LIUTO Development and Optimisation of the Propulsion System; Study, Design and Tests

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In fall 1996 ACTV, the two industrial companies SCHOTTEL WERFT and INTERMARINE and the three R&D institutions University of Naples (DIN), Maritime Research Institute Netherlands (MARIN) and Schiffbau-Versuchsanstalt Potsdam (SVA), with the financial support of the EC Brite-Euram programme, started an R&D project to develop and full scale test a new motor boat for public urban transports, to be used in water cities, such as primarily but not exclusively Venice.

LIUTO (Low Impact Urban Transport water Omnibus) is the name of the project, whose goal is to develop the prototype of Venice's 2000 M/b fleet with the following main aims and innovative features:

- achieve low hydrodynamic impact by wave and propeller washing generated in the navigation and the frequent manoeuvring, by means of an optimised hull and an innovative propeller designs;
- qualify and compare results with existing vessels by validated CFD numerical tools, model and full scale tests;
- test and apply composite materials, resisting heavy duty services, vandalism and environmental conditions, for the hull construction and the superstructure, to reduce maintenance costs and help achieving stability.

ACTV is responsible for co-ordinating the project and defining, as prime interested end user, the specification of the motor boat. This will also feature innovative technologies for propulsion energy generation (a hybrid diesel electric system with buffer batteries) and external and internal noise limitation which are the object of concurrent activities under ACTV own support.

This paper after an overview of the vessel operational profile develops in greater detail the characteristics of the propulsion system.

1. OPERATIONAL PROFILE

The passenger transport system of the city of Venice and its lagoon relies on a fleet in excess of 110 vessels, among water busses (54 M/B) and motor crafts (59 M/S). They have steel hull and are powered by diesel engines. Their navigation pattern, compared to other water transports, features a wide variation of payload and displacement, varying speed limits, relatively high acceleration and deceleration performances, for timetable optimisation and safety in the very congested urban traffic.

Fixed axis propellers and manoeuvring by rudder cause a significant turbulence and jetting in areas near berths, canal turns and buildings foundations.

The LIUTO characteristics (Table 1) allow an efficient and environmentally friendly operation in a variety of lines, both across the city and between the central Venice and the nearby islands.

The optimisation of the vessel took into account particularly the most important service lines, involving the crossing of the central urban area along the Grand Canal (30-60 m wide) and the larger Canal of Giudecca by very frequent stops (one every 2-3 minutes) and prevailing transient power conditions.

Traffic is there intense and congested. The service must comply with the speed limits stated by the competent authorities to keep boats waves low, respectively the Borough of Venice for the canals in the historical centre of the city and the Harbour Authority, for the larger canals for the maritime navigation.

The LIUTO design and main test conditions thus cover the following basic speed requirements, in calm waters and no wind conditions:

V_1 urban speed 5.94 knots

V_2 max full load speed 10.0 knots

V_3 max half load speed 10.8 knots

		S. 80 Existing	**E1 Existing**	**LIUTO New**
Passengers capacity		219	208	234
Seats		83	72	100
Displ. (ls./fl.)	t	39/57	35/50	34/50
Length B.P.	m	21.0	20.9	24.7
Max Speed	kn	11.5	8.9	10.8
Constr. height	m	1.85	1.90	2.03
Driver cont. power	kW	147	60	90
Type of driver		Diesel	Electric	Hybrid

Table 1 - Comparison of the LIUTO characteristics with present ACTV M/bs

The full range of operational water depths goes down to 2 m in the shallowest areas of the canals, the most common falling between 3 and 10 m.

The manoeuvrability will also be improved with respect to present M/bs, presently characterised by 25 m turning radius, with a rudder angle of 42°.

The choice of a directional propeller goes with this target, as it allows continuous 360° thrust direction variation. The maintained possibility of reversing the propeller revolution, thanks to the electric drive provided by a hybrid energy system, allows maximum flexibility and possibility to gradually shift from present pilots practice to the improved features offered by the directional thruster.

An important requirement of the propulsion and energy system is its capability to stop the vessel in a short distance both during regular service and when in emergency, e.g. to avoid collisions with crossing vessels. To limit the hydrodynamic impact under normal operation it should be avoided to exceed certain power limits, by a relatively “smooth” power demand attitude, within the nominal motor performances. Instead during occasional emergencies these power limits should be overcome allowing a stop within 2.5 x LOA from the speed of 10 kn and within 1 x LOA from the speed of 5.94 kn.

The power to the thruster motor is thus managed by a supervisory control system that is also in charge of the efficient and safe management of the whole hybrid energy system.

2. HYBRID PROPULSION ENERGY SYSTEM

The LIUTO energy system will be a ***series type, hybrid diesel electric*** system as shown in Figure 1, including the following main components:

- diesel engine, running at constant speed
- 3-phase synchronous electric generator
- 3-phase rectifier
- batteries stack (high charge/discharge rate lead-acid with gel type electrolyte)
- power management and battery charge control
- inverter unit
- 3-phase asynchronous electric motor
- Interface mechanical coupling with the propulsion system drive shaft

The system was studied in cooperation with the University of Naples Department of Naval Engineering [1,2] after detailed analysis of existing vessels performances and is now being designed and manufactured by ANSALDO, under ACTV contract.

The gen-set converts all the mechanical energy delivered by the diesel engine into AC electric energy. This is then rectified and supplied in parallel to the battery stack and the user functions, the main one being the propeller AC asynchronous motor, fed by the inverter. This latter operates at variable frequency and voltage, as shown in the control loop dotted in Figure 1.

