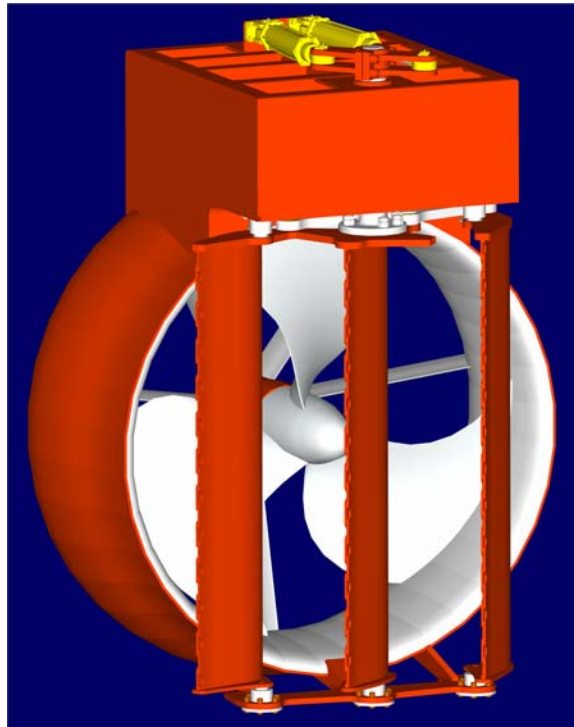


The Development and Application of High Efficiency Nozzles and Rudders

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ABSTRACT

Since 1933 when the Kort nozzle was invented, there has been very little change to the duct design. Netherlands Ship Model Basin (NSMB) performed systematic model tests of nozzles in the 1950's and nozzle 19a and 37 emerged as the standard. Established nozzle theory predicts a higher theoretical efficiency than a propeller alone even when the nozzles frictional drag is taken into account. However this was never accomplished with standard nozzle designs. There is a potential to close this gap between theoretical and practical application and to improve the efficiency of almost any type of vessel. Model tests of different nozzle sections show gains at lower speeds but fail to show gains at higher speeds of advance. The nozzle sections drag is many times greater than any standard NACA wing section and this difference has never been explained. In this paper the difference between nozzle theory and the practical application of standard nozzles 19a and 37 is explained as an effect of laminar separations due to the viscous drag on the model scale used during testing. This discovery, subsequent research, and full-scale trials lead to the development of the high efficiency nozzle.

NOMENCLATURE

- Q** - Quantity of water in unit time
- V_A** - Undisturbed velocity of the flow
- a** - Velocity increase at the propeller disk where velocity at the disk is $V_A (1+a)$
- b** - Velocity increase well behind the propeller where velocity behind is $V_A (1+b)$
- A_0** - Area of the propeller disk
- ρ** - Density of the water
- T** - Thrust of the nozzle and propeller
- T_P** - Propeller thrust only
- E** - Kinetic energy lost in the slipstream
- η_i** - Ideal efficiency of the nozzle and propeller system
- C_T** - Coefficient of thrust
- τ** - Ratio of the propeller thrust over total thrust T_P/T
- σ** - Velocity increase behind the propeller over the velocity increase at the propeller disk, b/a
- C_{DN}** - Coefficient of drag of the nozzle section
- F_Z** - Vertical lift force on the nozzle ring
- θ** - Angle of attack of the nozzle ring to the flow

INTRODUCTION

During the 1930's Kort was attempting to solve the problem of propeller wash causing soil erosion of riverbanks. According to propeller momentum theory only half of the increase in velocity of the propeller slipstream occurs at the propeller disk. The other half occurs in the slipstream behind the propeller (figure 1).

