Practical Design of Ships and Mobile Units
M.W.C. Oosterveld and S.G. Tan, editors.

LINEAR-Jet: A propulsion system for fast ships

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The JAFO-Technologie Hamburg and the Potsdam Model Basin (SVA) developed and investigated a propulsor for fast shallow-draught ships, unconventional ships especially SES, submarines and marine ships. The propulsor is called LINEAR-Jet. It works like a water jet. A rotor and a stator are ducted by a nozzle. The upstream and downstream pipes are cut off and the propulsor stands in the wake like a ducted propeller.

The propulsion system LINEAR -Jet has a couple of advantages especially for fast and flat going ships. The velocity in the area of the rotor is less than the velocity at the trailing edge of the nozzle. The inception of cavitation moves to higher advance coefficients. The cavitation behaviour was investigated in oblique flow in a range up to 5 degrees. The cavitation behaviour was nearly independent from the oblique flow. Propulsion tests have shown a reduction of the required power of 2.1% for a patrol boat at a ship speed of $V_S = 21.6$ kn. The thrust loading coefficient of a LINEAR-Jet can be up to ten times higher than the thrust loading coefficient of a ducted propeller, without cavitation problems. For that reason it is possible to reduce the diameter, compared with a free running propeller or reduce the propeller induced noise by reduction of the number of revolutions.

The stream of the propulsor is nearly spin free. If the LINEAR-Jet is powered by a Z-drive, the shaft is covered by a blade of the stator. For shaft-powered LINEAR-Jets working with a rudder, the danger of rudder cavitation is low because the stream is nearly spin free.

For these reasons the LINEAR-Jet is an attractive alternative for fast ships; especially with a design speed between $V_S = 20$ and 30 kn and for ships with a high thrust loading coefficient.

1. INTRODUCTION

Especially for the development of fast and/or unconventional ships suitable propulsion systems are necessary. The LINEAR-Jet is an alternative to the well known propulsion systems. The alternative propulsors will be discussed for a comparison with the LINEAR-Jet.

Depending on the ship design, propeller configurations for fast ships are difficult. Usually the propeller is powered by an inclined shaft. The shafts are supported by a boss and struts. The designers have to find a compromise between the optimum diameter of the propeller and the angle of the inclined shaft. The inclined upstream increases the risk of cavitation of the propeller. For shallow-draught ships there are relative small and high loaded propellers. For higher speeds it is impossible to get no cavitation. Because of cloud and bubble cavitation the propeller could be destroyed by erosion. Pressure pulses increase and there could be thrust deduction.

Water jets are often used for high speed ships. Usually the water enters the ship through an inlet in the bottom. Pipes lead the water to a pump. The pump increases the pressure level and the accelerated stream leaves the ships through a nozzle. The total efficiency of the system is influenced by the pump and the inlet. A good configuration delivers a high efficiency. For an unfavourable shape of the inlet flow separation and cavitation is possible. There is a risk of air suction and thrust reduction for surface effect ships.

The blades of surface piercing propellers are partly or full ventilated. To optimise the propeller in different conditions it is possible to make the pitch controllable. The thrust is completely generated by the pressure side, so that the thrust coefficient is low for a high efficiency.

2. CONSTRUCTION OF THE LINEAR-JET

The propulsor is a synthesis of a water jet and a ducted propeller. It is developed for fast ships in a speed range of V_S = 20 to 40 kn. Because the streamlines pass the propulsor linear, the propulsor is called LINEAR-Jet. The LINEAR-Jet was be divided into three parts: a rotor, a stator and a nozzle (Fig. 1).

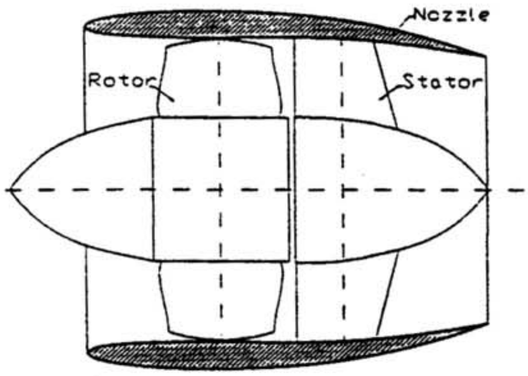

Figure 1. LINEAR-Jet

The construction is based on a water jet. The upstream and downstream pipes are cut off and the propulsor is positioned in the wake.

