# PRINCIPLES OF MECHANISMS USED IN CONTROLLABLE PITCH PROPELLERS

by J. Wind*)

## Summary.

A controllable pitch propeller has a central hub which serves not only for the attachment of the blades but also contains the mechanical components to make the blades rotate. Inside the hub a translation motion is transformed into rotation of the blades. This involves large actuating forces, sometimes amounting to three times the total thrust on the propeller.

Various types of blade suspension systems are described. The principles of crank-conrod, crank-slot, slot-pin and double-acting mechanisms are discussed in relation to their historical origin and development to modern conceptions. It is concluded that a sliding slot mechanism with slots in the rotating parts has favourable characteristics for application in normal and feathering propellers.

## Introduction.

The aspects involved in considering a controllable pitch propeller for the propulsion of a ship are usually different from those taken into account in the case of a solid propeller. The solid propeller will be examined for features essential to the performance: propeller efficiency, obtainable speed, noise level, risk of cavitation and vibration.

When a CP propeller is proposed, however, these essential features rapidly take second place. The CP propeller seems to be such a complex mechanical invention that it makes people think about quite different problems. There are, on the one hand, the advantages which it promises and, on the other, a number of questions concerning reliability, strength, lifetime, maintenance and the extra costs as compared to a solid propeller.

A controllable pitch propeller is indeed more complex than a solid propeller. It contains more parts, many of them moving, and it would be unrealistic to say that there is no extra risk entailed in installing a CP propeller. This should be seen in proportion, however: a propeller with movable blades is definitely not as complicated as a diesel engine or a turbine, has also proved its reliability in a wide field of applications, and can be accepted in the same manner.

Factors such as strength and reliability are largely influenced by the principles of the mechanisms used in the equipment. As there is rapidly increasing interest in the application of CP propellers, the purpose of this paper is to present some considerations concerning these principles.

## Historical data.

The mechanical propulsion of ships became a reality during the first part of the nineteenth century when reciprocating steam engines were first used for the purpose of driving paddle-wheels. During this period too the screw propeller was developed from a strange helical structure into a useful unit which was more effective and much more compact than the voluminous paddle wheels. [1]

Even at that early stage thoughts were already turning to the possibility of reversible blades. In 1844 a patent was granted to Bennet Woodcroft for the invention of an external mechanism to reverse propeller blades. About one century ago another Englishman named Bevis designed a mechanism completely contained inside the propeller hub. [2]

The first practical applications of the reversible propeller, however, were found in the early part of the present century, together with the in-

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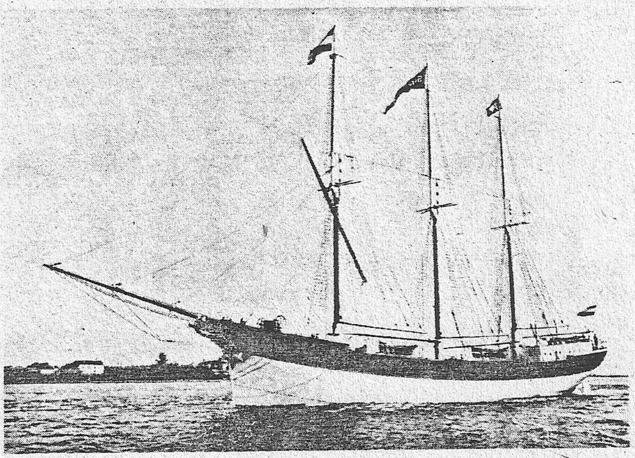


Figure 1. M.S. 'San Antonio', first diesel ship with reversible propeller in 1908.

troduction of the diesel engine [3]. The reason for this is easy to understand: direct reversing of a diesel engine was much more of a problem than reversing a steam engine. It is a remarkable fact that the diesel engine was first introduced for seagoing vessels in combination with a reversible propeller, only later being applied to drive a solid propeller [16]. In 1908 a 160 HP Werkspoor-type reversible propeller was installed in a Dutch schooner, named 'San Antonio'. The equipment was intended for supplying auxiliary power to sailing craft and remained in service for twenty-eight years [4].

Two years later, in 1910, directly reversible diesel engines were installed in what were known at that time as diesel-propelled steamers. The 'Vulcanus' and the 'Selandia' are unforgettable names in this respect [5] [16] [17].

The reversible propeller retained its popularity for a short period [18], but after 1920 the system of mechanical adjustment became inadequate for the steadily increasing power being installed on ocean-going ships, and the application of these propellers remained confined to small craft.

Hydraulic power was first introduced in 1934 as a means of providing the required adjusting forces, thus giving the CP propeller a new and unrestricted field of application [2].

For a long time the controllable pitch propeller was restricted to applications below 10,000 HP, but during the last ten years there has been a sudden increase in this respect. Propellers of 25,000 HP have already been put into service. In fact, the largest four units on order in our works at present are designed to absorb 34,700 HP. As far as we know these units are the most

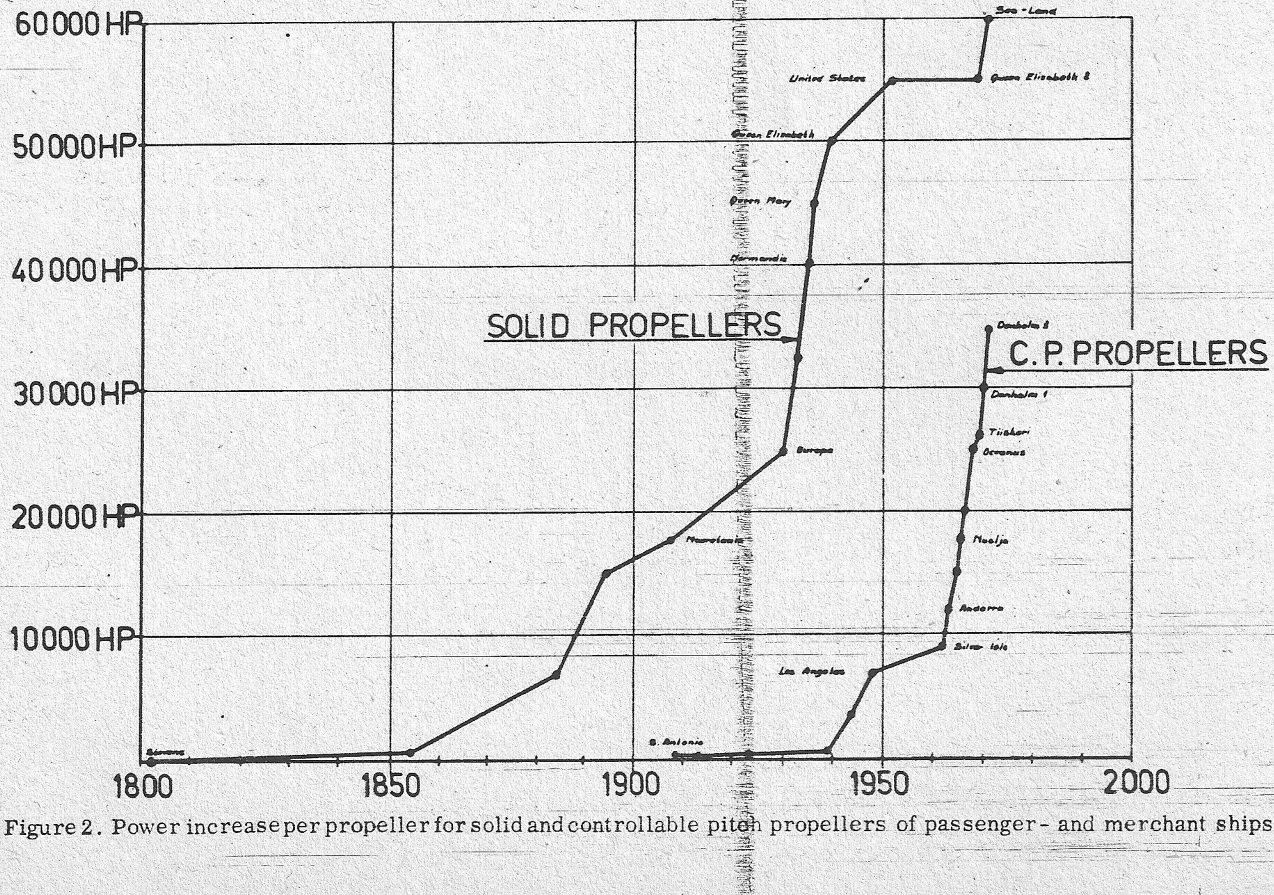


Figure 2. Power increase per propeller for solid and controllable pitch propellers of passenger- and merchant ships.

