SELECTION OF LATERAL DISTANCE AND SENSE OF PROPELLER ROTATION FOR A HIGHLY LOADED TWIN-SCREW INLAND CARGO MOTOR SHIP

Laila Kamar

Naval Architecture and Marine Engineering Department,
Faculty of Engineering, Suez-Canal-University, Port Said

ABSTRACT

The work described in this paper is a part of an extensive research programme which aims at the development of high quality after-bodies for large inland cargo motor ships in pusher trains. The pushing operation in shallow water causes high load conditions and necessitates a twin-screw propulsion system. Previous investigations yielded a novel stern type with excellent performance characteristics. The present study applies to further developments of this stern type by optimising details of the propulsion system. In this context, the lateral distance of the propellers as well as their sense of rotation are altered and the effect on the available thrust power to push barges are examined. The investigation is based on tow-rope pull tests with self-propelled divided models and a hereon adapted evaluation method. This procedure allows to explain the advances obtained with the investigated variants by partial effects as, for example, improved propulsion characteristics.

Keywords: Inland cargo ship, Tunnel stern, Twin-screw ship, Lateral distance of propellers, Sense of propeller rotation

INTRODUCTION

The improvement and the further development of large motor ships for a service in pushed barge trains on inland waterways aim at increasing the effective thrust power or minimising the driving power demand, respectively. Especially the design of the after-body, including the propulsion device, offers a potential for optimisation. Due to the high load in the pushing operation the motor ship generally requires a twin-screw system. The propellers are symmetrically arranged below the tunnel of the after-body. The tunnelled construction of the stern allows to realise propeller diameters larger than the minimum draught [1].

Former research work [2, 3] has been conducted on different stern shapes of after-bodies for future large inland cargo motor ships. It could be demonstrated that the efficiency of the motor ships in pusher trains strongly depends on the stern shape. Two high quality after-bodies with different stern types of inland motor ships already in service as well as a new developed conception of the 80s were investigated in model tests with identical middle- and fore-body. In order to assure unequivocal results, the tests covered a large set of parameters with draughts t = 1.7 to 3.5 m and five water depths in the range of h = 3.0 to 15.8 m. The novel stern type revealed its clear superiority especially at typical service speeds. The after-body with this stern shape allows to increase the ship's thrust performance by more than 20% compared to the other two after-bodies.

During the above mentioned steps of development the new stern shape was always applied with an inward sense of rotation and a constant lateral distance of the propellers. It is established that the direction of rotation may strongly influence the driving power demand [4]. Therefore, the present work focuses on the effects on the ship's performance when changing the sense of rotation and the lateral distance of the propellers. The investigations are based on the results of tow-rope pull tests with self-propelled divided models which have been carried out by the Duisburg Towing Tank and Research Institute for Shallow Water Hydrodynamics (Versuchsanstalt für Binnenschiffbau Duisburg, VBD) [2, 5]. Draughts and water depths of the above mentioned parameter range have been selected with ratios between $H/t = 1.43$ to 3.0 in order to keep the experimental efforts within bounds. The present work comprises the first complete analysis of the experimental results.

INVESTIGATED MOTOR SHIP AND VARIATIONS

The considered after-body is designed for large inland motor ships with a length of 105 m and a breadth of 11.4 m. The ship shall operate as a pushing unit in trains with up to three barges. The length of the tunnelled after-body which comprises the propulsion system is twice, the length of the fore-body approximately 1.5 times the ship's breadth. Both lengths are measured by reference to the transition to the parallel middle-body. The variations considered in the frame of this work concern exclusively the lateral distance of the propellers, in effect 52% and 36% of the ship's breadth, and their sense of rotation, inward and outward. The propellers themselves and the rudder device are not modified. Table 1 indicates the various parameter combinations as well as the water depths and draughts.

Figure 1 shows the body-plans of the after-body for both propeller arrangements and illustrates, that the alteration of the lateral distance does not change the shape character of the stern. This stern type is named Gondola-stern. It was designed in analogy to a recently developed stern shape for relatively shallow-draft full-form seagoing vessels [6]. The hull form beneath the tunnel roof may be divided in outer side-parts and the Gondola-shaped central middle-part. The side-parts are characterised by gradually rising buttock-lines and more or less horizontal sections with angled transitions to the Gondola-part. This Gondola-part resembles a strongly thickened keel fin. It reveals steep sections and slender water lines. The inflow of water to the propeller disks arrives mainly from the sides and from below. As pointed out in References 6, this stern type entails a favourable wake distribution.