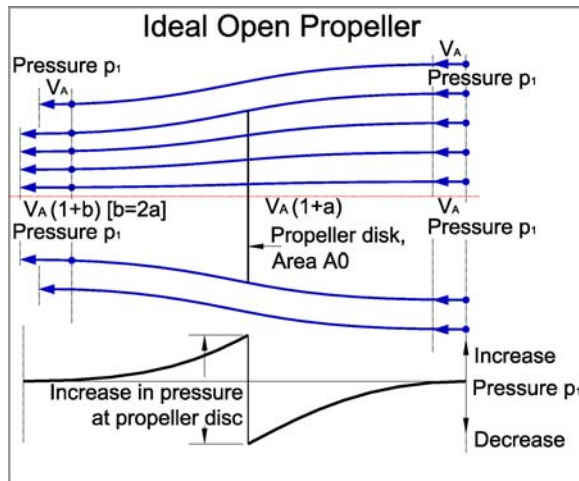


Figure 1. Propeller momentum theory - Open propeller

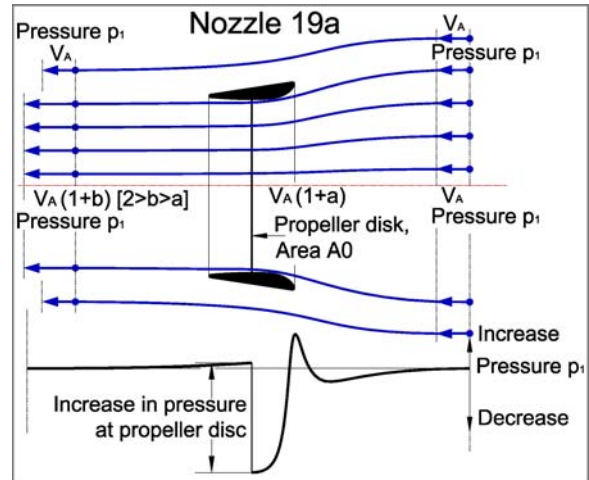


Figure 2. Propeller momentum theory – 19a nozzle

Kort reasoned that if he could prevent this slipstream contraction, the speed of the propeller wash would be reduced and with it the damage to riverbanks. Placing a tube around the propeller tips would prevent slipstream contraction (figure 2). To avoid flow separation on the leading edge of the tube, Kort flared the tube outward and added an outside cone. This altered tube became known as the Kort nozzle (figures 3 and 4). It has not been published if the nozzle was successful in reducing riverbank erosion; however, improved propeller performance was observed. Kort patented the nozzle in 1935 and the Kort Company maintained tight control over the application and marketing of the nozzle until the 1970's. Today nozzle 19a, which is fundamentally the Kort nozzle, is manufactured and widely distributed by many different companies.



Figure 3. A typical steering Kort nozzle – tug *Island Warrior*



Figure 4. *Island Monarch* with a modified Kort nozzle

THE DEVELOPMENT OF NOZZLE THEORY

It was not until the 1950's that theoretical work and systematic testing was performed on nozzle sections. In the simple nozzle model, a vortex ring surrounding the propeller tips represents the nozzle. The strength of the vortex ring represents properties of the airfoil section with a coefficient of lift of 1.0.

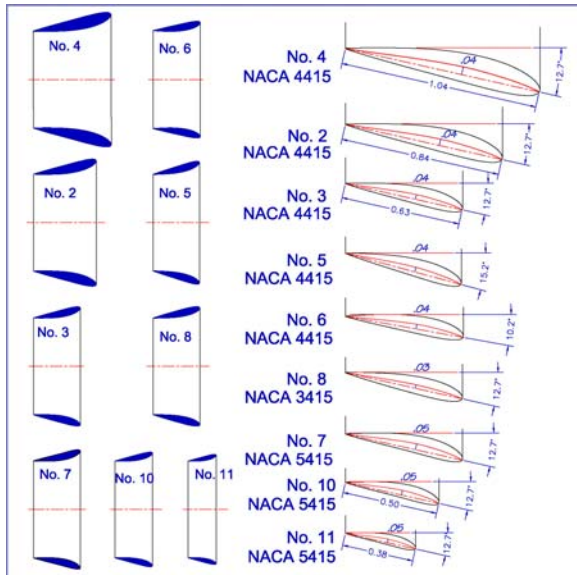


Figure 5. Nozzle series sections

Dr. J. D. van Mannen and members of the Netherlands Ship Model Basin (NSMB) performed the first systematic nozzle profile tests. Since the Kort nozzle was well established in Europe at the time, the NACA profiles selected for the test closely resembled the Kort nozzle (figure 5). The selected profile NACA 0015 with 0.15 thickness to chord ratio was used for all of the nozzles. This is an older NACA profile from before the theory of wing section was applied to profile