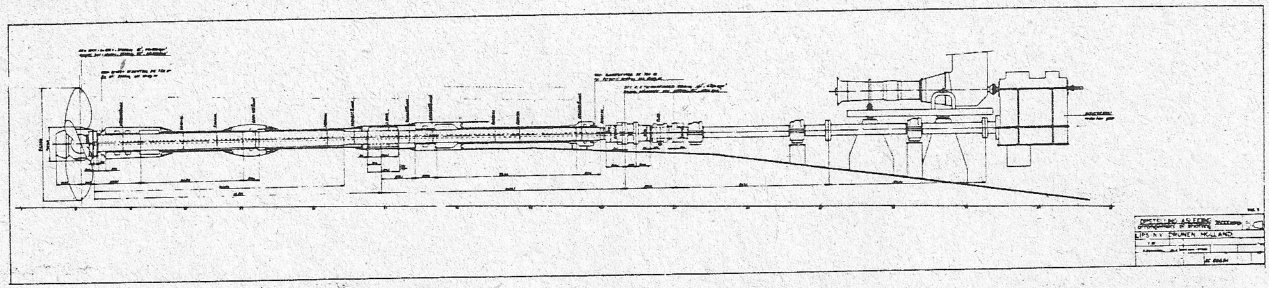


Figure 3. Shafting arrangement of a gas turbine driven 34,700 SHP CP propeller installation.

powerful CP propellers under construction today. See Figure 3.

Table I gives more detailed data concerning the development of screw propellers, while Figure 2 illustrates how the power absorbed per propeller has increased for both solid and controllable pitch propellers. The highest-powered solid propellers ever made up to now are also under construction in our works. These are sixteen units of 60,000 SHP each, to be installed in twin-screw container vessels. The rapid increase in power of CP propellers after 1962 leads to the conclusion that to-day's experience with large CP propellers is only available over a period of less than one-third of a ship's life.

Table I

| | |
|---|---|
| 1802 | Three-bladed propeller of Colonel Stevens |
| 1828 | Worm propeller of Josef Ressel |
| 1836 | Practical application of the propeller by Pettit Smith |
| 1836 | John Ericsson's propeller with peripheral blades |
| 1844 | Bennet Woodcroft's patent for reversible blades |
| 1902 | Invention of the diesel engine by Rudolf Diesel |
| 1904 | Reversible propeller of Carl Jastram |
| 1908 | M.S. 'San Antonio', first diesel ship with reversible propeller |
| 1910 | M.S. 'Vulcanus', first diesel ship with solid propeller |
| 1934 | Hydraulically-controlled propeller of Escher Wyss |
| 1947 | Lips-Schelde controllable pitch propeller |

**Definitions.**

A controllable pitch propeller installation consists basically of five main parts:

- the propeller with its mechanism
- the shafting or at least a hollow tailshaft
- the actuating gear
- a hydraulic circuit
- a remote control system

These main parts are arranged in diagrammatic form in Figure 4.

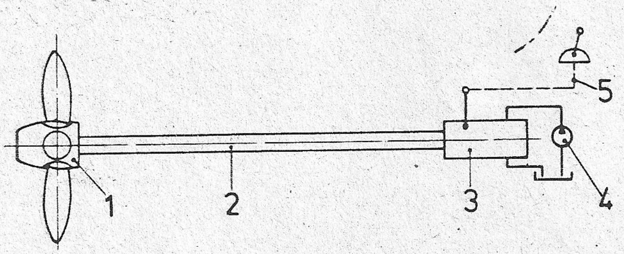


Figure 4. Main parts of a CP propeller equipment.
1 = propeller; 2 = shafting; 3 = actuating gear;
4 = hydraulic circuit; 5 = remote control.

There are also five main functions to be observed. These involve:

- the propeller hub mechanism (P)
- the hydraulic actuating cylinder (C)
- the oil distribution valve (V)
- oil transfer into the rotating shaft (O)
- feedback (F)

These main functions can be represented in a cybernetic diagram. See Figure 5. Feedback is necessary in order to achieve a proportional relation between the control lever position and the position of the blades.

The arrangement of the main functions with respect to their location in the vessel, is made in different ways by the various manufacturers.

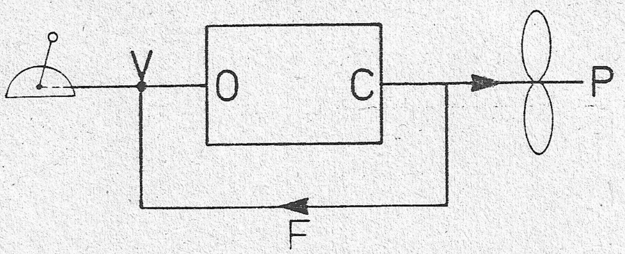


Figure 5. Feedback is necessary for a proportional relation between control lever position and pitch.

There are two basic types: one with the cylinder inboard and the other having the cylinder in the hub [6]. In the former arrangement a push-pull rod in the hollow tailshaft provides a solid mechanical connection between the piston inboard and the blades outside. In the latter arrangement there is a hydraulic oil flow through piping in the hollow tailshaft to the cylinder in the hub. It is estimated that today a small majority of CP propellers still have push-pull rods. But there is a predominating trend towards accomodating the cylinder in the propeller, since this represents a more adequate solution in the case of large propellers and long propeller shafts. As there are thousands of propellers of both types in service, both must be considered as being reliable.

The functional symbols mentioned above can be helpful in analysing reliability with respect to the location of vital functions in the system. For instance, when a push-pull rod system has to be compared with a double-acting mechanism which also has the oil distribution valve in the hub, the two can easily be visualized as follows.
The push-pull rod version is represented by:

P———————FCOV

The double-acting cylinder arrangement by:

CVPC———————OF

The dash between the letters represents the tailshaft. It is clear that in the second case more vital functions are exposed to the risk of damage