This construction has a lot of advantages in comparison with alternative propulsors:

- There isn't any loss of friction and jet deflection in the pipes.
- The nozzle reduces the stream from the leading edge to the rotor. So the risk of cavitation is reduced and moved to higher ship speeds. It reduces the pressure equitation from the pressure side to the suction side and reduces the noise because of the stationary pressure field. In addition to this the nozzle saves the rotor of damage.
- The combination of the rotor and the stator delivers a nearly spin free stream. This increases the efficiency and decreases the noise. A relative high thrust is available due to the induced velocities of the stator to the rotor In combination with the reduced velocity in the rotor plane it is possible to reduce the diameter and/or reduce the number of rotations.
- The optimal LINEAR-Jet has a relative big hub. This reduces the risk of hub cavitation.

A configuration with a LINEAR-Jet powered by a Z-drive gives some further advantages:

- No additional resistance by shafts. struts and rudders.
- No cavitation on rudder and struts. Higher efficiency in fact of axial inflow. The big ratio of the hub diameter to the rotor diameter gives enough space to integrate a gear box. The shaft of the gear box is covered by an enlarged stator blade.

Several arrangements of the LINEAR-Jet at the ship are possible. Powered by a shaft, by a Z-drive or electric.

3. CALCULATION METHOD

JAFO Technology developed a design tool for the LINEAR-Jet [1]. It is a re-calculation method. Giving the design point and a starting point, the propulsors data will calculate iterative by variation of single parameters.

The interaction of the rotor and the stator is calculated after Gibson and Lewis [2].

To calculate the flow through the LINEAR-Jet, a powerful vortex panel method was developed. The singularities are located on the surfaces of the blades. The strength of the singularities are calculated with a numerical program. So the normally used correction factors are not needed [3]. The rotor is simulated by a simple model. It is sufficient to replace the rotor with a semi-infinite vortex cylinder [4-5].

Fig. 2 shows the scheme of the program. In the following chapters, the program is described more in detail.

3.1 Calculation of the flow round the nozzle

The calculation of the flow round the nozzle is based in majority on Gibson and Lewis [4].

Following assumptions are made:

- The flow is symmetrical to the axis.
- The effect of the rotor-stator combination is simulated by a vortex cylinder.
- The surface of the nozzle is simulated by vortex rings with a constant circulation around the circumference.
- For the nozzle, the pressure equitation at the tip of the rotor blades is neglected.
- The influence of the finite number of blades is corrected after Tachmindji and Milam [6], the boundaries are corrected after Kopeeckij [7].

