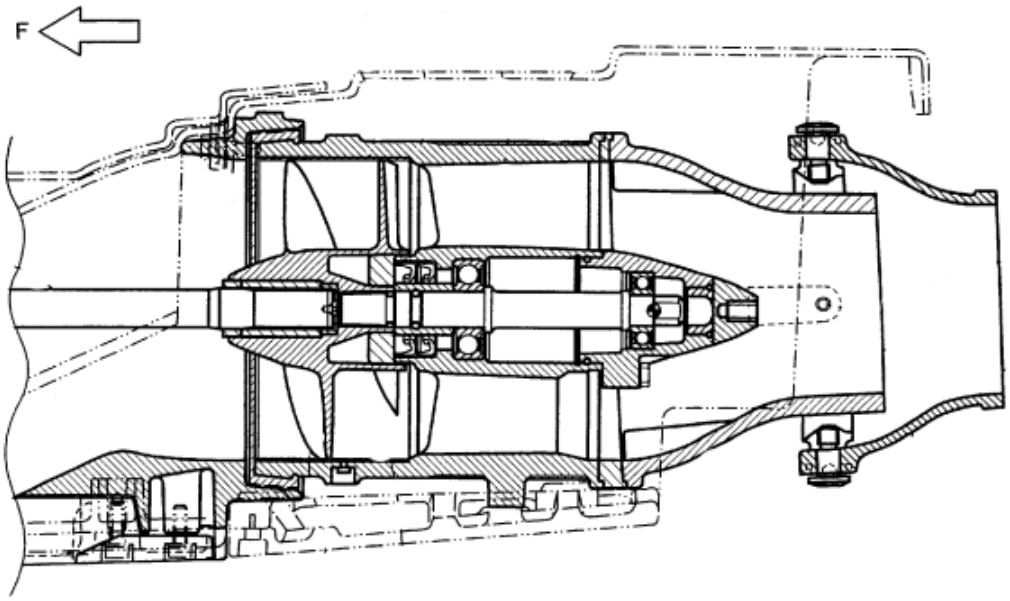


dT = Thrust p_u: Negative pressure
dL = Lift p_o: Positive pressure

In a Kort nozzle, the inflow velocity is increased, reducing pressure. This lowers thrust and torque of the propeller. At the same time, a circulation occurs, resulting in an inward aimed force, that has a forward component. The duct therefore has a positive thrust. This is normally larger than the thrust reduction of the propeller. The small clearance between the propeller and duct reduces tip vortex, increasing efficiency.

As drag increases with increasing speed, eventually this will become larger than the added thrust. Vessels that normally operate above this speed are therefore normally not fitted with ducts. When towing, tugboats sail with low speed and heavily loaded propellers, and are often fitted with ducts. Bollard pull can increase up to 30% with ducts.

Pump-jet



Typical 'jet ski' pump jet

Rear view of pump-jet on a Mark 50 torpedo

A **pump-jet**, **hydrojet**, or **water jet**, is a marine system that creates a jet of water for propulsion. The mechanical arrangement may be a ducted propeller with nozzle, or a centrifugal pump and nozzle. The first functioning man-made pump-jet engine was created by New Zealand inventor Sir William Hamilton in 1954.

In the Ordovician period the first known cephalopods swam by a natural built-in reciprocating hydrojet.

Advantages

Pump jets have some advantages over bare propellers for certain applications, usually relate to requirements for high-speed or shallow-draft operations. These include:

- Increasing the speed before the onset of cavitation, because of the raised internal dynamic pressure

- High power density (with respect to volume) of both the propulsor and the prime mover (because a smaller, higher-speed unit can be used)
- Protection of the rotating element, making operation safer around swimmers and aquatic life
- Improved shallow-water operations, because only the inlet needs to be submerged
- Increased maneuverability, by adding a steerable nozzle to create vectored thrust
- Noise reduction, resulting in a low sonar signature; this particular system has little in common with other pump-jet propulsors and is also known as "shrouded propeller configuration"; applications:
    - submarines, for example the Royal Navy *Trafalgar*-class and *Astute*-class, the US Navy *Seawolf*-class, the French Navy *Triomphant* class, and the Russian Navy *Borei* class.
    - modern torpedoes, such as the Spearfish, the Mk 48 and Mk 50 weapons.