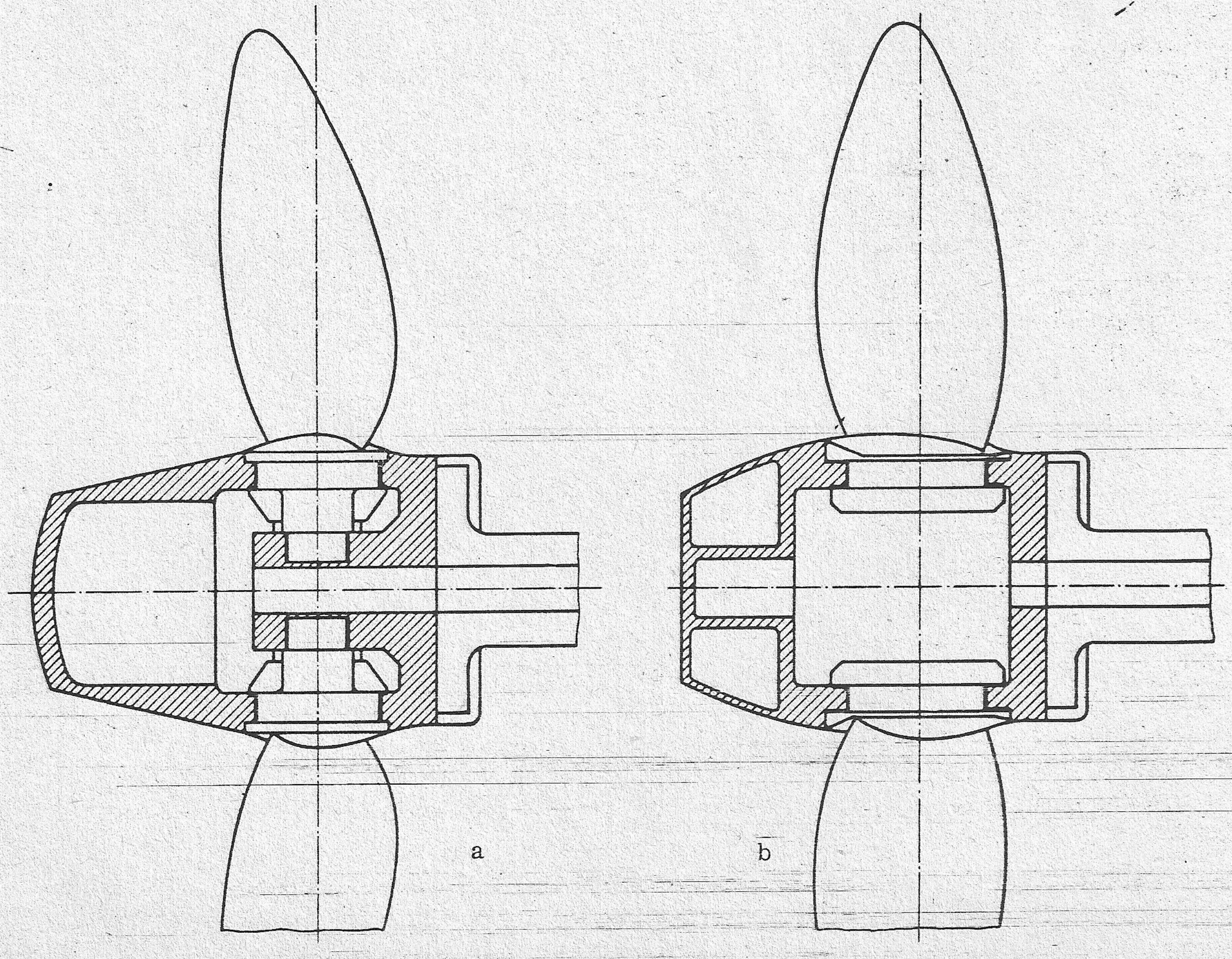


Figure 6. Blade suspension principles. a = trunnion type, b = collar type.

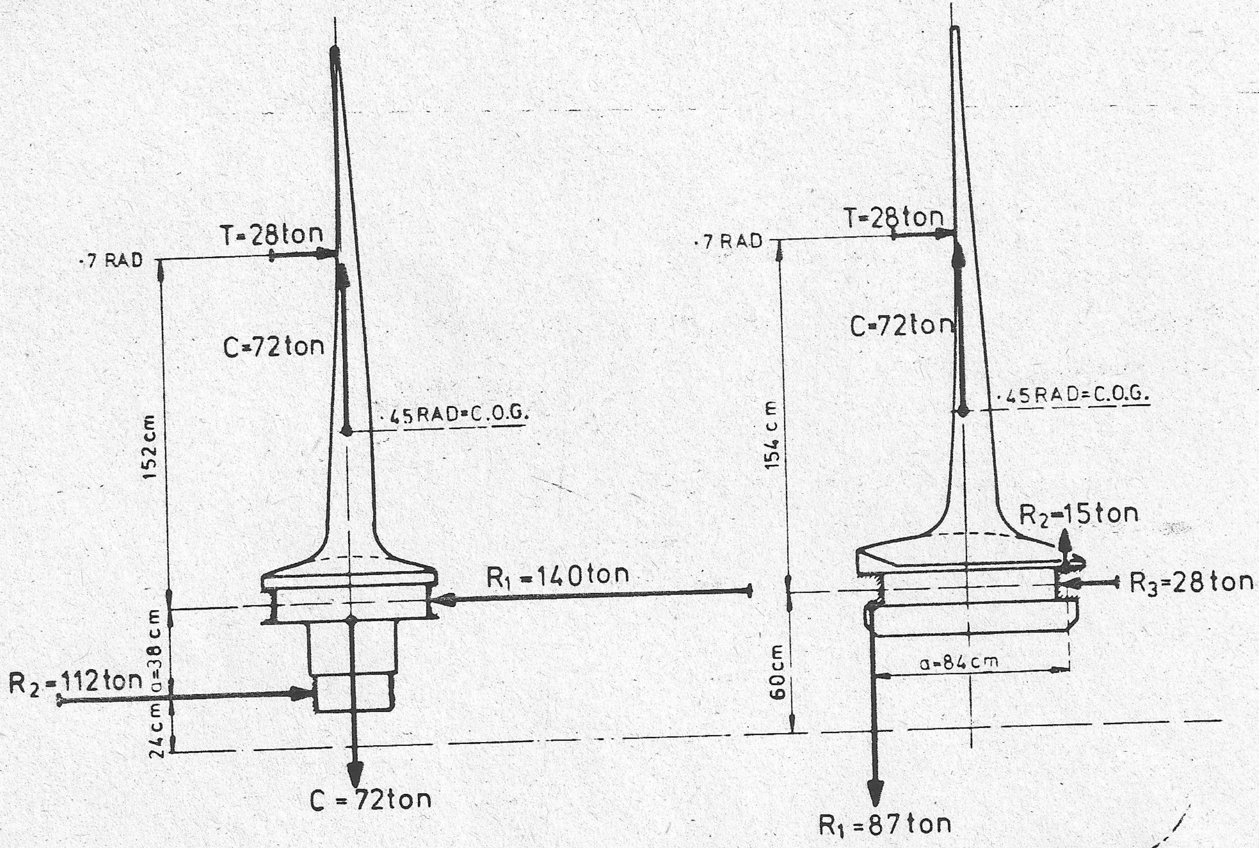


Figure 7. The trunnion-type blade suspension leads to far higher forces in the hub.

due to violent shock loads on the propeller outboard.

The comparison leads us to ask important questions: Is there a real need to have two cylinders in the hub, thus doubling the risk of jamming? Might it not at least be possible to fit the distribution valve inboard? The equipment would then be symbolized by:

CP———————FOV

which at least appears to be less vulnerable.

## Blade suspension.

The hub of a CP propeller performs a double function: not only must the blades be attached to it, but it must also serve to turn them. In spite of the blades being movable, the strength of their connection to the hub must be fully equivalent to that of a monobloc propeller. This is one of the reasons why a controllable pitch propeller has a relatively large hub.

Two types of blade suspension systems are known: the trunnion type and the collar type. The former type has trunnion-shaped blade carriers which are supported in journal bearings. In the other type the blade carriers have flanges. These are supported on collar bearings in the hub-shell. Both types are shown in Figure 6.

The reaction forces created by propeller thrust and rotation are completely different in the two systems. In the trunnion type there is little space to keep the journal bearings apart, as the separation must be achieved within half the diameter of the hub. This results in large reaction forces on the hub. With the collar type a far larger moment arm is available, more than twice the value of the trunnion type, in fact. Moreover thrust and centrifugal forces counteract each other at the front part of the hub, which is very advantageous. Hence the reaction forces are considerably smaller.

Figure 7 illustrates the forces to be absorbed by the hub in a four-bladed 20, 000 SHP propeller, 20 feet in diameter, for a fast cargo liner. The figures show that with trunnion bearings the total of the three reaction forces even amounts to 324 per cent of the external load, while in the case of collar-type blade suspension the figure is only 130 per cent. This striking difference in amplification factor on the external load is also im-