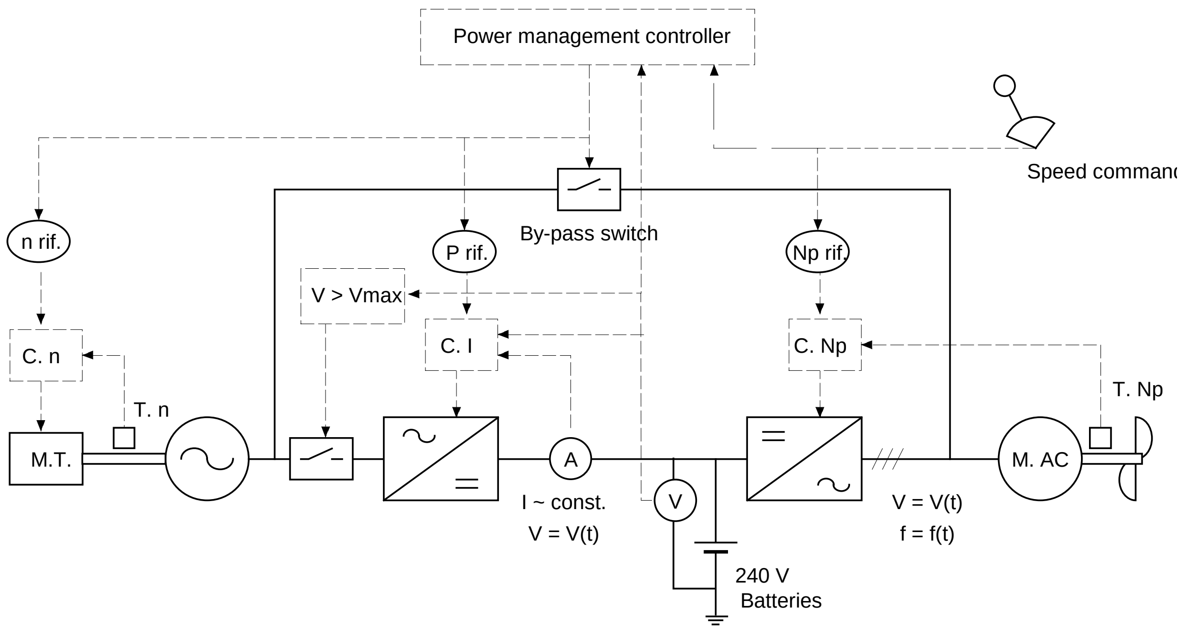


Figure 1 - Scheme of the hybrid system and its main control structure - Feedback to battery charger (T = transducer, C = controller). The main and the emergency AC motors are shown as a unique one.

The power generating set runs at either no power (idle or off) or at a single power level. The battery stack features mostly peak power supply and energy buffer, under very high but short charge/discharge power levels.

The system is twofold redundant, against failure of any of the static or rotating subsystems. If the inverter fails a by-pass switch allows the AC generator to directly drive an emergency, lower power, AC motor (not shown in Figure 1). The batteries are made by two stacks in parallel, that can individually be isolated, keeping the system operational, yet at lower power performance, if either fails. Should the engine, the generator or the rectifier fail instead, the energy capacity of the battery stack is largely sufficient to complete the mission and go to the repair yard, with the engine off.

3. PROPULSION SYSTEM DESIGN

3.1. Propulsion unit generally

SVA and SCHOTTEL-Werft were in charge and have developed an efficient propulsion system for LIUTO. Propellers with different diameters and optimum numbers of revolutions have been designed. The calculations showed that a propeller diameter of D ≈ 0.750 m should be used.

Different propulsion systems are practicable for the water omnibus. Aspects of the propulsion systems conventional propeller, propeller made out of fibre reinforced material, ducted propeller, SCHOTTEL Twin Propeller and LINEAR-Jet have been discussed

Finally a new Z-drive was designed. An optimised, streamlined shape of the lower gearbox housing with low drag was realised. The drag of the housing is 3 - 5 % lower than at conventional shaped housings. The influence of the housing on the propellers was minimised. This means that the increase of thrust and torque coefficient and the decrease of the efficiency caused by the disturbed wake field due to the housing could be reduced distinctly. Compared with the state of the art it can be stated that there is no housing existing today with such outstanding stream properties. The use of spheroidal cast iron makes it possible to realise streamlined laminar profiles with an unconventional form with an optimised relation of length to thickness. The blades camber and the angle of attack was optimised in model tests so that flow separation is completely prevented. Previous investigations about asymmetrical arrangement of the shaft showed that the spin recovery can be improved but the resistance of the housing increases in the same value. Therefore the symmetrical version was chosen.

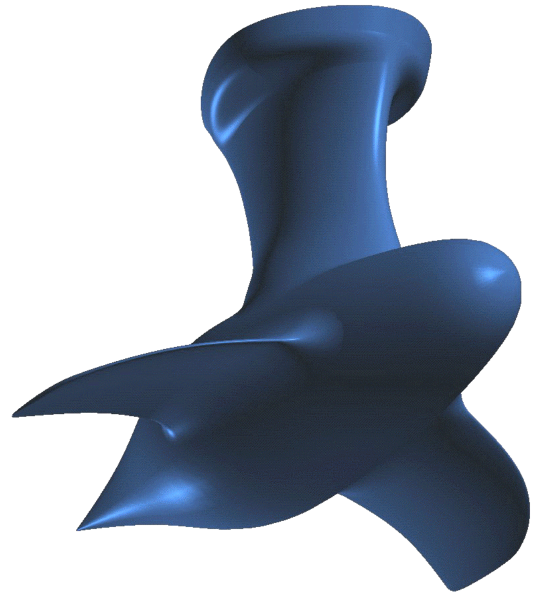


Figure 2 - 3D-Drawing of the Lower Gear Box

3.2. Materials - Propellers and Foils / Fins

Propellers are available normally in CuNiAl or manganese-bronze and, for special fields of operation, even in stainless steel. For the LIUTO-project it is suitable to have parts with low weight due to the frequent speed reversals. In this case the use of unconventional materials (carbon fibre reinforced material) for the propellers and the foils/fins of the TWIN-Propeller was examined.