Table 1 Parameter set

Water depth [m]	Draught [m]	Propellers' Lateral Distance[% of ship's breadth]	Sense of rotation [-]
3.5	1.7	52 / 36	inward
7.5	2.5	52 / 36	inward
5.0	3.5	52 / 36	inward
5.0	2.5	52 / 36	outward
3.5	2.0	52	in-/ outward
5.0	2.5	52	in-/ outward
5.0	3.5	52	in-/ outward

TOW-ROPE PULL TESTS WITH DIVIDED MODELS AND EVALUATION METHOD

An alteration of the propellers' lateral distance or of their sense of rotation does not only influence the flow around the after-body and the flow conditions at the propellers. It also affects the flow around the remaining ship's body and its flow resistance. When considering the after-body being a propulsive unit, the effects due to a modification of the propulsion device are reflected in changed propulsion characteristics and simultaneously in a changed thrust demand of the forward loaded part, the fore- and the middle-body. In addition, the available thrust power of the motor ship in pusher trains may be changed as well. In order to take these effects into account during the evaluation of the variants, tow-rope pull tests with self-propelled divided models scaled 1:16 have been performed by the VBD.

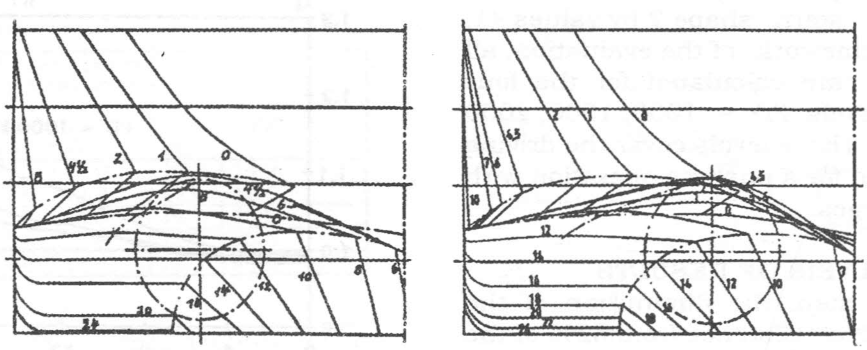


Figure 1 Body-plan of the investigated after-body

It is evident that the models were divided between the propulsive and the loaded part. The joint was equipped with a dynamometer in order to measure the force acting from the after-body on the remaining forward part of the vessel, the so-called effective thrust. The thrust demand of barges was simulated by tow-rope pulls acting externally on the loaded part. For each test series the tow-rope pull F_P, the effective thrust F_P^* and the shaft power P_D are available for different speeds. The effective thrust demand of the loaded part follows from the difference F_P^* F_P.

The comparison of results from two test series with the stern shapes 1 and 2 at identical speed and identical shaft power allows to define the evaluation system below [3, 5]. The overall rating corresponds to the ratio of the tow-rope pulls Q:

$$Q = \frac{F_{P1}}{F_{P2}} = Q^* \cdot Q_f \qquad (1)$$

which represents a rating value for the forces available for pushing additional barges. Equation 1 contains as partial rating factors the ratio of the effective thrusts or of the effective thrust efficiencies, respectively, Q*:

$$Q^* = \frac{F_{P1}^*}{F_{P2}^*} = \frac{\eta_1^*}{\eta_2^*} \qquad (2)$$

and the ratio of the tow-rope pull rates Q_f:

$$Q_f = \frac{f_{P1}}{f_{P2}} = \frac{F_{P1}}{F_{P2}} \cdot \frac{F_{P2}^*}{F_{P1}^*} \qquad (3)$$

Q* may be considered as rating value for the propulsion qualities and Q_f as rating value for the impact of the stern shapes. An additional rating factor may be introduced which presents the ratio of the effective thrust demands of the loaded part:

$$Q_N = \frac{\left(F_P^* - F_P\right)_1}{\left(F_P^* - F_P\right)_2} \qquad (4)$$

In order to assure a correct relation of the partial effects in Equation 1 even in the particular case of an identical effective thrust demand, Equation 3 is transformed into:

$$Q_f = \frac{Q^* - Q_N \cdot \left(1 - f_{P2}\right)}{Q^* \cdot f_{P2}} \qquad (5)$$

Supposing an identical effective thrust demand Q_N = 1 the so-called neutral tow-rope pull ratio can be deduced from Equation 5:

$$Q_{fN} = \frac{Q^* + f_{P2} - 1}{Q^* \cdot f_{P2}} \qquad (6)$$

Thereby, the overall rating Q can be expressed by modified partial rating factors:

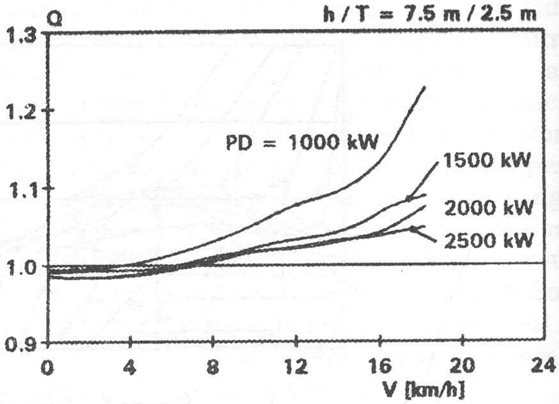
$$Q = Q^* \cdot Q_{fN} \cdot \frac{Q_f}{Q_{fN}} \qquad (7)$$

All three rating factors, the overall rating Q, the relative influence of the propulsion quality $Q^* \cdot Q_{fN}$ and the relative influence of the stern shape Q_f / Q_{fN} indicate advantages for stern shape 1 by values >1 and advantages for stern shape 2 by values <1. Within the framework of the evaluation, all rating factors are calculated for the four shaft power levels PD = 1000, 1500, 2000 and 2500 kW. These levels cover the driving power demand for a pushing operation with up to three barges.

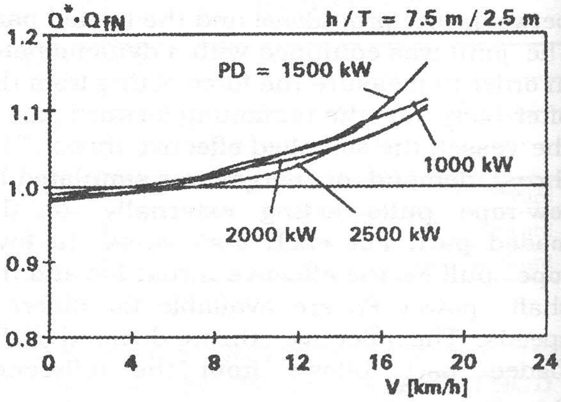
ANALYSIS OF RESULTS

In a first step, the diminution of the propellers' lateral distance from 52% of the ship's breadth (variant 1) to 36% (variant 2) will be considered. Figure 2 shows the rating factors of Equation 7 as function of speed for inward rotating propellers at a ratio water depth to draught of h/T 7.5 m/2.5 m. In the lower speed level, there are only slight differences. However, at speeds V < 6 km/h variant 1 reveals more and more advantages, (Figure 2-a). Especially at lower power levels, the available tow-rope pulls are significantly higher at the large lateral distance of the propellers. Taking the partial rating factors into account, one can clearly see that this result is mainly due to a higher propulsion quality, (Figure 2-b). This effect even predominates the favourable stern shape effect of the variant 2 in case of high shaft powers and speeds in the range of V > 12 km/h, compare Figure 2-c, where the small lateral distance causes a greater tow-rope pull rate or a smaller effective thrust demand for the identical load part, respectively.

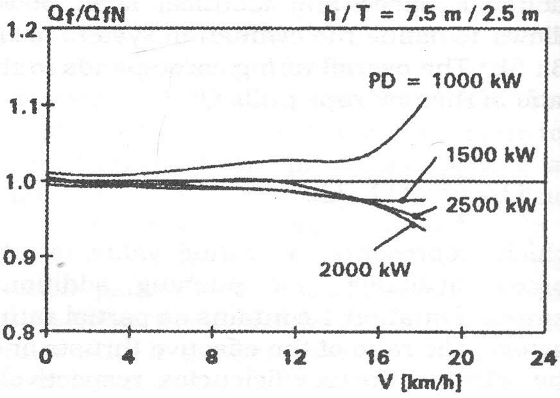
The other ratios water depth to draught reveal in quality a similar speed-depending behaviour of the rating factors, also for outward rotating propellers. The final evaluation and selection of the propellers' lateral distance is performed on the basis of rating factors in the range of service speeds of pushed barge trains. The reference are empirical values of the VBD, (see Table 2) which are based on the values indicated in References 7.