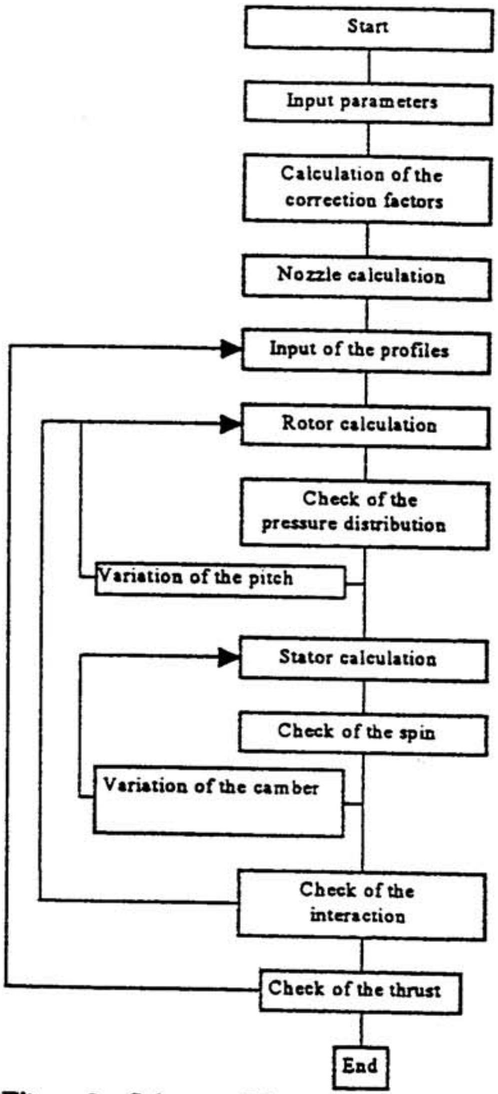

Figure 2. Scheme of the design program for LINEAR-Jets

A vortex panel method was developed for the calculation of the pressure distribution on the nozzle and the induced velocity in the planes of the rotor and the stator. N control points are located on the surface of the nozzle, in the middle of two contour points (Figure 3). A vortex ring around the nozzle is located on each control point.

$$x_i = 1 - \sin^n\left(\pi \frac{i-1}{N}\right) \qquad y_i = f(x_i) \qquad (1)$$

The requirement in the control points is:

$$u_{ti} = 0 \qquad (2)$$

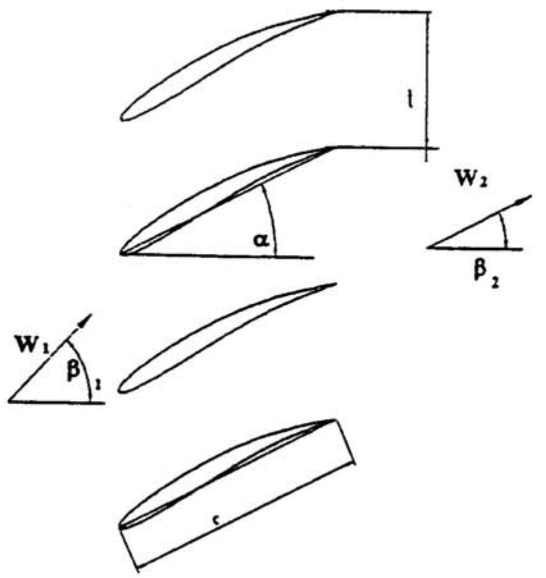

Figure 3. Geometrical and kinematical parameters of the grid flow

The strengths of the circulation are calculated with the requirement on the surface of the nozzle and the Kutta condition at the trailing edge. For the strengths of the circulation we get the following Fredholm formula.

$$-\frac{\gamma}{2} + \oint_{S_D} tu_i^* \gamma_D(s) ds + tu_P^* \gamma_P + tu_a = 0 \qquad (3)$$

The solution of this equation is similar to the solution of the grid flow in chapter 3.3.

The pressure coefficient of the nozzle is:

$$c_p = 1 - \left(\frac{\gamma_D}{U_\infty}\right)^2 \qquad (4)$$

By integration with the x-component of the normal vector n_x, we get the thrust of the nozzle:

$$T_D = \int_{S_D} c_p n_x \, \rho/2 \, u^2 ds \qquad (5)$$

The influence of the nozzle is considered by a global correction.

The hub is modelled by ring vortexes. For a given velocity in the plane of the rotor and the stator we make demands for a minimum resistance of the nozzle.

3.2 Influence of the rotor on the nozzle

The modelling of the rotor as a semi-infinite vortex cylinder leads to considerable simplifications.

The induced velocities of the vortex cylinder are calculated by the formula of Biot-Savart [4]. For the ring vortexes the integration of the Biot-Savart formula is necessary.

3.3 Calculation of the grid flow

The profile grids are calculated with the potentional theory. The presented design program calculates with the finite thickness of the blades. The following parameters are relevant for the program (Fig3.):

- Shape of the profile.
- Ratio of the gap t of the profiles and the chord length c.
- Geometrical angle of attack of the profiles α.
- Hydraulic angle of attack β_1.