It was the first time that such kind of propeller was driven at a Z-drive with it's special operation conditions (oblique flow during steering, disturbed wake field due to the housing etc.)

The manufacture of this kind of propeller has shown a very high accuracy. The material's very good damping properties lead to operation with low noise and pressure vibrations. Another effect is the positive influence to the elastic mass system. Because of the low rotational inertia it is possible to relinquish an additional elastic clutch at the cardan shaft. A propeller weight saving of approx. 65 % could be achieved compared to standard materials.

4. PROPULSION SYSTEM

4.1 The TWIN-Propeller

The TWIN-Propeller Technology, is characterised by two propellers on the same shaft with the same rotation direction and a guide arrangement between the propeller (Figs. 3,4,5).

Figure 3 - SCHOTTEL-Twin Propeller, Standard Version

This results in improvement of efficiency and noise emission (pressure fluctuations) for two main factors:

a. Power distribution at two propellers: a lower thrust load of each propeller reduces the impulse losses. The blade geometry of both low loaded propellers can thus be designed in a more efficient way (profile geometry, chord-length, thickness, camber etc.). Interference effects among the blades are by comparison lower than in a high loaded single propeller, usually designed with a higher number of blades. Furthermore this power distribution leads to low level of cavitation and pressure fluctuation, which cannot be achieved by another system.

b. Recovery of lost spin energy: lost spin energy is recovered and flow is directed to the rear propeller by using an integrated guide arrangement consisting of a specially formed housing and additional guide fins.

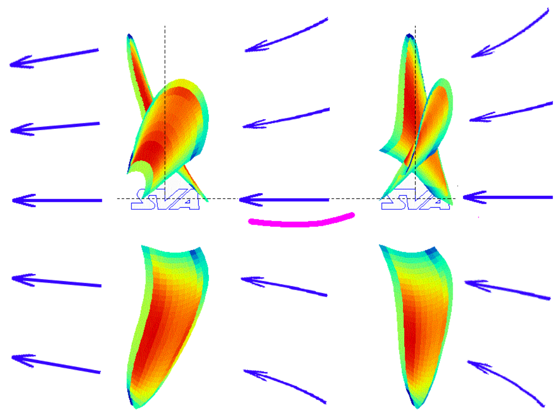


Figure 4 - Hydrodynamic model of a SCHOTTEL-Twin-Propeller

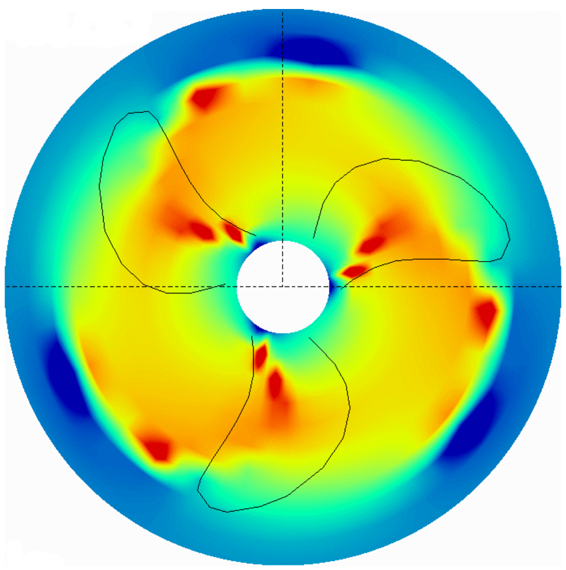


Figure 5 - Computed wake distribution in the position of the second propeller

4.2. Previous developments and LIUTO's step forward

SCHOTTEL has delivered or in order 26 STP-units in a power range from 80 kW to 1250 kW. For example some Double Ended Ferries for Norway, among which one is equipped with two STP 1010 (2 x 1250 kW). The STP-units enable an efficient operation at low noise and high degree of manoeuvrability. Extensive tests were done recently and confirmed the excellent performance of the units. The full scale test results were also very close to the model based predictions.

SCHOTTEL is using the Twin-Propeller Technology also in PoD-Propulsion. In co-operation with SIEMENS AG SCHOTTEL has developed the SSP. The SSP is a podded electric drive available in a power range from 5 to 30 MW. A new permanently excited electric motor from SIEMENS is integrated in the underwater gondola of the Rudderpropeller. Boths propellers are driven directly. The motor is the most efficient and smallest electric motor that is built today. Therefore a very slim streamlined gondola with a low resistance has been developed.

The combination with the TWIN-Propeller Technology leads to a convincing PoD-Propulsor.

The TWIN-Propeller Technology was a big step to improve the efficiency of high loaded rudder-propellers. Using the same technology with two plus two bladed propeller system is the consequent development for low loaded rudder-propellers.

LIUTO made it possible to examine such systems and to approve it in practice.

It was the first examination of 2-bladed TWIN-Propeller. The investigations include theoretical calculations, model tests in cavitation tank and full scale tests with a prototype at test pontoon of SCHOTTEL.

The safety against cavitation is given by the fact that each one of the two propellers is driven with lower load and the total propeller load of the LIUTO-vessel is very low too.