(a): Overall rating



(b): Rating of propulsion quality



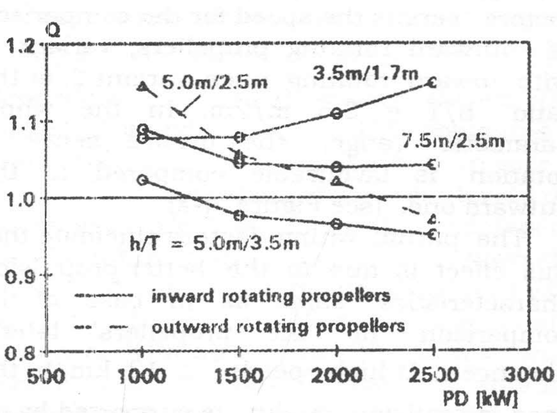
(c): Rating of stern shape quality

Figure 2 Comparison of large/small lateral distance, inward rotating propellers

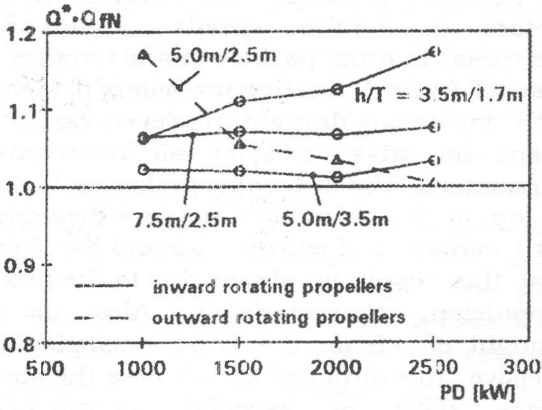
Table 2 Typical service speeds

Water depth [m]	Draught [m]	Service speeds [km/h] for shaft powers:			
		1000 kW	1500 kW	2000 kW	2500 kW
3.5	1.7	12.3	13.0	13.7	14.3
3.5	2.0	11.6	12.3	13.0	13.6
5.0	2.5	13.3	14.0	14.7	15.5
7.5	2.5	14.0	14.8	15.7	16.5
5.0	3.5	11.0	11.6	12.3	13.0

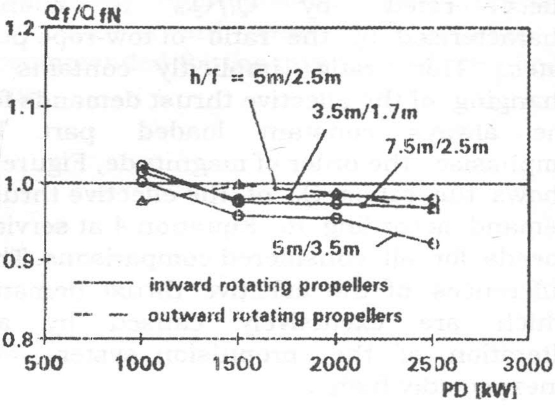
In Figure 3, the rating factors for the comparison of large and small lateral distances of the propellers at the service speeds are given as function of the shaft power for all investigated cases. For all parameters, variant 1 with large lateral distance reveals better propulsion characteristics, (see Figure 3-b). The flow conditions at the two screws are obviously more suitable than in case of a small lateral distance where the flow may be affected by interactions. Though, for a large lateral distance, the influence of the stern shape is disadvantageous, (see Figure 3-c). Except the lowest power level, there are always slight advantages for variant 2 with the smaller lateral distance, especially in case of the greatest draught of 3.5 m or of the smallest ratio of under keel clearance to water depth (h-T)/h, respectively. The latter one dominates the overall rating at this draught, (see Figure 3-a) and the small lateral distance enables therefore higher tow-rope pulls in the power range $P_D > 1,000$ kW. However, for the other draughts the large lateral distance is preferable. Especially at the smallest draught of 1.7 m, the tow-rope pulls are significantly higher by 7% to 15% than the results obtained with variant 2. Furthermore, Figure 3-a clearly shows that the formation of average values of the rating factors over all parameters h and T leads to a positive evaluation of variant 1 for all power levels. Therefore, the variant with the large lateral distance seems to be the more optimal solution and will be further investigated concerning the propellers' sense of rotation.