The strength of the circulation of a vortex sheet with the length ds is:

$$\gamma ds = (u_t - u_{ti}) ds \qquad (6)$$

The vortexes are located on the surfaces of the blades. There are no sources. If the velocity inside the blade u_{ti} is zero, the strength of the circulation on the surface of the blade γ is identical to the tangential velocity u_t on the blade.

To determine the strength of the circulation we calculate the velocity for each point on the surface. With $u_{ti} = 0$ we get the Fredholm formula for the distribution of the surface.

$$-\frac{\gamma}{2} + \oint u^* t\gamma ds + u_a t = 0 \qquad (7)$$

The factor for the velocity u^*, calculated with the Biot-Savart formula, depends on the geometry. T is the tangential vector of the profile contour and u_a the upstream velocity.

We calculate the unknown strength of the circulation with a numerical program. The induced velocities from the single panels are integrated by the trapezoidal formula. The induced velocities from the single vortexes are known and described analytic.

Based on the flow around a single profile, the profile grid will be calculated. The components of the factors of the velocities are:

$$u_x^* = \frac{1}{2\pi} \frac{(y_a - y_w)}{(x_w - x_a)^2 + (y_w - y_a)^2} \qquad (8a)$$

$$u_y^* = \frac{1}{2\pi} \frac{(x_a - x_w)}{(x_w - x_a)^2 + (y_w - y_a)^2} \qquad (8b)$$

For a row of vortexes the induced velocity on a control point could be calculated by an analytical formula. It is calculated in the complex plane (Fig. 4). For a row of vortexes with a gap t between the single vortexes, located on the imagine axis, the conjugated complex velocity is:

$$\overline{u}^* = -\frac{i\Gamma}{2t} \frac{\cos\left(\frac{\pi D}{t}\right)}{\sin\left(\frac{\pi D}{t}\right)} = -\frac{i\Gamma}{2t} \cot\left(\frac{\pi D}{t}\right) \qquad (9)$$

z =x+iy describes the location of the single point. The Fredholm formula (7) will be transformed to a linear equation system:

$$\sum_{j=1}^{N} u_{ij}^* \gamma = -u_a t_i \qquad (i = 1,N) \qquad (10)$$

The distribution of the control points and the contour points is similar to the distribution of the nozzle (Fig. 5). To fulfil the Kutta requirement we set the pressure on the pressure side equal to the pressure on the suction side at the trailing edge.

$$\gamma(N) = -\gamma(1) \qquad (11)$$

Insert formula (11) in (10); the equation system is solvable and we get the unknown strength of circulation.

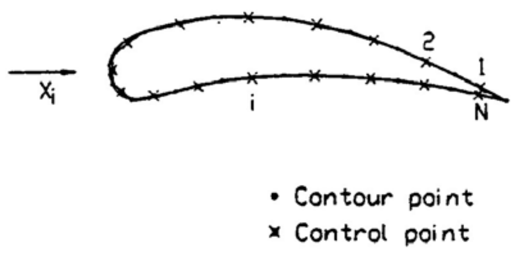

Figure 4. Distribution of contour and control points

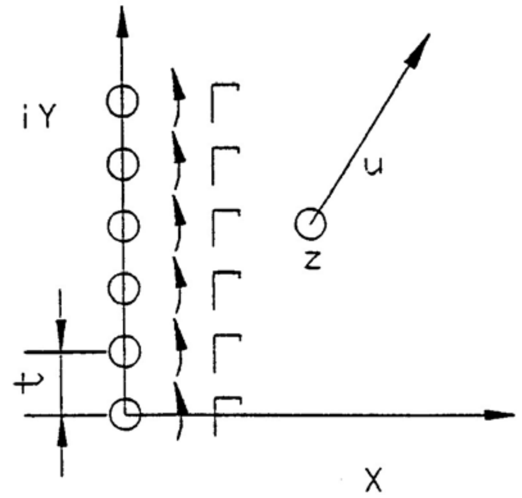

Figure 5. Calculation of the induced velocity of a vortex row on a point

3.5 Design concept

The design conditions implicit a high volumetric discharge rate and a low discharge head. To decrease the risk of cavitation, the nozzle is designed as a diffusor from the leading edge to the rotor.