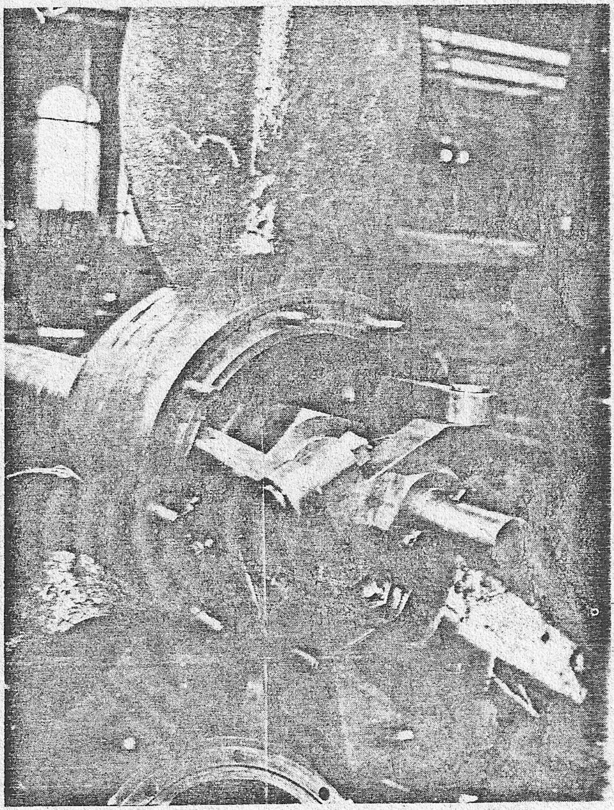
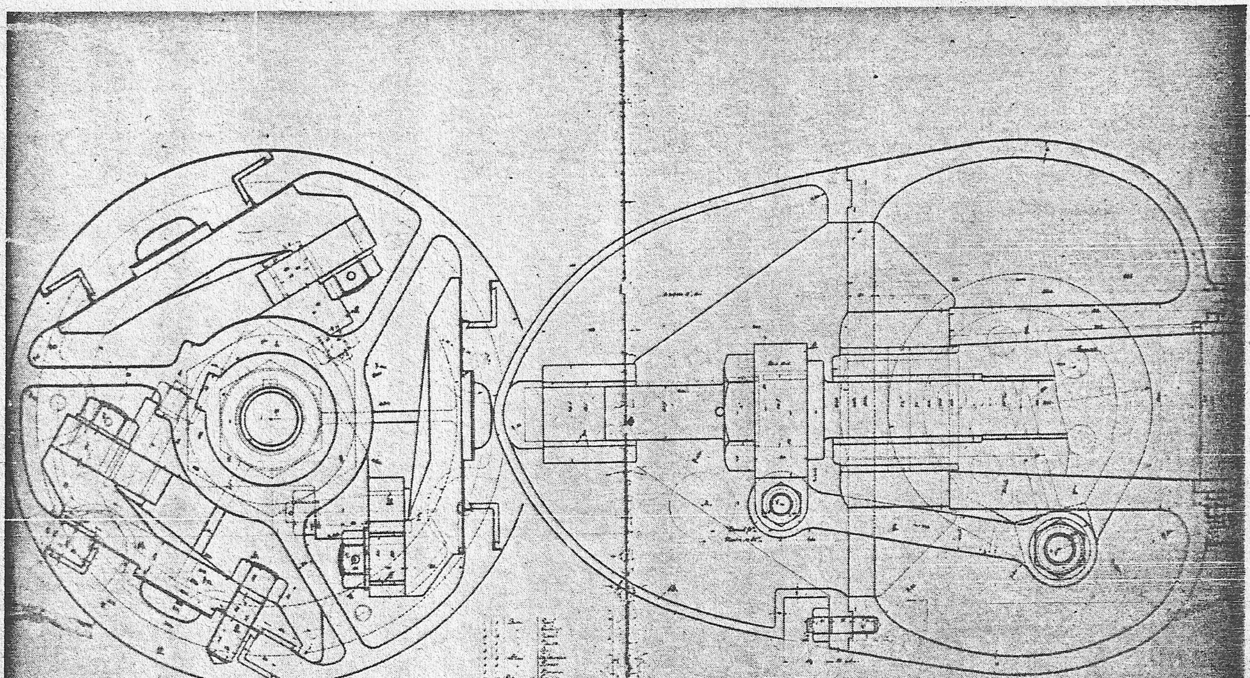


Figure 8. Reversible propeller from the year 1909 showing a crank-conrod mechanism.

portant for navigation in ice. The trunnion-type blade suspension leads to far larger shock forces being transferred to the hub. There is also a considerable difference in the bearing area, which can be achieved in the two types of hub. For a trunnion type this amounts to barely 0.7 $D^2$ while the corresponding value for a hub type with collar bearings is nearly 1.1 $D^2$. D = hub diameter. It is therefore not surprising that the majority of CP propellers - which means roughly eighty per cent - have collar-type blade suspension. The advantages are:

- Lower stresses in blade carriers and hub parts
- The blade carrier can be larger in diameter, thus permitting a stronger blade bolt connection
- Larger blade-foot diameter to provide slender blade root sections, thus reducing the danger of root cavitation for high-speed propellers
- Lower bearing pressures. In the trunnion type the pressures are roughly twice as high and call for special material in liners
- Simple hub casting as there is no central part. The central part remains available for the ac-



commodation of a hydraulic cylinder between the blade carriers so that the hub can be kept shorter [7]. See also Figure 15.

A less favourable factor is the crank radius, which can be accommodated on collar-type blade carriers. In this respect the features of the trunnion type provide better blade operating forces.

As the majority of the CP propellers have been equipped with collar-type blade suspension, this type has clearly been tried and tested in a wider field of application than the trunnion type. Both types have been built in our works but the trunnion type was taken out of production some years ago as the collar type proved to be superior.

**Hub mechanisms.**

A large variety of hub mechanisms is in use for CP propellers. All of them have one thing in common: they have to convert pull into torque, which means that a reciprocating and a rotating part are always involved. These mechanisms differ from similar constructions used for aircraft propellers and for adjustable axial flow pumps, in which a system of conical gear wheels is sometimes applied. The high blade spindle torque level and the danger of shock loads to the blades of a marine propeller, call for a sturdier type of mechanism, consisting of heavy, solid components.

The oldest type is undoubtedly the crank-connecting rod mechanism, the principle of which is obviously derived from the reciprocating steam-engine, complete with piston rod, cross-head, connecting rod and crank. Bevis' design one century ago, was a mechanism of this type. Another old-timer is shown in Figure 8, which illustrates a Werkspoor-type reversible propeller dating from 1909 [3]. The crank-conrod principle is still frequently used today [8], [9], in combination with both trunnion and collar-type blade carriers. To the trunnion type there is in fact hardly an alternative. The most modern version of the crank-conrod mechanism in CP propellers, resembles the trunk-piston arrangement of high-speed internal combustion engines. The cross-head has been omitted and direct links are introduced between the blade carrier cranks and a trunk piston located in the propeller hub. Figure 9 shows the arrangement of a device such as this. The crank-conrod mechanism has a relatively large number of parts and usually requires a rather long hub to accommodate these parts.

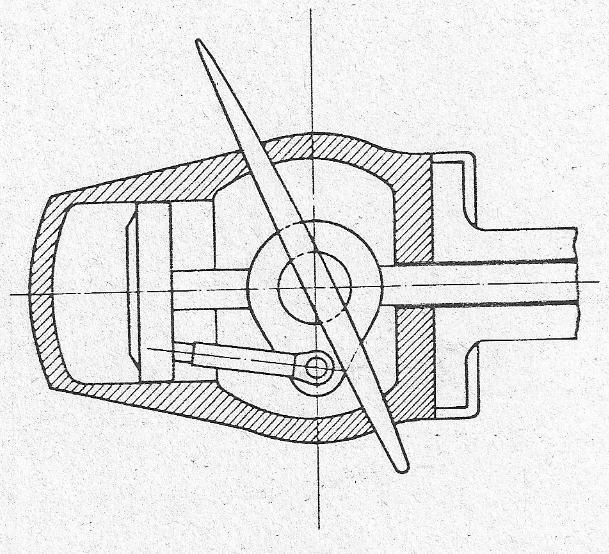


Figure 9. Modern trunk piston arrangement with connecting rods in a CP propeller hub.