The result is an additional efficiency increase by using 2-bladed propellers was achieved. The mechanical problems of 2-bladed propeller systems - the torsional vibrations and the pressure vibrations - could be solved by a special blade geometry, a comfortable distance between propeller and housing and by the use of very light propeller blades made of carbon fibre reinforced material.

The procedure of calculation of 2-bladed TWIN-Propeller and the transformation of the model test results to full-scale values was verified.

Figure 6 - Double Ended Ferry, MRF-Norway

Figure 8 - SSP 7 TWIN-Propeller as PoD-Propeller (test model in the SVA cavitation tunnel

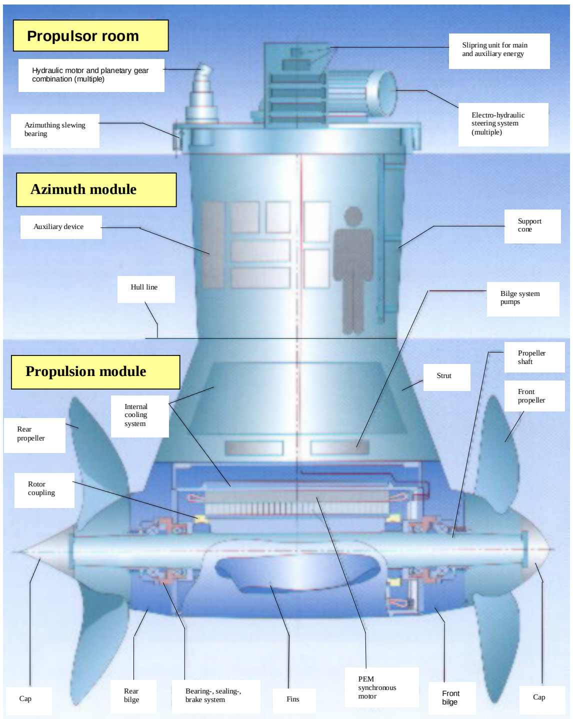


Figure 7 - SSP 7 TWIN-Propeller as PoD-Propulsor

Figure 9 - SCHOTTEL- STP 1010

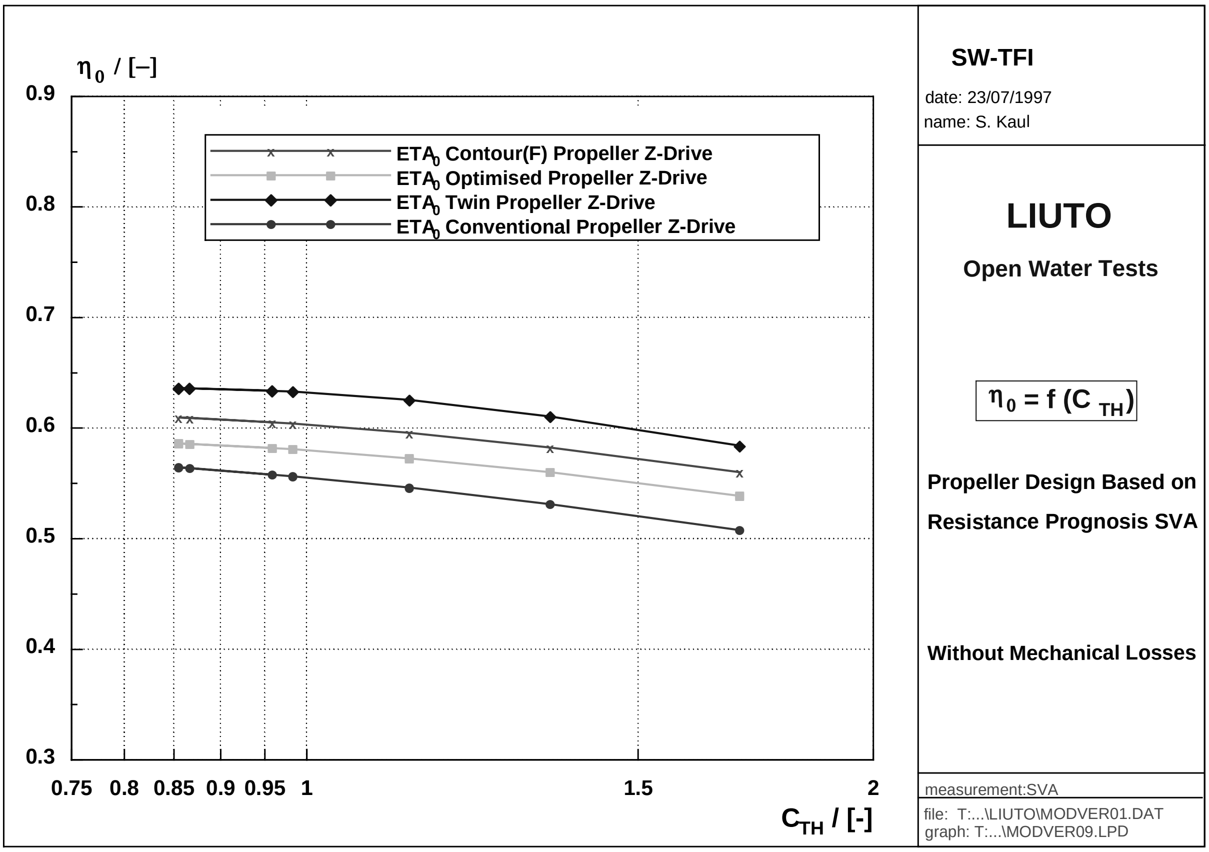


Figure 10 - Model Test Result, Comparison of the different Systems studied for LIUTO.