Disadvantages

- Can be less efficient than a propeller at low speed
- More expensive
- Higher weight in the boat because of entrained water
- Will not perform well if the boat is heavier than the jet is sized to propel
- Can suffer more easily from cavitation than a conventional propeller
- Can become clogged with debris; e.g., seaweed

Pleuger rudder

The **Pleuger rudder** is a power assisted ship's rudder. It creates a flow of water in the direction the rudder points powered by an auxiliary electric motor. This aids maneuverability at low speeds greatly, since it operates on a similar principle to a thruster.

A ducted propeller is mounted as an integral part of the rudder and is fixed to it. The duct is a Kort nozzle and enables the propeller to develop more thrust than an unducted propeller.

The Pleuger rudder is necessarily mounted in the flow from the main engine's propeller in a ship with an odd number of propellers. If the Pleuger and the main engine are run at the same time, the Pleuger can often be torn away. The thrust produced by the Pleuger rudder is sufficient to power the ship in slow speed maneuvers when the force required to move the vessel is relatively small. The pleuger rudder is meant to be assisting in the fast maneuverability of ships, in tight harbor operations. Thus,it is only an improvement of rudder by controlling the water flow pattern passing a rudder and thus giving it an artificial flow and thus an extra power to steer even in slow engine r.p.m. It is absolutely not a substitute of propeller, without which, the mammoth energy required to make a ship move over water is hard to generate.

Propulsor

Mark-50 torpedo propulsor

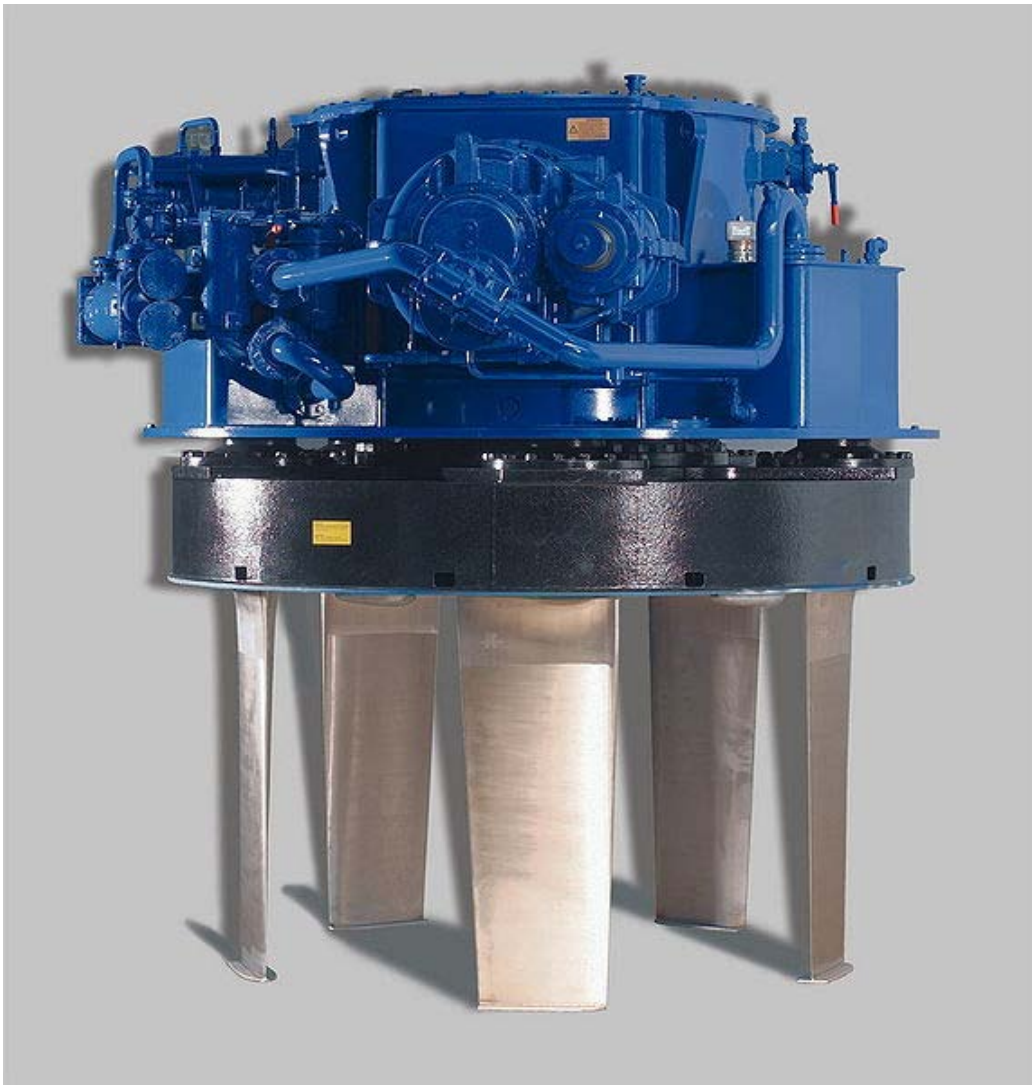
A **propulsor** is a mechanical device that gives propulsion.