(a): Overall rating



(b): Rating of propulsion quality



(c): Rating of stern shape quality

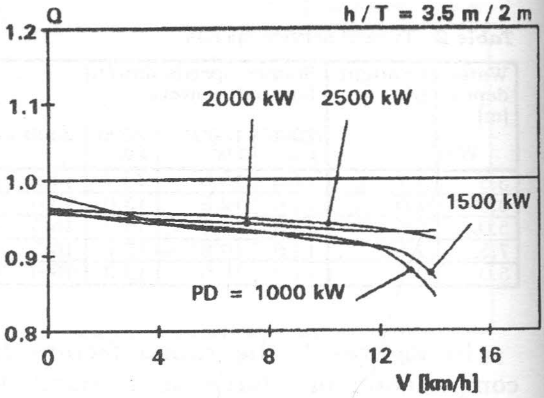
Figure 3 Comparison of large/small lateral distance at service speeds, inward rotating propellers

Figure 4 exemplary shows the rating factors versus the speed for the comparison of outward rotating propellers, variant 1, with inward rotating ones, variant 2, at the ratio h/T = 3.5 m/2m. In the whole parameter range, the inward sense of rotation is favourable compared to the outward one, (see Figure 4-a).

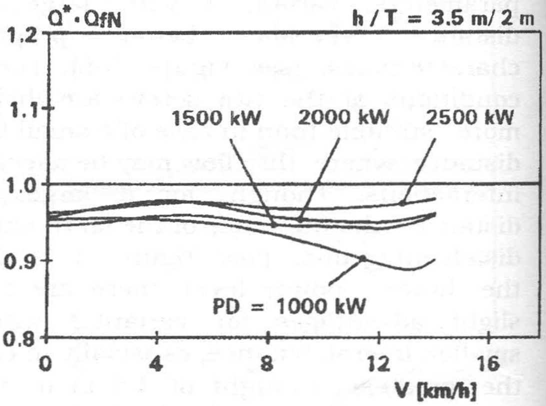
The partial rating factors elucidate that this effect is due to the better propulsion characteristics, same as in case of the comparison of the propellers' lateral distances. At high speeds $V \geq 12$ km/h, the good propulsion quality is supported by an advantageous stern shape effect, (Figure 4-c).

Figure5 presents the overall rating factors at service speeds. Figure 5-a indicates, that the positive characteristics in case of inward rotating propellers decrease with increasing draught. However, variant 2 keeps its advantages at all investigated parameters. The tow-rope pulls are higher by up to 9% compared to those measured with variant 1. Figures 5-b and 5-c show, that this result is always due to the better propulsion characteristics. Also for a draught of 3.5 m, the latter ones play the decisive role although in this case the stern shape effect is especially detrimental, compare Figure 5-c.

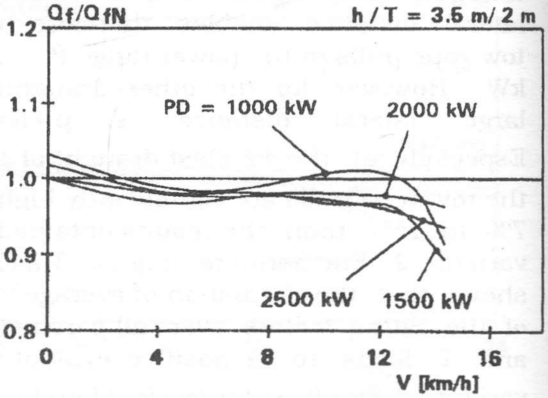
The several times mentioned stern shape effect rated by Q_f/Q_{fN} is mainly characterised by the ratio of tow-rope pull rates. This ratio implicitly contains a changing of the effective thrust demands for the always constant loaded part. To emphasise the order of magnitude, Figure 6 shows the ratios Q_N of the effective thrust demand according to Equation 4 at service speeds for all considered comparisons. The differences of the effective thrust demand which are exclusively caused by an alteration of the propulsion system, are unexpectedly high.