4.3. CONTOUR(F/S)-Propeller

The CONTOUR(S)-Propeller is a specially designed propeller. Carbon fibre reinforced composites enables a very slim profile geometry. This kind of profile geometry leads to a higher total efficiency of the propeller.

The combination of CONTOUR(S)-design and the TWIN-Propeller join the mechanical advantages of the light and highly accurate manufactured propeller with a new hydrodynamic technology. The result: propulsion system with highest efficiency for the LIUTO vessel.

The CONTOUR(F)-Propeller is the flexible type of CONTOUR-Propellers which deforms in operation in a defined way depending on the load. That leads to an optimum efficiency in a wide range of operation. For example, at overload conditions (stopping, acceleration) the pitch ratio is reduced automatically. Therefore overload can be reduced and the engine operates at better conditions.

The theoretical pre-calculation led to an efficiency increase of 2 % at higher ship speed and up to 10 % at low speed (overload conditions).

There are still some difficulties of the fibre structure design to achieve the hydrodynamic parameters at each operation point.

Therefore for the LIUTO M/b prototype the 2 blade STP is being made by CONTOUR(S) type blades.

Further research work is required to control the deformation characteristic. A lot of companies all over the world have started the development of such systems. The interest in this technology has increased. Special installations are military and hydrographical ships or special requirements on environmental protection aspects for example.

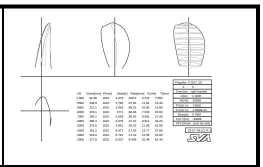
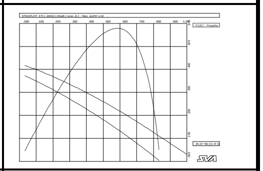
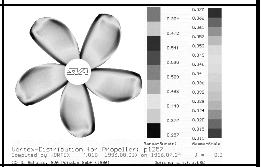
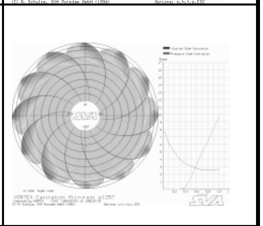
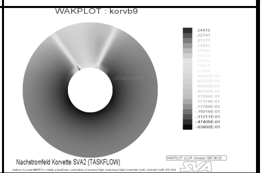
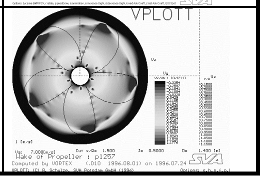
PFFEDIT the routine PFFEDIT yields the propeller draw and represents the main data as a function of the radius r	
VTXPLOT yields the graph of K_T, $10K_Q$ and η_0 as a function of J or C_{th}, the graph of the cavitation buckets	
DENPLOT represents the vortex strength distribution	
CAVPLOT represents the cavitation bucket chart and the cavitation behaviour of the blades in the wake (regions with critical pressure are marked)	
WAKPLOT represents the wake	
VELPLOT computation and representation of the velocity distribution around the propeller (in the propeller jet)	

Table 2 - Components of the numerical cavitation tunnel of the SVA-Potsdam GmbH

5. PROPELLER DESIGN BY SVA POTSDAM

5.1. Introduction

A modern design method for marine propellers is in general based on a collection of computer programs (Table 2) to calculate

- the propeller - hull interaction
- the propeller - machine interaction
- the propulsive performance which includes propeller efficiency
- the cavitation on blades and fluctuation pressure on ship hull
- the strength.

The usual strategy for the realisation of the design process consists in a iterative trial and error algorithm to

- increase the propeller efficiency
- decrease the cavitation on blades and the fluctuation pressure on ship hull.

This iteration process can be started with a conventional design method such as some series charts techniques.

The calculation for propellers can be accomplished by using the lifting line and the lifting surface theories under steady and unsteady conditions respectively.

Contrary to the trial and error strategy we determine the propeller geometry by an optimization technique.

5.2. Inverse methods for the design and optimisation of marine propellers

The strategy of Potsdam Ship Model Basin consists of the construction of a “Toolbox Propulsive Performance Optimisation“

- definition of a “weighting function“ to determine the propeller efficiency (η), cavitation behaviour, etc.
- variation of the propeller geometry by an optimisation algorithm
- calculation of propellers by using series charts techniques lifting line methods lifting surface methods NSE-Solver

The geometry (G) of propellers can be described

r/R	c	P/D	rake	Xe	f/c	t/c
.200	479.71	1.10	.000	295.41	.0385	.118
.400	587.56	1.20	.000	352.51	.0274	.074
.600	641.93	1.30	.000	358.32	.0202	.047
.700	636.72	1.40	.000	335.21	.0171	.037
.900	486.39	1.30	.000	194.56	.0111	.022
1.000	20.00	1.20	.000	.000	.00000	.000

Table 3 – Propeller geometry definition
(c, P/D, rake, Xe, f/c and t/c are functions of r/R.)

by (e.g. 42) real numbers like in Table 3.