The calculation method considers all interactions of the single components. A powerful singular method gives a good simulation stream characteristic, especially the pressure distribution. Factors correct the influence of the finite number of blades and the boundaries.

The nozzle is replaced in the calculation by vortexes with constant circulation around the circle. The rotor is simulated by a semi-infinite vortex cylinder.

This design tool was validated in different investigations [8-10]. A comparison of the latest investigations with the predicted behaviour is given in Fig. 6. The induced velocities of the rotor, the stator and the nozzle were confirmed. The calculated thrust of the nozzle was corrected with former experimental data. So it is possible to design every rotor-stator combination for an investigated nozzle with an acceptable accuracy. The cavitation behaviour will be predicted by a comparison of the local pressure with the vapour pressure.

4. DESIGN OF A LINEAR-JET FOR A PATROL BOAT

The KBN-Konstruktionsbüro Nord in Bremen developed a patrol boat for German country Saxon-Anhalt. After consultation of KBN a LINEAR-Jet was designed for this small and fast ship. The design speed is $V_S = 21.6$ kn. A model of this ship was investigated for the shipyard Genthin in the SVA Potsdam. The original design with two propellers at inclined shafts was compared with the new design with two LINEAR-Jets powered by Z-drives. For this design the shafts, the struts an the rudder were taken away. The tunnels of the boat were partly refilled to adapt the upstream and the downstream for the new propulsion system. The nozzles were partly integrated. Based on the geometrical and hydrodynamic mean data in Table 1 and 2 we get the mean design parameters in Table 3. The mean parameters of the rotor, the stator and the nozzle are summarised in table 4 and 5.

Table 1
Mean data of the patrol boat

				Propeller	LINEAR-Jet
Length	L_{PP}	[m]	:	13.20	
Breadth	B	[m]	:	4.00	
Draught	T	[m]	:	0.86	
Displacement	∇	[m³]	:	14.42	14.67
Wetted surface	S	[m²]	:	46.47	45.19

Table 2
Hydrodynamic data

Thrust	T	[kN] :	11.111
Ship velocity	V_s	[kn] :	21.6
Wake number	w	[-] :	0.049
Diameter of the rotor	D	[m] :	0.55
Number of rotation	n	[1/s] :	13.9
Draught of the shaft	h_0	[m] :	0.57

Table 3

Design data			
Advance coefficient	J^*	[-] :	1.383
Cavitation number	σ^*	[-] :	3.66
Total thrust coefficient	K_{TT}^*	[-] :	0.628

Table 4

Mean data of the LINEAR-Jet				Rotor	Stator
Diameter	D	[m]	:	0.55	0.55
Pitch ratio	P/D	[-]	:	2.086	25.95
Numbers of blades	Z	[-]	:	5	7
Diameter ratio	d_H/D	[-]	:	0.48	0.47

Table 5

Mean data of the nozzle			
Inner Diameter	D	[m] :	0.551
Length ratio	L/D	[-] :	1.2
Inflow diameter	Di	[m] :	0.589
Outflow diameter	Da	[-] :	0.482

Two LINEAR-Jets were manufactured in a scale λ =2.2 in SVA Potsdam. For the propulsion tests with the stock propellers, Gawn propellers 3.80 with following mean data were used.

Table 6

Mean data of the model propeller			
Diameter	D	[m]	0.130
Pitch ratio	P/D	[-]	1.4
Numbers of blades	Z	[-]	3
Area ratio	A_E/A_0	[-]	0.8

5. MODEL TESTS

Model tests were carried out to validate the prediction of the open water characteristic and to check the influence of the oblique flow on the open water characteristic and the cavitation behaviour. Additionally the influence of the strut for a Z-drive was investigated. Finally propulsion tests were carried out to compare a LINEAR-Jet configuration with a propeller configuration for a patrol boat. The cavitation tests were carried out in the cavitation tunnel of the SVA Potsdam. The torque and the thrust of the rotor were measured by a dynamometer located upstream. The propulsion tests were made in the towing tank of the SVA.