(a): Overall rating

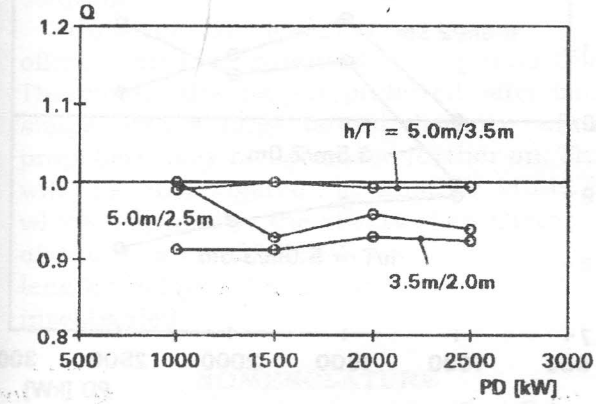


(b): Rating of propulsion quality

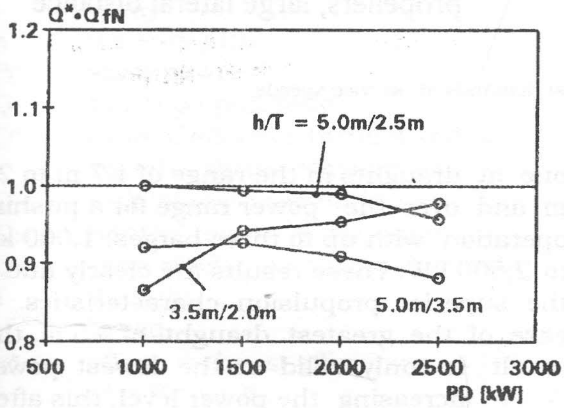


(c): Rating of stern shape quality

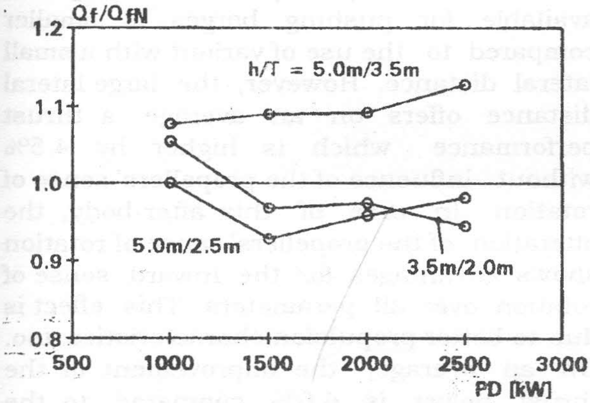
Figure 4 Comparison of outward/inward rotating propellers, large lateral distance



(a): Overall rating



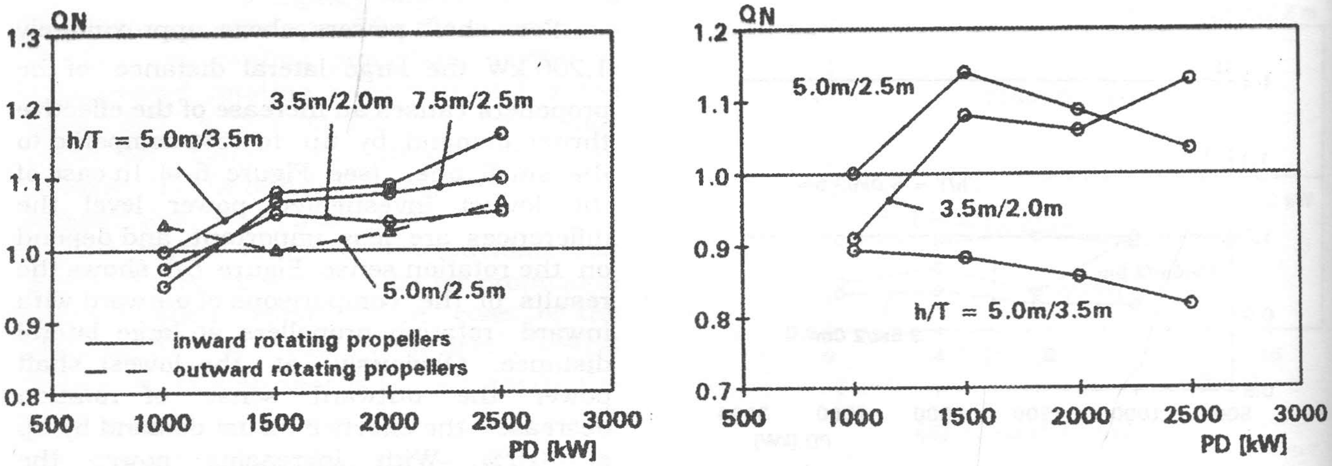
(b): Rating of propulsion quality



(c): Rating of stern shape quality

Figure 5 Comparison of outward/inward rotating propellers, large lateral rotating propellers at service speeds,

For shaft powers above approximately 1,200 kW the large lateral distance of the propellers causes an increase of the effective thrust demand by up to 15% compared to the small one, (see Figure 6-a). In case of the lowest investigated power level the differences are less important and depend on the rotation sense. Figure 6-b shows the results of the comparisons of outward with inward rotating propellers at large lateral distance. Obviously, at the lowest shaft power the outward sense of rotation decreases the effective thrust demand by up of 10%. With increasing power the conditions further improve at a draught of 3.5 m. Thereby, the effective thrust demand of the loaded part is smaller by even up to 19% compared to the case of inward rotating propellers. On the contrary, at draughts of 2 m and 2.5 m, inward rotating propellers give rise to a smaller effective thrust demand which is lower by up to 13% compared to the one of the referential variant. In the overall rating of the variants, the stern shape effect is decisive only in case of the comparison of the lateral distances at a draught of 3.5 m, (compare Figure 3-a). In all other cases the propulsion quality predominates. Summing up it can be stated, that a large lateral distance of the propellers and an inward sense of rotation is recommended for the investigated after-body type.