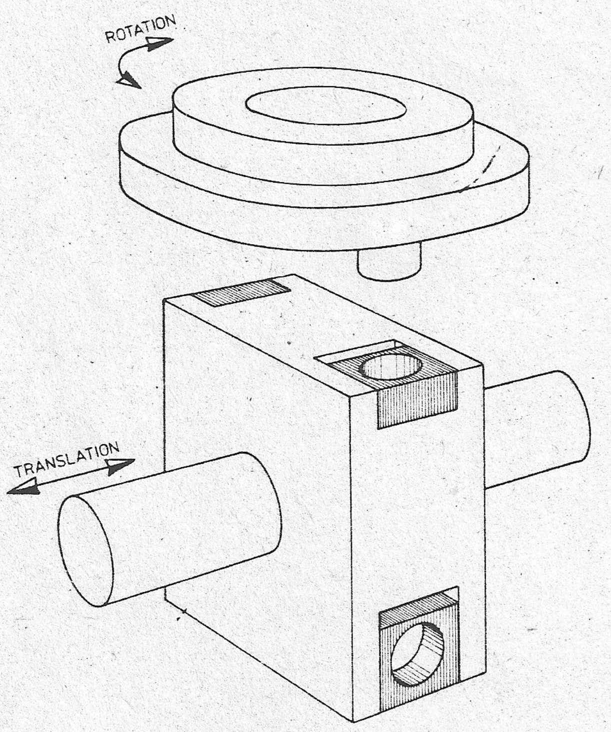


Figure 10. Crank-slot mechanism.

A simpler mechanism is possible when use is made of the fact that only a small angle of rotation is needed. The number of parts can be substantially reduced by applying the sliding-slot principle, in which the conrod is replaced by one single sliding block acting in a slot, thus resulting in a very compact mechanism. Two different types are well-known: the crank-slot mechanism and the slot-pin mechanism. The principles of both are shown in Figures 10 and 11 respectively. In spite of their apparent similarity, these mechanisms have quite different operating characteristics.

The lever arm of the crank-slot mechanism decreases as the pitch angle increases, according to a cosine relation:

$$Q_s = P r \cos \alpha$$

in which $Q_s$ = maximum available spindle torque, excluding the influence of friction
$P$ = piston force
$\alpha$ = pitch angle
$r$ = crank radius (1)

The influence of friction increases rapidly at wide angles due to a sine relation of the sliding block friction, and at an angle of about sixty de-

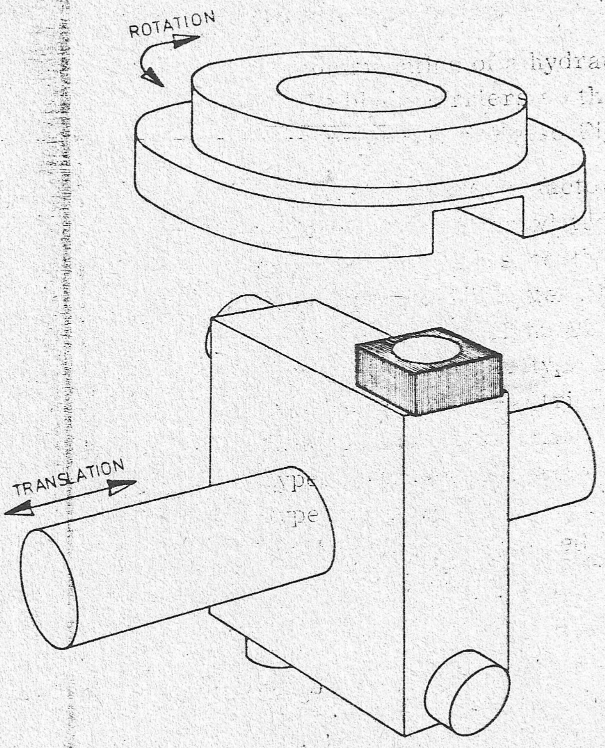


Figure 11. Slot-pin mechanism.

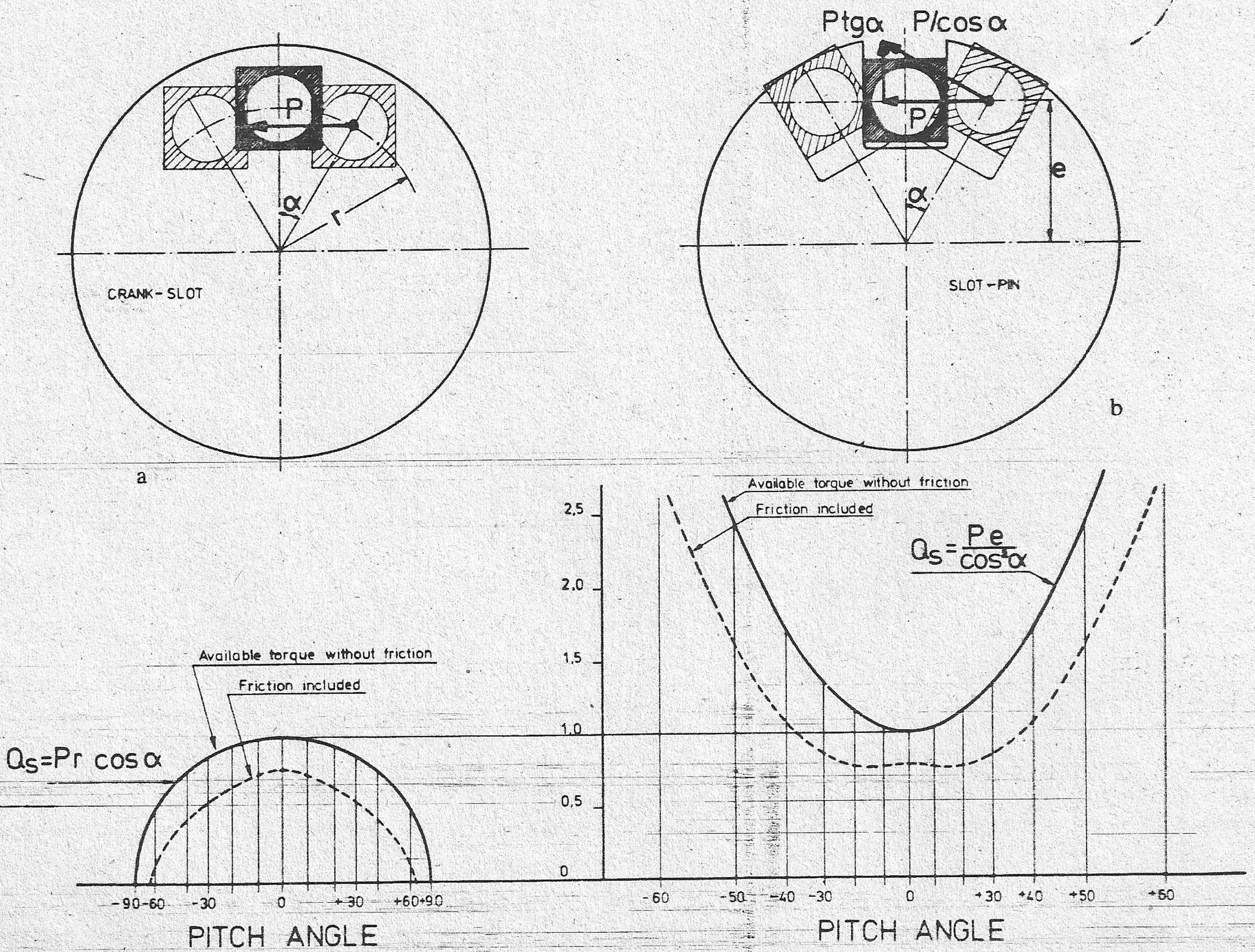


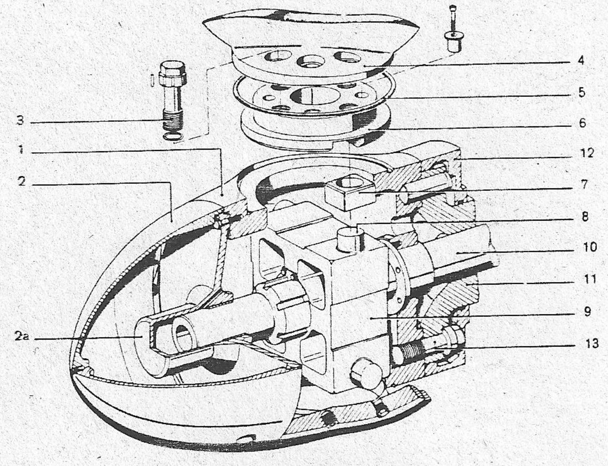
Figure 12. Movement of sliding block and diagrams of available blade spindle torque as a function of the pitch angle. a = crank-slot; b = slot-pin mechanism.

grees this mechanism is completely dead. Such wide angles are only required for feathering propellers however, and this mechanism cannot be used for this purpose. On the other hand, its features are very advantageous in the case of normal propellers, in which a pitch angle beyond thirty degrees is seldom needed. The drooping character of the available spindle torque is shown in Figure 12a.