The geometry G of the “best propeller“ in the sense of efficiency (η) is the solution of the following optimisation problem:

$$f(G) := \eta_0(G) \;\; ===> \max !$$

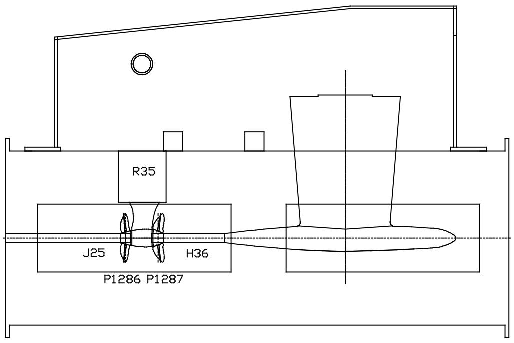


Figure 11 - SVA test facility (Kempf and Remmers) for the SCHOTTEL - TWIN - Propeller

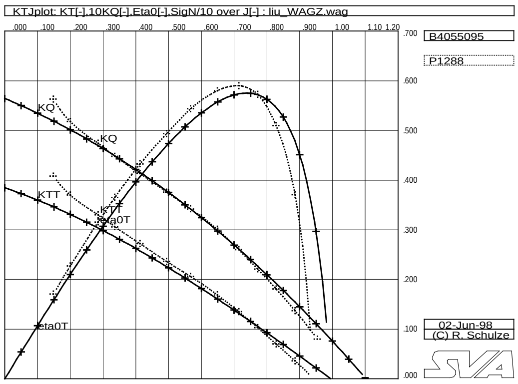


Figure 12 - Comparison of the open water behaviours of a single Wageningen propeller (continuous line) with the optimised SVA-propeller P1288 (dotted line), with the influence of the Z-drive.

6. MODEL AND FULL SCALE TESTS

6.1 Model Tests of the SCHOTTEL Twin Propeller (SVA design TP1286/1287)

The tests performed at SVA followed the steps listed herebelow:

- open water tests with the first and the second propellers of the twin pair with the dynamometer J 25

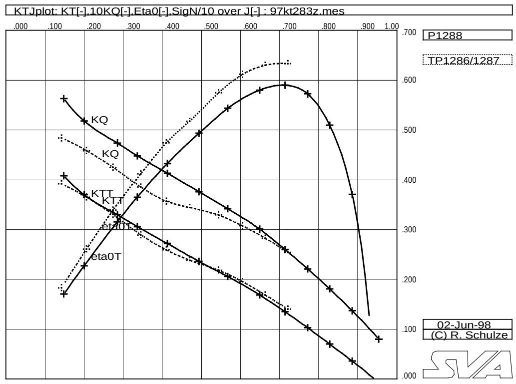


Figure 13 - Comparision of the single optimised pull-propeller P1288 (continuous line) and the Twin-propeller-system TP1286/1287 (dotted line), with the influence of the Z-drive.

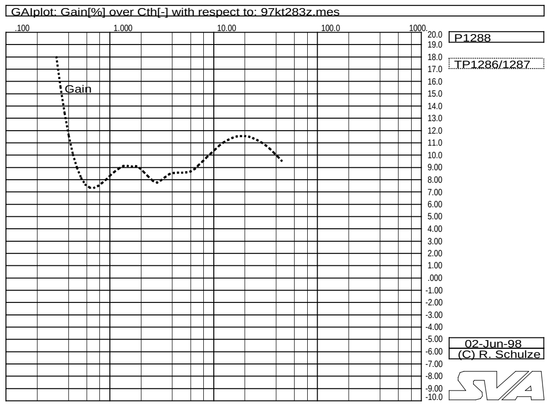


Figure 14 - Comparision of the single optimised pull-propeller P1288 and the Twin-propeller-system TP1286/DP1287/Z-drive, efficiency gain over C_{TH} [%] with respect to P1288.

- open water tests with the z-drive housing and the pull propeller (dynamometer J 25, balance R 35X). (control of the pitch ratio for the design point of the pull propeller)
- open water tests with the z-drive housing and the pull and push propeller (dynamometer J 25, H 36, balance R 35X). (control of the pitch ratio for the design point of the push propeller and the STP)
- open water and cavitation tests with a variation of the phase angle between both twin propellers (fixing of the phase angle)

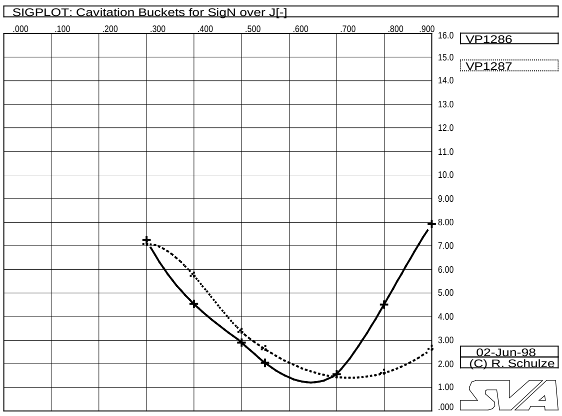


Figure 15 - Cavitation bucket of the Twin-propeller-system TP1286/1287. The cavitation bucket of the first propeller P1286 (continuous line) and of the second propeller P1287 (dotted line). Only the end of the suction/pressure side cavitation depending on the advance coefficient was drawn.

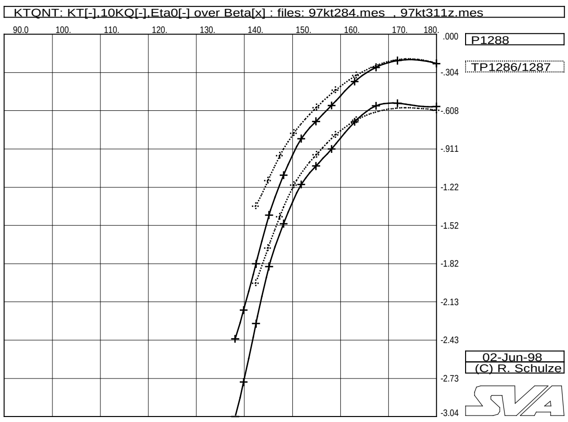


Figure 16 - Crash stop manoeuvre for the Schottel-Twin-Propeller TP1286/1287 in comparison with the optimised pull propeller P1288