(a) Comparison large/small lateral distance

(b) Comparison inward/outward rotating propellers, large lateral distance

Figure 6 Ratio of the effective thrust demands at service speeds

CONCLUSIONS AND PROSPECTS

The present investigation deals with a further optimisation of a recently developed new stern shape for large twin-screw inland motor cargo ships operating in pushed barge trains. The alteration of the propellers' lateral distance and of their sense of rotation aims at determining the most efficient variant. The investigations are based on tow-rope pull tests with self-propelled divided models. In the context of the results' analysis an overall rating is defined. The latter is based on the comparison of the tow-rope pulls which simulate the forces available for pushing the barges. The model's division between the after-body and the remaining part of the ship, e.g. the fore- and middle-body, allows to measure the forces exerted by the after-body and acting at the interface. In addition to the overall rating, this test method allows to evaluate the influences of the propulsion characteristics and of the stern shape of the after-body.

The alteration of the propellers' lateral distance for the herein investigated after-body type proved that the large lateral distance is more efficient than the smaller one at draughts in the range of 1.7 m to 2.5 m and over the power range for a pushing operation with up to three barges, 1,000 kW to 2,500 kW. These results are clearly due to the superior propulsion characteristics. In case of the greatest draught of 3.5 m, this result is only valid at the lowest power. When increasing the power level, this after-body causes a comparatively high effective thrust demand for the loaded forward part of the ship. Consequently, the thrust power available for pushing barges is smaller compared to the use of variant with a small lateral distance. However, the large lateral distance offers on an average a thrust performance which is higher by 4.5% without influence of the propellers' sense of rotation. In case of this after-body, the alteration of the propellers' sense of rotation shows advantages for the inward sense of rotation over all parameters. This effect is due to better propulsion characteristics, too. On an average, the improvement of the thrust power is 4.6% compared to the outward rotating variant. Consequently, the after-body type with a large lateral distance of the propellers and an inward sense of rotation is rated to present the more optimal solution.

However, the design of the tunnel region offers further potential of optimisation. Therefore, the herein preferred after-body shape with a large lateral distance of the propellers may be optimised further on. This will be investigated in another study in which especially the effects of an alteration of the degree of fullness and of the tunnel's length before the propeller plane will be investigated.

NOMENCLATURE

f_P	tow-rope pull rate: $f_P = F_P / F_P^*$
F_P	tow-rope pull
F_P^*	effective thrust of the ship's after-body
h	water depth
P_D	shaft power
Q	tow-rope pull ratio
Q^*	ratio of effective thrusts and of effective thrust efficiencies
Q_f	ratio of tow-rope pull rates
Q_{fN}	neutral tow-rope pull ratio
Q_N	ratio of effective thrust demands
T	draught
V	speed
η^*	effective thrust efficiency: $\eta^* = F_P^* \cdot V / P_D$

REFERENCES

1. H. H. Heuser, "Neue Entwicklungen beim Entwurf von Flachwasserschiffen", 8th Duisburger Kolloquium Schiffstechnik/ Meeerestechnik, Vol. 8, pp. 33-41, Duisburg, (1987).
2. N. Von der Stein, Hinterschiffsoptimierung Durch Systematische Untersuchung Einer Neuentwickelten Tunnelform für Groβmotorschiffe", VBD-Report No. 1266, Duisburg (1989).
3. L. Kamar, "Comparative Evaluation of Stern Shapes of Pushing Inland Cargo Motor Ships", 8th Int. Congress of IMAM, Vol. 1, pp. 52-21, Istanbul (1997).
4. H.H. Heuser, "Einfluβ des Propellerdrehsinns auf den Leistungsbedarf von 2-Schrauben-Düsenschiffen der Binnenschiffahrt", Schiff und Hafen, Vol. 23, No.10, pp. 48-59, (1971).
5. N. Von der Stein, "Hinterschiffs- und Antriebsoptimierung für Groβmotorschiffe auf dem Rhein, VBD-Report No. 1215, Duisburg (1988).
6. N. Von der Stein, "Beitrag zur Formgebung und deren Systematischer Bewertung bei hochbelasteten Mehrschrauben-Tunnelschiffen", Ph.D. Thesis, Technical University Aachen (1986).
7. H.H. Heuser, "Optimized Hull Form and Propulsion for Inland Cargo Ships", Wegemt 21th Graduate School, University Duisburg, September (1994).