The slot-pin mechanism displays precisely the opposite characteristics. Since in this case the slot is situated in the rotating part, an increasing lever arm is obtained at raising pitch angles, according to:

$$Q_s = \frac{P_e}{\cos^2 \alpha} \qquad (2)$$

in which e = the eccentricity of the yoke-pin. When friction is taken into account, the available torque appears to be practically constant within the normal operating range, while it improves considerably beyond that level. This type of mechanism is suitable for both normal and



| | | | |
|---|---|---|---|
| 3 | blade connecting bolt | 12 | protecting cap |
| 1 | propeller hub | 7 | guide block |
| 2 | hub cap | 8 | pin, cast on |
| 2a | hub cover | 10 | push rod |
| 4 | blade foot | 11 | tailshaft |
| 5 | blade sealing ring | 9 | yoke |
| 6 | blade carrier | 13 | tapbolt |

Figure 13. Lips LWH hub employs a slot-pin mechanism to rotate the blades.

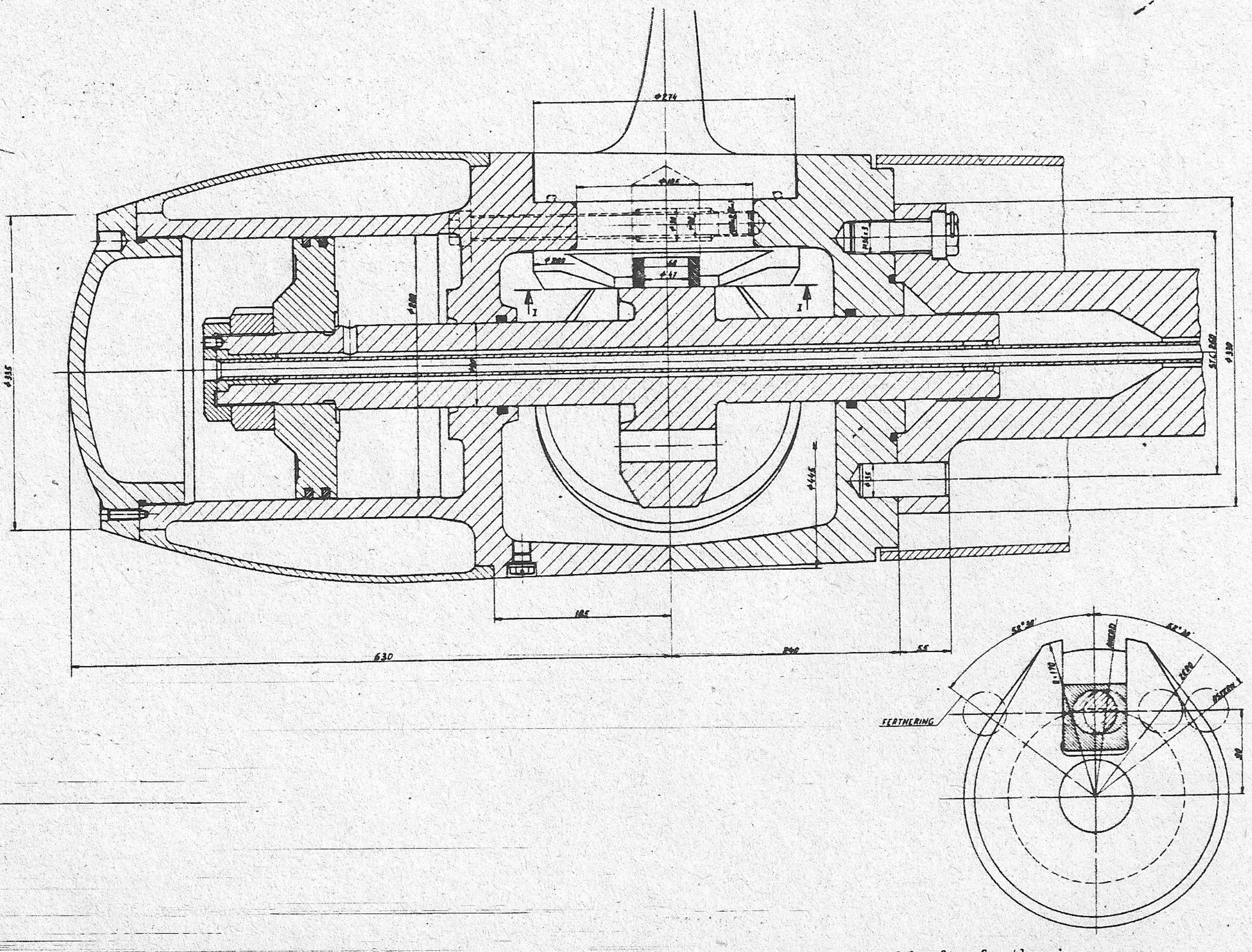


Figure 14. High-speed propeller hub with slot-pin mechanism suitable for feathering.

feathering propellers. In the case of the latter the yoke-pin eccentricity must be reduced in order to prevent the block from slipping out of the slot. The improved properties of this mechanism with regard to off-neutral positions is shown in Figure 12b. The hubs of our modern CP propellers are built according to this principle. See Figures 13, 14 and 15.

There are of course a number of other methods of converting pull into torque, but those are usually more complex and have found a smaller field of application than the mechanisms described. Examples are the oblique slot mechanism [10] and the curved slot mechanism [11].

## Double-acting mechanisms.

Double-acting mechanisms have two working cylinders in the hub, or employ a counteracting piston and cylinder as shown in Figure 16.

Double-cranks [12] [13] [14] and double-slot mechanisms are both feasible. As two forces are applied to the blade carrier, it is often supposed that a double-acting mechanism is intended to eliminate the influence of friction. This is not true, however, since the component of the friction in the sliding blocks still remains. The real purpose is to improve the torque capability by fitting an erlarged actuating arm between the pins. Full doubling of this arm is not possible within the geometry of the hub, but a gain of sixty per cent can be achieved with the same size of blocks and pins, and this means a significant increase in available torque.

Double-acting mechanisms should not be seen as the most natural answer to every CP propeller problem, however, since the hub is overcrowded with a multitude of parts, some of which are very complex in shape [13]. This makes the equipment susceptible to failure and damage. Reliability is improved by the use of simple mechanisms which contain no more parts than are strictly necessary. A double-acting mechanism should therefore only be considered in cases where there is an évident lack of operating torque, while there is nevertheless sufficient strength to carry the blades, but this should not be done until all other means have been tried and found inadequate. These means are:

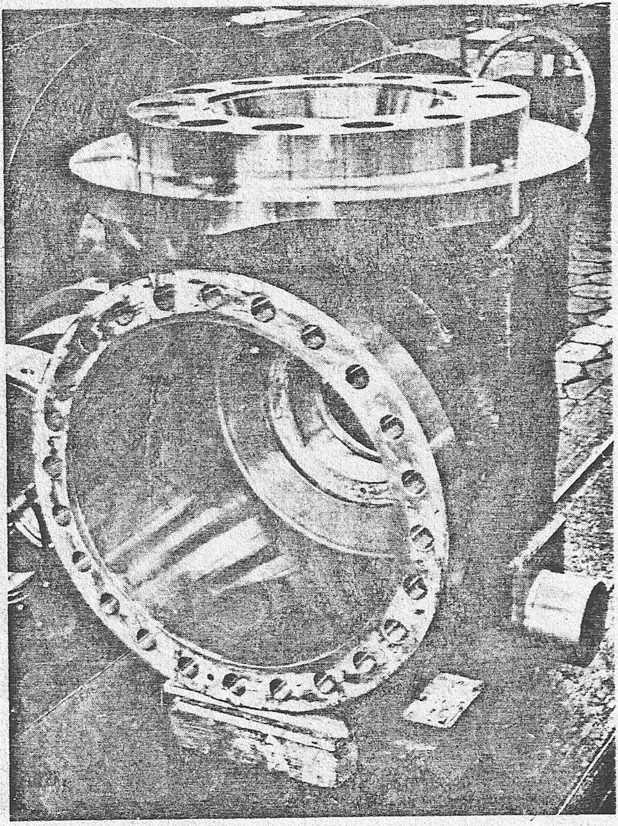


Figure 15. Mechanism for a 29,700 SHP propeller. A moving cylinder is located between the blade carriers.