5.1 Open water characteristic

The LINEAR-Jet has a high efficiency for a width area of advance coefficients. The maximum efficiency of the model is about η = 70% (Fig. 6). Due to the induction of the velocities of the single components of the LINEAR-Jet, the inflow to the rotor is shockless for a width area of advance coefficients. Depending on the design, the combination of the nozzle and the stator delivers small resistance or small thrust in the design point. With a good adjustment of the components the stream of the LINEAR-Jet is nearly spin free (Fig. 7). Only behind the hub in the interior of the jet are higher tangential velocities. There is no flow separation at the nozzle.

For the characteristic of the engine, the torque characteristic has a good, flat shape. For these reasons, the LINEAR-Jet is suitable for fast ships with medium or fast rotating mean engines.

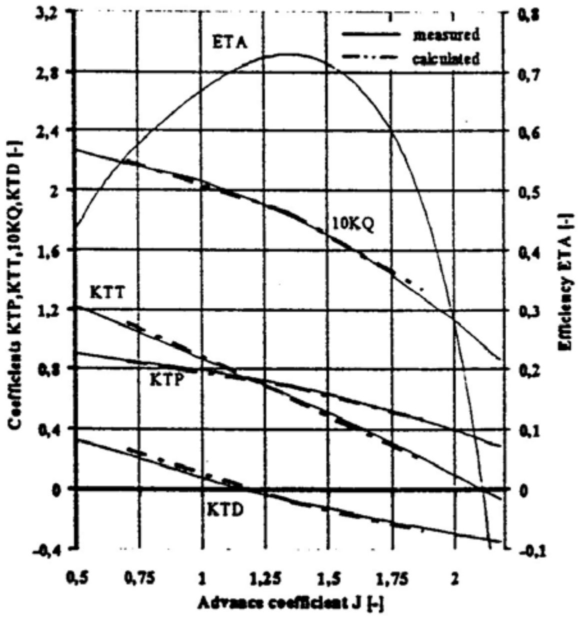

Figure 6. Calculated and measured open water characteristic

The rotor is normally powered by a gear box. So it is possible to drive backwards. Investigations show adequate backward behaviour of this system. The reason for that is the moderate contraction of the nozzle and the nearly axial orientation of the stator blades.

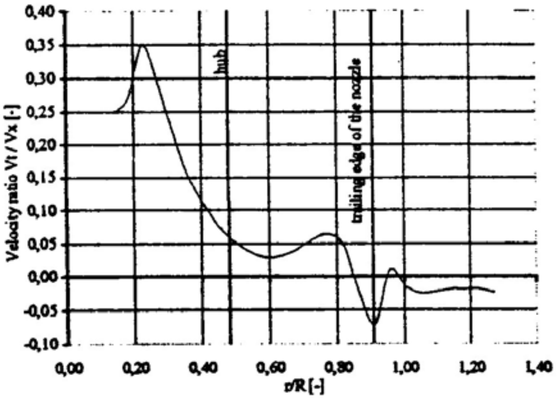

Figure 7. Tangential velocity behind the stator

5.2 Influence of the oblique flow

The influence of the oblique flow on the open water characteristic was investigated up to an angle of 5 degrees. The thrust and the torque of the rotor were nearly independent of the inflow angle in the investigated range. Only the thrust of the nozzle decreases, which was measured together with the stator. It decreases ca. K_{TD} = -0.014 per degree (Fig. 8). The cavitation behaviour is nearly independent of the angle. This is the effect of the nozzle, which guarantees an axial inflow for the rotor.

So it is possible to install the LINEAR-Jet at an incline shaft, without getting cavitation problems at least up to the investigated angle of 5 degrees.