Received June 28, 1998
Accepted September 7, 1998

الاختيار الأمثل للبعد العرضى واتجاه دوران الرفاصات لسفن النقل الداخلى ذات الرفاصين والتى تعمل تحت أقصى تحميل

ليلى قمر
قسم الهندسة البحرية وعمارة السفن - جامعة قناة السويس

ملخص البحث

يتناول هذا البحث التطور فى تصميم مؤخرة سفن النقل التجارية الكبيرة المخصصة للملاحه فى الانهار ذات العمق المحدود وتستخدم كوحدة نقل منفردة أو لدفع عدة صالات أمامها.

ونظرا لأهمية هذا النوع وثبوت جدارته واقتصاديته فى نقل البضائع. قام مركز أبحاث السفن بديوسبورج (المانيا) بإجراء تجارب عديدة بغرض الحصول على الشكل الأمثل لمؤخرة تلك السفن.

تتميز تلك المؤخرة بوجود **Tunnel** يحتولى على رفاصين بالحجم المطلوب ولقد ثبتت فاعلية تلك المؤخرة ومدى أهمية تحسين وتطوير شكلها للحصول على **Thurst Power** مطلوبة لدفع الوحدات التى تصل عددها فى بعض الأحيان الى ثلاثة.

ولقد قام الباحث فى عمل سابق بالمقارنة بين ثلاثة تصميمات **Tunnel Stern** والتى تستخدم بصفة عامة لهذا النوع من السفن وأثبتت أحدى تلك الأنواع المعروفة **Gollden Stern** جدارتها باعطائها **Thrust Power** تزيد عن النوعين الآخرين بمقدار ٢٠ %.

ويتناول هذا العمل الأن تلك المؤخرة بمزيد من الدراسة لمعرفة مدى تأثير التغير فى البعد العرضى بين الرفاصين وكذلك اتجاه دورانهما على طول **Thrust Power** الناتجه.

حيث استخدم الباحث قياسات **Tow-Rope Pull Test** بمساعدة **Self-Propelled Divided Models** وتتضمن القياسات الـ **Tow Rope Pull (Fp)**-الـ **Shelf Power (PD)** والـ **Effective Thrust (Fp)** وهى القوة التى تقاس فى مكان الانفصال بين جزء الموديل الخلفى المحتوى على **Tunnel Stern** وجزء الموديل الأمامى المكون من **Fore-and Middle Body** وذلك عند سرعات مختلفة وعلى أعماق مياه تتراوح من **h=3.5-5m** وغاطس السفينة **T=1.7-3.5m** مكونا بذلك النسبة **h/T= 1.43 to 3.0** ، وقد استخدمت طريقة للتقييم تعطى نتائجا تفيد تأثير المتغيرات السابقة **Thrust Power** وتحديد سبب التحسن.

وقد أثبتت الدراسة أن زيادة البعد العرضى للرفاصين تعطى قدرة دفع أكبر بنسبة ٤,٥ % لجميع القدرات التى تم بحثها والتى يتراوح فيها الغطاس مابين ١,٧ متر الى ٢,٥ متر ، وذلك نظرا للتحسن فى **Propulsion Quality** أما فى حالة الغاطس الأكبر (٣,٥متر) فإن هذا التحسن لايظهر الا فى القدرات المنخفضة وبمقارنة قياسات التجارب عند تغير اتجاه دوران الرفاصات أظهرت النتائج أن اتجاه دوران الرفاصان للداخل يعطى قيمة أكبر لـ **Thrust Power** تصل الى ٤,٦% عنها فى حالة اتجاه الدوران للخارج ويرجع السبب أيضا الى **Propulsion Quality**.

ويتضح من ذلك أن زيادة المسافة بين الرفاصات مع دورانها للداخل يعطى أحسن **Thrust Power** مع أقل طاقة مبذولة **Driving Power Demand** وهذا يرجع الى التحسن فى الانسياب الى الرفاصين وقلة تداخله.