The word is commonly used in the marine vernacular, and implies a mechanical assembly that is more complicated than a propeller. The Kort nozzle and Pump-jet are examples.

A propulsor, as the one that can be seen in the accompanying picture, has a shroud, which cuts down on blade-tip cavitation and radiated noise. It also has a rotor element and a stator. The stator concentrates the thrust in axial direction and reduces energy wasted in the tangential flow (therefore eliminating torque on the hull). The number of blades in the rotor & stator will typically be odd-numbered, and different prime numbers to avoid standing waves. The blades in the rotor or the stator may be angled to further reduce noise. The physical design and layout is very much similar to a single stage Axial-flow compressor.

Other propulsors

Voith Schneider



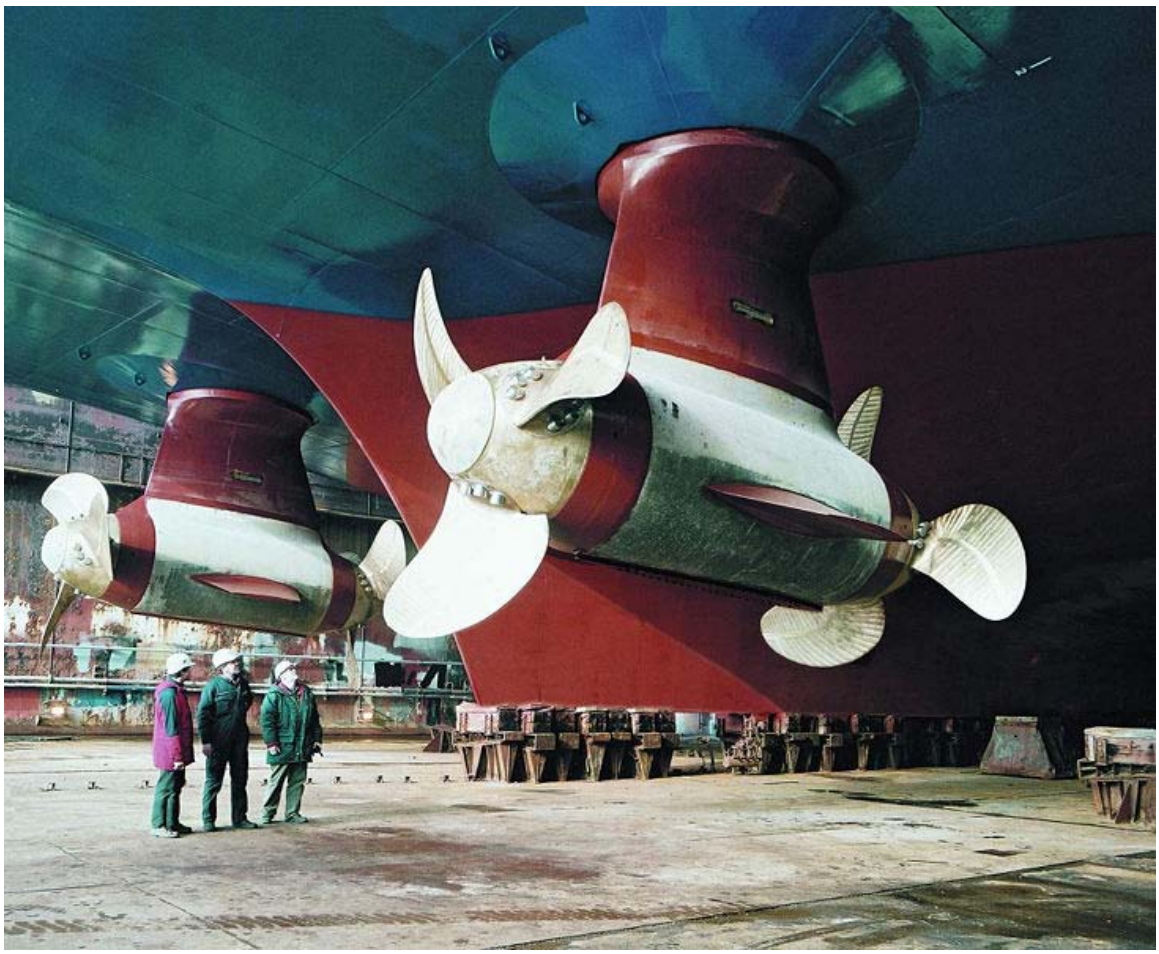
Voith Schneider Propeller

The **Voith Schneider** propeller (VSP), also known as a **cycloidal drive** (CD) is a specialized marine propulsion system (MPS). It is highly manoeuvrable, being able to change the direction of its thrust almost instantaneously. It is widely used on tugs and ferries.

From a circular plate, rotating around a vertical axis, a circular array of vertical blades (in the shape of hydrofoils) protrude out of the bottom of the ship. Each blade can rotate itself around a vertical axis. The internal gear changes the angle of attack of the blades in

sync with the rotation of the plate, so that each blade can provide thrust in any direction, very similar to the *collective pitch control* and *cyclic* in a helicopter.

Azimuth thruster



Siemens *Schottel* azimuth thrusters

An **azimuth thruster** is a configuration of ship propellers placed in pods that can be rotated in any horizontal direction, making a rudder unnecessary. These give ships better maneuverability than a fixed propeller and rudder system.

Magnetohydrodynamic drive

A **magnetohydrodynamic drive** or **MHD propulsor** is a method for propelling seagoing vessels using only electric and magnetic fields with no moving parts, using magnetohydrodynamics. The working principle involves electrification of the propellant (gas or water) which can then be directed by a magnetic field, pushing the vehicle in the opposite direction. Although some working prototypes exist, MHD drives remain impractical and exist mostly in the world of science fiction.

Bow thruster

A ship equipped with a tunnel thruster, the indicating symbol is visible below the R of *MARIE*