5.3 Influence of the strut of the Z-drive

To simulate the influence of the partial blocking of the nozzle by the shaft of a Z-drive, a blade of the stator covered by a profile. The dimension of the profile is calculated by the minimum shaft diameter for full scale.

The influence of the covered shaft of the Z-drive on the open water characteristic is low. The torque coefficient increases from $K_Q = 0.179$ to $K_Q = 0.182$. The thrust coefficient of the propulsor decreases from $K_{TT} = 0.574$ to $K_{TT} = 0.568$ (Fig. 9).

5.4 Propulsion tests

For a comparison, propulsion tests were carried out with two CPPs type Gawn 3.80 (Table 6). The propellers were powered by an inclined shaft of 8 degrees. For the tests with the LINEAR-Jets, the lines were adapted. The tunnels were partly refilled to get an optimal inflow to the LINEAR-Jets.

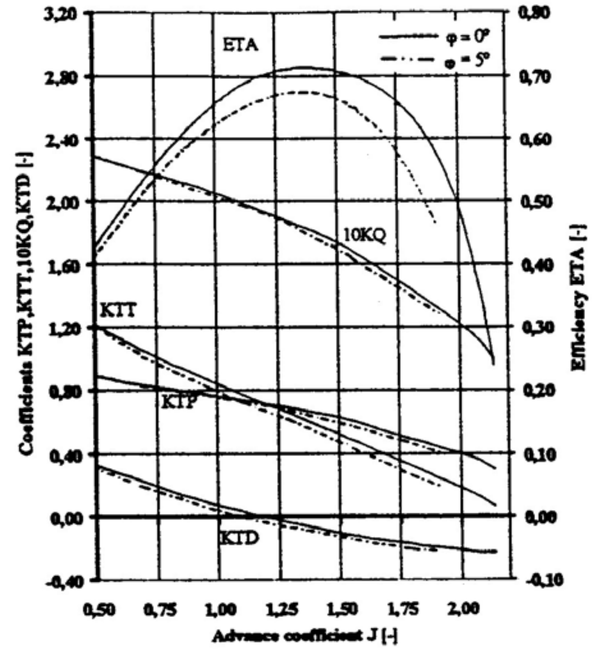

Figure 8. Influence of the oblique flow on the open water characteristic of the LINEAR-Jet

The Jets were partly integrated in the tunnels. For backward investigations, the LINEAR-Jets were rotated by 180 degrees.

The tests were carried out for the same draught. For the little difference in the displacement, the results of the tests were referenced to the Froude number related to the displacement.

$$Fn = \frac{V}{\sqrt{g\nabla^{1/3}}} \qquad (12)$$

The patrol boat with the LINEAR-Jets needs more power for low ship speeds. From V_s = 14 kn and higher, the configuration needs less power. For the maximum design speed V_s = 21.6 kn the new propulsion system needs 2.1 % less power as the conventional system with the propellers (Fig. 10).

There was not made any prognosis for the full scale ship. The difference of the needed power will increase for the LINEAR-Jet configuration. Due to a correction of the Reynolds number, the efficiency will increase for both systems. For the LINEAR-Jet system more, because rotor, stator and nozzle have to be corrected and for the propeller system only the blades.