- The use of the best values for skew and rake in the blade design.
- The application of a larger hub diameter, which can sometimes also contribute to suppressing root cavitation and noise phenomena in high-speed propellers
- Combined control of propeller pitch and engine revolutions so that pitch adjustment is carried out at reduced speed or only in the full-ahead range, where the operating forces are lower Figure 17c.

If no pitch adjustment is required at full rpm, the only function of the hub mechanism is to keep the blades in position. The friction in the main bearings and seals contributes to this purpose. It is clear that the mechanism with slots in the blade carriers gives the best pitch-holding performance of all, since this must take place in the full-ahead position of the blades, a situation in which the lever arm of this mechanism is most favourable.

In many cases where a double-acting mechanism is proposed, a single-slot mechanism

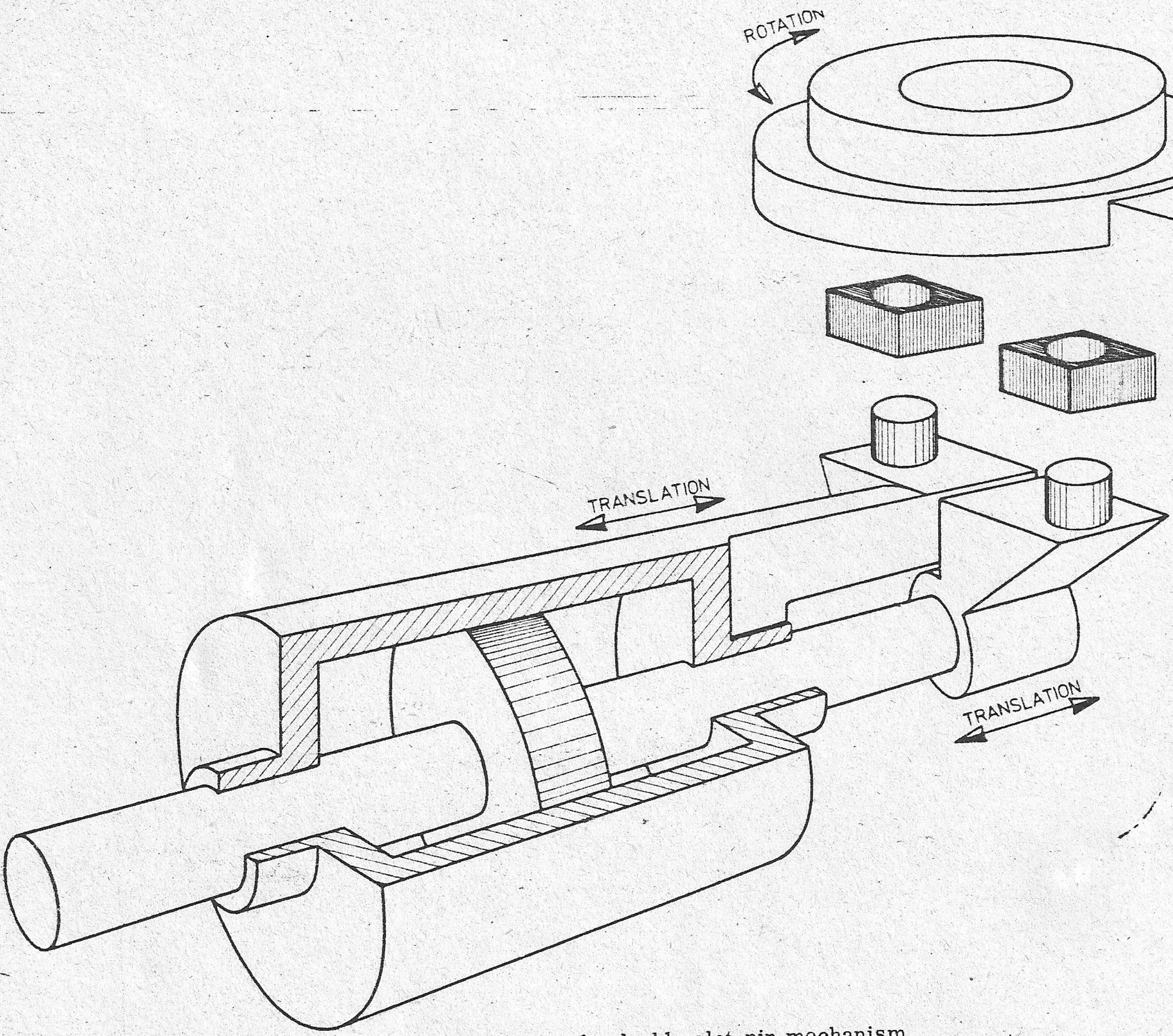


Figure 16. Principle of a double slot-pin mechanism.

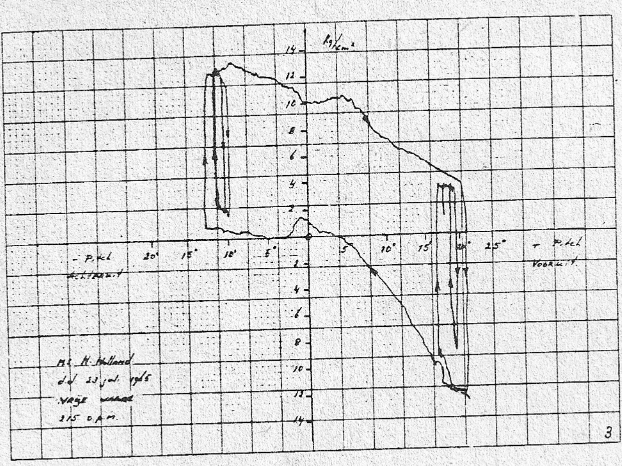
will fulfil the requirements just as well, so that the complexity of a double-acting mechanism can be avoided. In this respect hydrodynamic consultants should be fully aware of the mechanical consequences of their requirements. Unnecessarily severe requirements can lead to senseless complex hub-mechanisms.

**Blade spindle torque characteristics.**

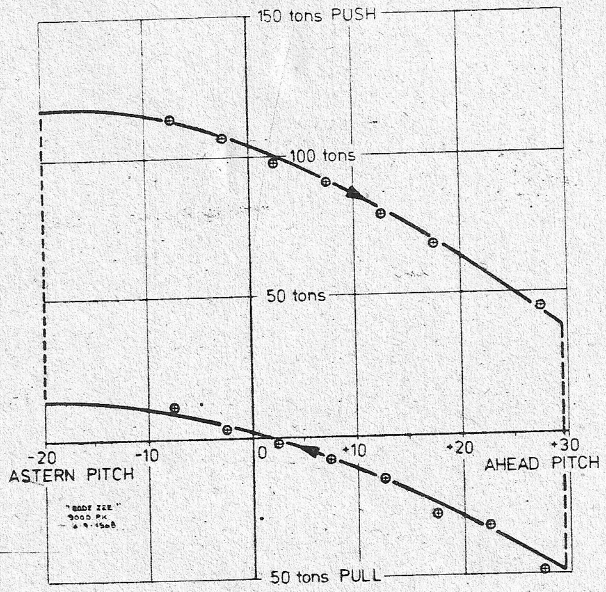
The blades of a CP propeller usually move easily from ahead to astern. On the other hand, large forces must be applied in order to bring the blades into the ahead position again, because in this case hydrodynamic as well as frictional forces are opposed to the movement of the blades. The maximum is normally found somewhere between the astern position and neutral pitch. Some examples are given in Figure 17.

Figure 17a shows an oil pressure diagram recorded during a crash-stop manoeuvre with the 3000 HP ocean-going tug 'Noord-Holland'. The engine revolutions were kept at maximum value throughout. As the propeller has a crank mechanism, the curves diverge from neutral pitch towards maximum values in both directions. Since the blades were designed without skew, considerable force is required to reduce pitch from the maximum ahead position.