A **bow thruster** is a transversal propulsion device built into, or mounted to, the bow of a ship or boat to make it more maneuverable. Bow thrusters make docking easier, since they allow the captain to turn the vessel to port or starboard without using the main propulsion mechanism which requires some forward motion for turning. A stern thruster is of the same principle, fitted at the stern.

Tunnel thrusters

A bow thruster

Large vessels usually have one or more tunnels built into the bow below the waterline. An impeller in the tunnel can create thrust in either direction which makes the ship turn. Most tunnel thrusters are driven by electric motors, but some are hydraulically powered. These bow thrusters, also known as **tunnel thrusters**, may allow the ship to dock without the assistance of tugboats, saving the costs of such service. Ships equipped with tunnel thrusters typically have a sign above the waterline over each thruster on both sides, a big white cross in a red circle.

Tunnel thrusters increase the vessel's resistance to forward motion through the water, but this can be mitigated through proper fairing aft of the tunnel aperture. Ship operators should take care to prevent fouling of the tunnel and impeller, either through use of a protective grate or by cleaning. During vessel design, it is important to determine whether tunnel emergence above the water surface is commonplace in heavy seas. Tunnel emergence hurts thruster performance, and may damage the thruster and the hull around it.

Externally mounted bow thrusters

A boat with an externally mounted bow thruster shown in the water

Instead of a tunnel thruster, boats from 30 to 80 feet in length may have an **externally mounted bow thruster**. As its name suggests, an externally mounted bow thruster attached to the bow making it suitable for boats where it is impossible or undesirable to install a tunnel thruster due to hull shape or outfitting. Externally mounted bow thrusters have one or more propellers driven by a small reversible electric motor which provides thrust in either direction. The added control provided by a bow thruster helps the captain to avoid accidents while docking.

Waterjet bow thrusters

A boat with an externally mounted bow thruster shown out of the water

A Waterjet thruster is a special type of bow thruster that utilizes a pumping device instead of a conventional propeller. The water is discharged through specially designed nozzles which increase the velocity of the exiting jet. Waterjets generally have the advantage of smaller hull penetrations for an equivalent size thruster. Additionally, the higher exit velocity of the discharged water increases the relative efficiency as speeds of advance, or currents, increase, as compared to standard tunnel thrusters. Some waterjet bow thrusters can be configured to provide forward and aft auxiliary propulsion, or even full 360 degree thrust.