- cavitation tests for all design points in homogeneous inflow
- open water tests for measuring the characteristic of the STP during the reversing process

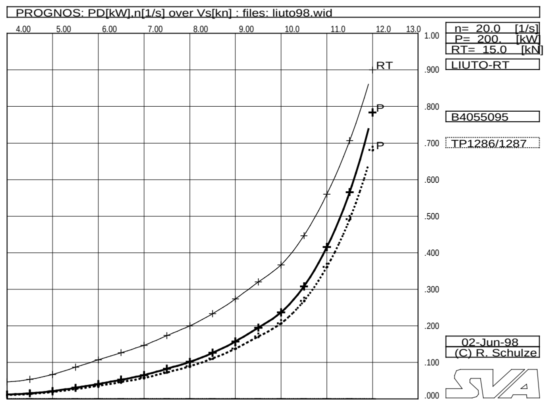


Figure 17 - Comparison of delivered powers in dependence of the water omnibus speed (kn) for the Schottel-Twin-Propeller and a classical Wageningen propeller, with Z - drive correction (RT: resistance curve. Continuous line: PD for the Wageningen propeller. Dotted line: PD for the Twin-Propeller).

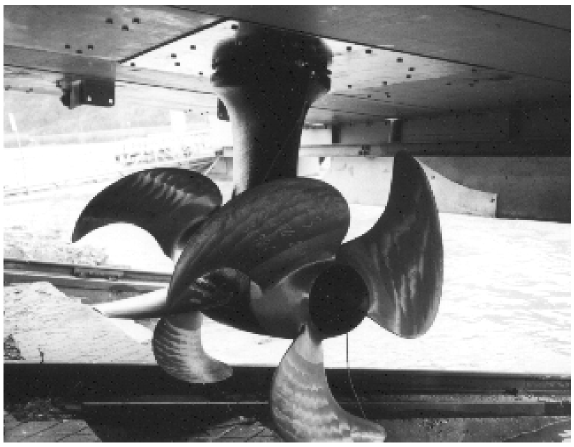


Figure 18 - Test arrangement of a SCHOTTEL-TWIN Propeller

6.2. Full Scale Tests

The test facilities at SCHOTTEL allow extensive examinations in full scale including the following tests like

- Torsional Vibrations
- Crash back
- Crash ahead
- Steering
- Load of the foils
- Bollard Pull

A careful comparison of full-scale tests and model tests is an important step to show some scale effects especially for new developments. This gave the opportunity to verify model tests and computerised calculations. In the case of LIUTO full-scale tests confirmed the very good model tests.

After the parallel activities made in the project on the hull hydrodynamics optimisation and, in particular, after the resistance tests results on large scale ship model, it could be confirmed that more than 60% efficiency is achieved over a large range of LIUTO's operational speeds (Figure 21).

7. CRASH STOP PERFORMANCE OF THE PROPULSION SYSTEM

An important aspect of the performance of LIUTO's propulsion system is its breaking and acceleration performance, particularly the former as regards safety. As after the discussion of the operational profile under emergency conditions the stop distance should be within the limits of 2.5 or 1 times the LOA, i.e. 63 and 25 m, respectively when stopped from 10 and 5.94 kn respectively.

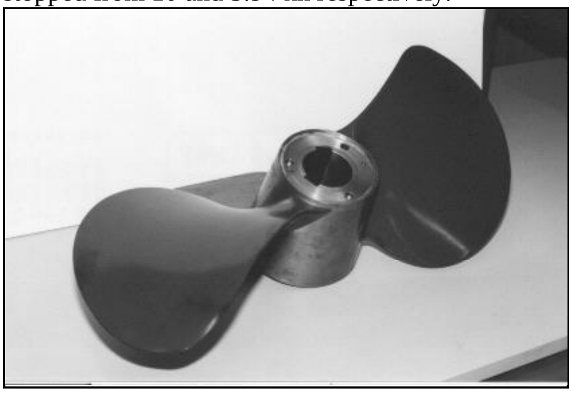


Figure 19 - 2-Bladed Optimised Propeller for the Twin-Propeller-System for LIUTO.

To verify this performance and the requirement on the electric motor, inverter and batteries dynamic simulations of the motor-mechanical transmission-propeller-ship dynamics were performed, based on the characteristics of the vessel and the STP propeller, derived from model tests. The dynamics account for the delay in motor shaft acceleration to reverse the propeller speed and the variation of the propeller working point (K_T & K_Q vs. J) and ship total resistance at each time.

The electric motor is supposed to be driven at constant negative torque during the whole breaking phase.

The results of the simulations and of a sensitivity analysis are summarised in Figure 22. With a torque overload factor of 1.4 both breaking requirements are satisfied, the overload lasting 24 and 16 s respectively. The peak motor power under these conditions is 132 kW.

The electric motor shall withstand these conditions only occasionally for the duration of the breaking phase without damage, starting from the thermal state corresponding to a typical mission power profile [Refs. 1, 2], without repetition of this stress. Under normal operating conditions, instead the electric motor shall be used within its nominal torque, yielding a breaking distance of 2.9 or 1.3 LOA, respectively from 10 and 5.94 kn, and a peak motor power of 76 kW.

Figure 20 - 5 bladed model of the CONTOUR (F) single rotor propeller (Carbon fibre reinforced material).

8. CONCLUSIONS

The LIUTO project is a step towards the achievement of low impact and efficient propulsion systems. It pursued by a broad view of applicable solutions and extensive modelling and tests this goal and it achieved it.