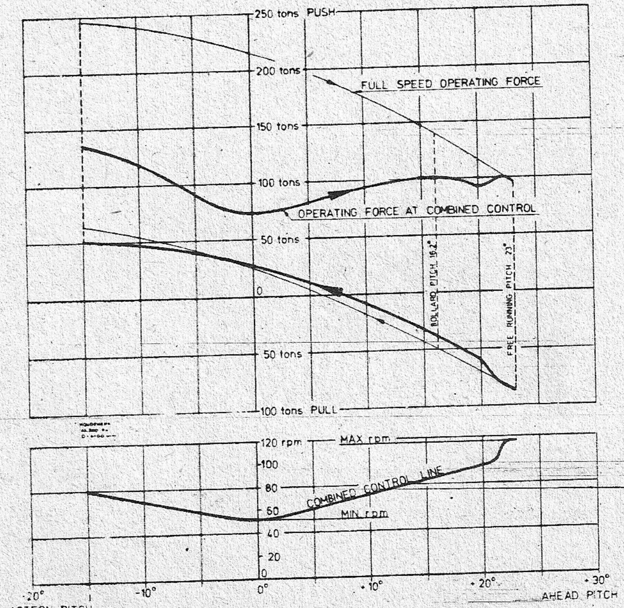
Figure 17b represents the course of the blade-operating forces of the propeller of another ocean-going tug, the 9000 HP 'Rode Zee'. This vessel is fitted with a single-nozzle CP propeller, having a slot-pin mechanism in the hub. The blades have five per cent skew, as can be seen from Figure 18. The diagram in Figure 17b was derived from pressure measurements during step-wise changing of pitch. Note that this diagram is slightly converging, in accordance with



a = crank mechanism;



b = slot-pin mechanism;



c = combined control of speed and pitch.

Figure 17. Blade spindle torque characteristics.

formula (2).

Finally, Figure 17c illustrates the effect of combined control of speed and pitch on the blade-operating forces. The fact is that these forces are fundamentally proportional to the rotational speed squared, except for a portion which remains constant due to friction in the reciprocating part and seals, and due to the decreasing effect of cavitation at high rotational speed. A reduction in speed therefore results in a rapid drop in these forces. Combined control keeps the whole procedure on a lower force level, which is of course favourable for the situation in blocks and pins, while pitch-changing can still be carried out unrestrictedly in the full-ahead range.

## Hub contour.

Though this paper deals with the internal parts of the hub, we cannot neglect to say something about the external aspect as well. The shape of the hub body is determined by mechanical and hydrodynamic requirements.
If strength were the only consideration, the hub could be spherical in shape. A sphere would not be long enough to accommodate the reciprocating

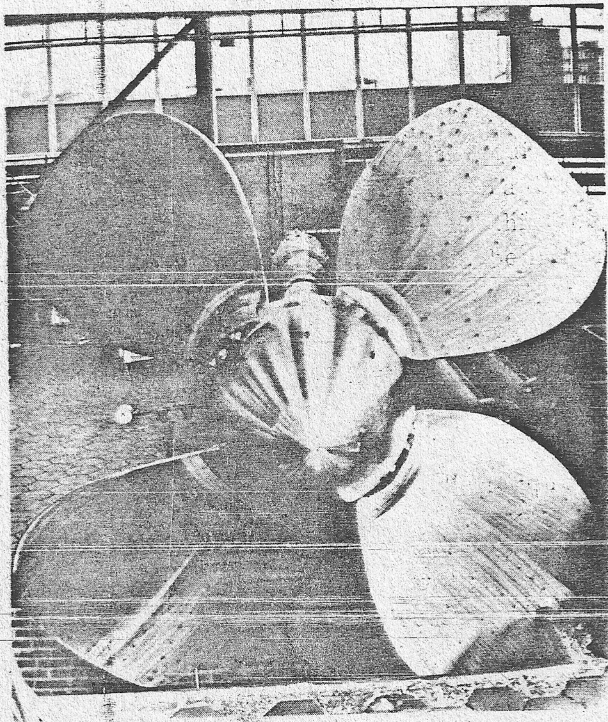


Figure 18. Blades of the 9000 HP tug 'Rode Zee' have five per cent skew to improve pitch operation in the ahead range.

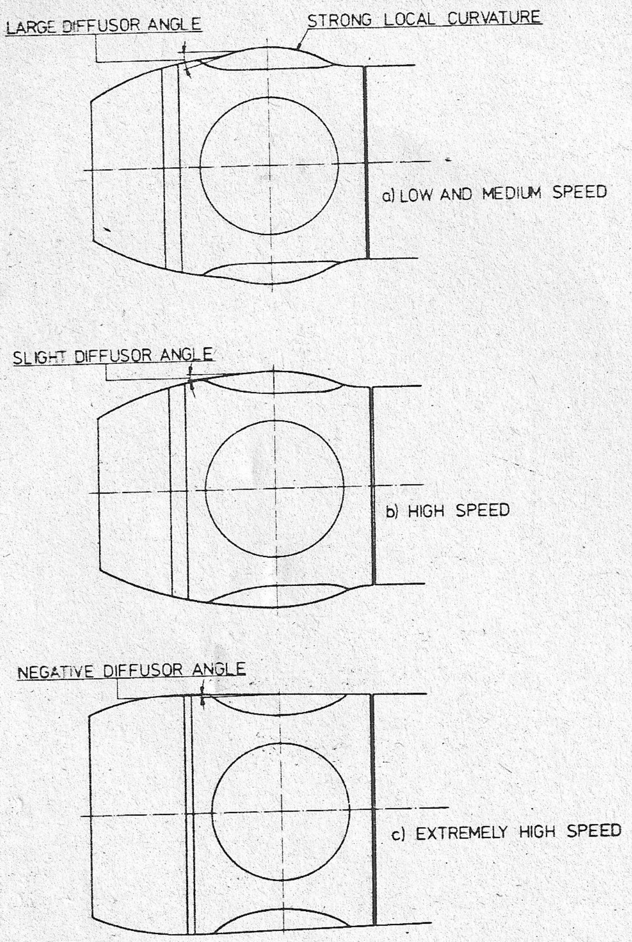


Figure 19. The shape of the hub body should be adapted to the application for wich the propeller is intended.

parts, however. Moreover, the mechanical components must be assembled in the hub, and this calls for an opening which, in turn, must be reinforced. The result is that a CP propeller hub always has a more or less elongated shape.

Figure 19a shows a hub contour, that has been developed in accordance with the desire to keep the weight of the hub as low as can reasonably be achieved. As can be seen, the central part is spherical in shape.

Flow requirements can be of paramount importance to the outline of the hub. This does not apply to low and medium-speed propellers, but in high-speed applications large negative pressure gradients may cause cavitation due to separation of flow from the hub body. Since large diffuser angles in the aft part of the hub and strong local curvatures in the outline are always associated with large pressure gradients, such shapes should then be avoided. See Figure 19b.

For extremely high-speed applications, combined with shaft inclination, a slightly diverging hub has the best contour, Figures 14 and 19c. The present state of the art indicates that this contour is the best compromise between the requirements of pressure gradient in view of flow separations, and the need to maintain sufficient pressure in the fluid - hence low acceleration - in view of cavitation.

It should be understood that the flow requirements for high-speed propellers with respect to the outline of the hub inevatibly have an unfavourable effect on the weight of the hub body.

## Conclusions.

1. Controllable pitch propellers have already been fitted to ships for half a century, but their application for large powers is of more recent date. Experience with propellers of over 10,000 HP is only available over a period of less than one-third of the lifetime of a ship.
2. Blade suspension by means of collar bearings provides a lower reaction force level in the propeller hub than that achieved with trunnion bearings.
3. The mechanisms used in the hub to turn the blades are usually based on simple principles. A sliding slot mechanism with the slots in the rotating part has favourable characteristics for universal application in normal and feathering propellers.
4. The choice of mechanism and the shape of the hub body should be considered with respect to the application in view. High-speed propellers require a different hub contour and sometimes a more complicated mechanism than low-speed propellers.
5. Reliability can be promoted by the choice of a simple mechanism containing no more parts than are stricly necessary.