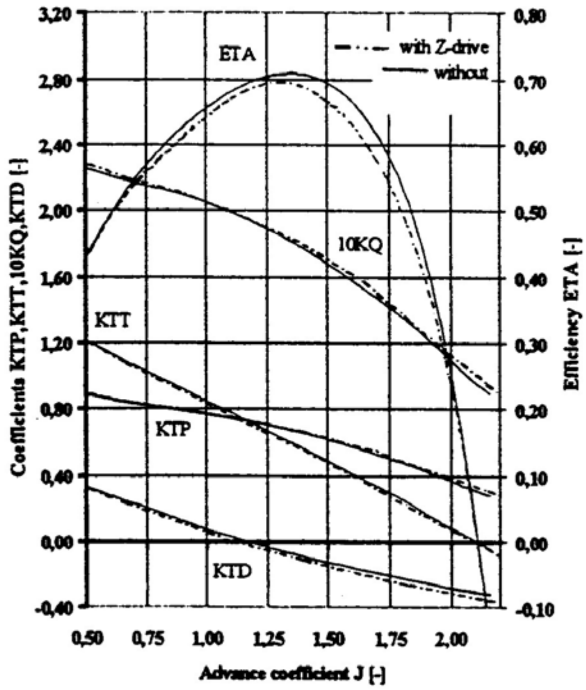

Figure 9. Influence of the Z-drive strut on the open water characteristic

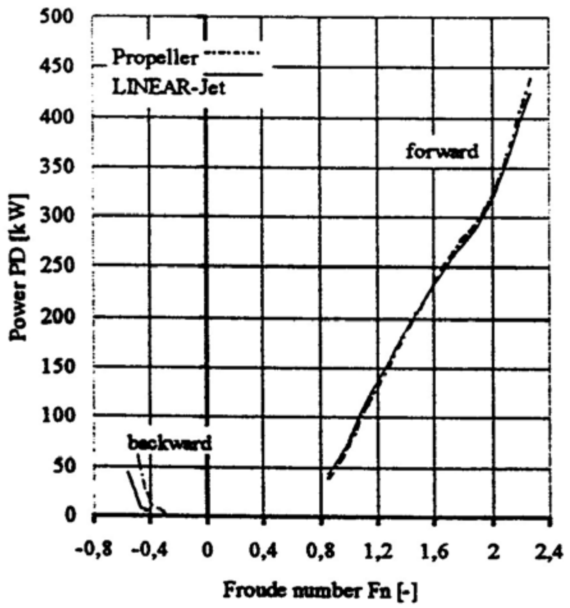

Figure 10. Propulsion tests

6. CONCLUSIONS

The propulsion system LINEAR-Jet was developed in different R&D projects as an alternative propulsion system for fast ships.

The LINEAR-Jet system has following mean advantages:

- High efficiency for a wide region of advance coefficients.
- Flat shape of the torque coefficient.
- Minimum loss because of low tangential velocity components.
- High safety against cavitation at the hub for a great hub diameter ratio.
- Rotor diameter can be reduced.
- Number of rotation can be lower.
- Lower noise level because of the nozzle, the nearly spin free stream and the low number of rotation.
- No additional resistance by inclined shafts, struts and rudders.
- Protection of the rotor by the nozzle.
- No cavitation on struts and rudders.
- Safety against cavitation by axial inflow to the rotor.
- The LINEAR-Jet can be used as a rudder propulsor.

Symbols

c	m	chord length
c_p	-	pressure coefficient
dn	m	diameter of the hub
D	m	diameter
Fn	-	Froude number
g	m^2/s	gravity constant
J	-	advance coefficient
K_Q	-	coefficient of the moment
K_{TD}	-	coefficient of the nozzle and the stator thrust
K_{TP}	-	coefficient of the rotor thrust
K_{TT}	-	coefficient of the total thrust
n	m	vector normal to the surface
nx	m	x component of n
[illegible]	m^2	Surface of the nozzle
t	m	tangential vector
t	m	gap between two profiles
T	N	trust
T_D	N	trust of the nozzle
V_s	kn	Ship speed
u	m/s	velocity
u_a	m/s	velocity vector of the inflow
u_{ti}	m/s	velocity inside the blade
u_∞	m/s	velocity vector of the inflow
u*	-	factor for the velocity
v	-	velocity
x_i	-	normalised co-ordinate
y_i	-	normalised co-ordinate
ρ	kg/m^3	density of the water
γ	m/s	strength of circulation
α	deg	geometrical angle of attack
[illegible]	deg	hydraulic angle of attack
η	–	efficiency
σ	–	cavitation number
Γ	m^2/s	circulation
∇	m^3	displacement

Indicees

a	-	position of an investigated point
w	-	position of a vortex

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