The most important results are:

- the efficiency of the propulsion system exceeding 62% for speeds going from 2 kn up to the maximum speed foreseen of 11 kn.
- the acceleration and crash-back performances, allowing a reduction of nearly 40% of the installed motor power with respect to present M/b's.

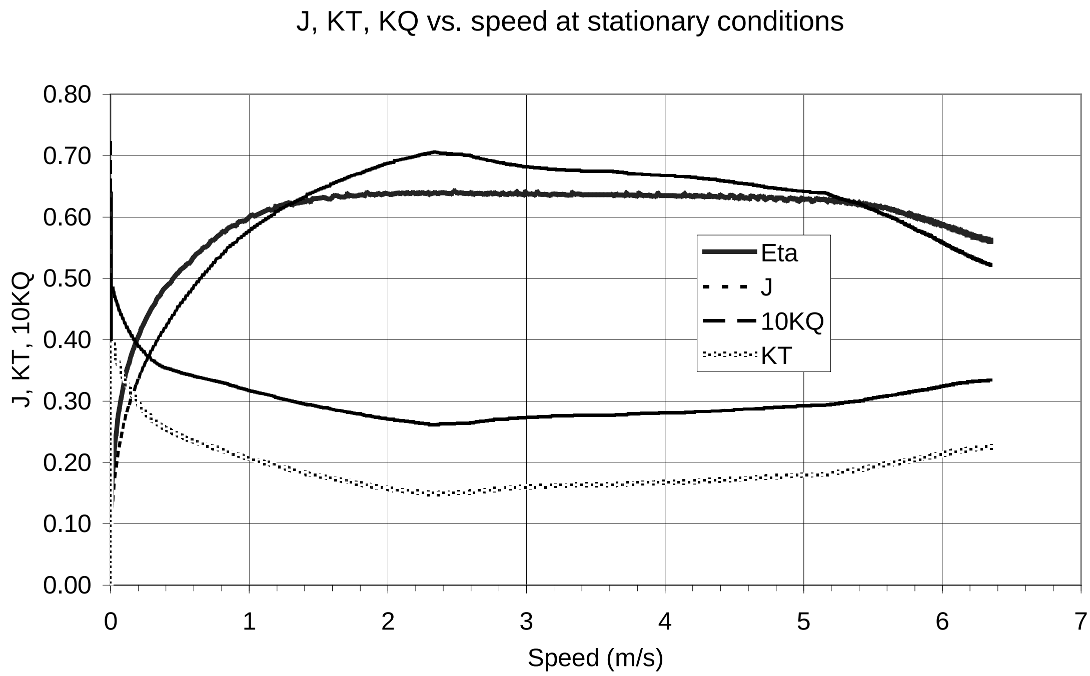


Figure 21 – J, KT, KQ and η curves vs. LIUTO speed.

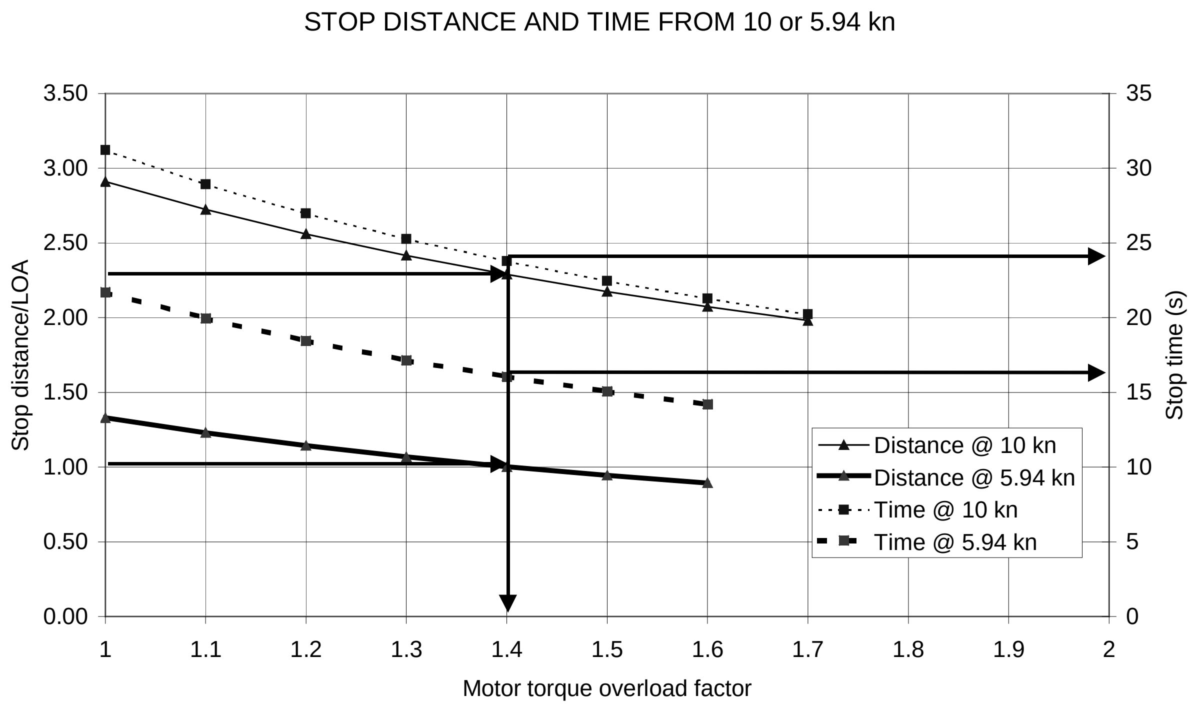


Figure 22 - Stop distance and duration - Sensitivity analysis vs. motor torque overload factor.

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