design and it is often used for the rudder section. By combining this basic symmetrical section with the camber, different profiles were generated. The location of the maximum camber was 0.40 chord length from the leading edge. The nozzle's chord to diameter ratio was varied as 0.5, 0.67, 0.83, 0.4 and 0.3. A section camber of 0.04 and 0.05 of the chord length was selected with one exception of 0.03. The section angle of attack was set at -12.7° with the exception of two cases, -10.2° and -15.2° .

The nozzle section selection was chosen to approximately match the previous experiences achieved with Kort nozzles. The section angle of attack was selected so the diffusion angle behind the propeller would not exceed 3.5° , as recommended by Dickmann and Weissinger in *Betrag zur Theorie optimaler Düsen-schrauben (Kortdüsen)* (1955). This is a very conservative limit since Kort nozzles used a strait cone for the diffuser. In the Venturi tubes where a continuously changing curvature is used, diffusion angles of up to 10° - 15° can be achieved without separation. Standard open B-series propellers were used in the tests.

The results from this extensive series of tests were published by J.D. van Manen in *Recent Research on Propellers in Nozzles* (1957). Although the theoretical model of a nozzle predicts an improved efficiency over the propeller alone, even when the frictional drag of the nozzle is taken into account, greater efficiency at a higher speed of advance was not achieved. This difference between the predicted outcome and the test results was explained as an effect of the nozzle section drag. However, the drag of the nozzle section is many times greater than an equivalent airfoil wing section.

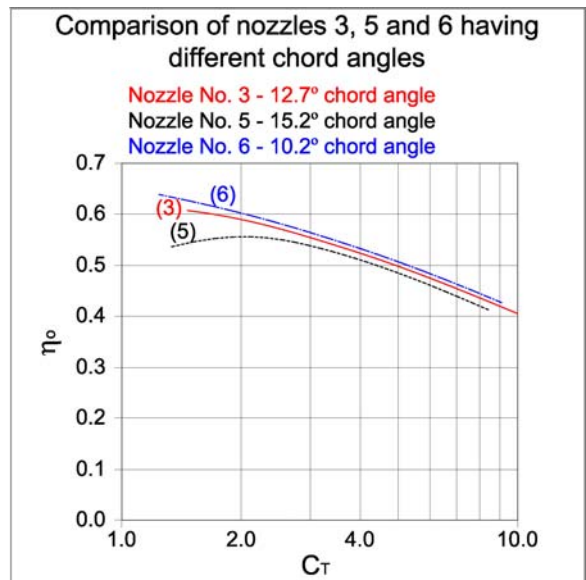


Figure 6. The effect of the nozzle section angle

An important trend is depicted in figure 6 where nozzle sections with different chord angles are compared. Increasing the negative angle of attack decreased efficiency while decreasing the negative angle improved efficiency. No attempts were made with a diffusion angle greater than 3.5° because of a self-imposed maximum. It should be noted that the NACA 4415 section is used for nozzles 2, 3, 5 and 6, which has an angle of zero lift equaling -4° . This means that the nozzle sections at -10.2° , -12.7° and -15° produce a negative lift, which is contrary to nozzle theory. At lower speeds with a high propeller loading and where flow converges toward the propeller, this angle of attack may become positive which would make the nozzle accelerating.

At a higher speed of advance with a lower propeller loading, when flow lines are close to parallel, the sections are operating outside of the operating range where flow will separate on the face of the airfoil; the outside of the nozzle surface. Negative lift will make the nozzles operate as decelerating nozzles.

A trend in efficiency is seen when comparing nozzles of the same section with different chord lengths (figure 7). Progressively shorter nozzles are more efficient at higher speeds with a lower propeller loading. The proportionally lower section drag of the shorter nozzles is the cause of the efficiency and not more efficient airfoils.

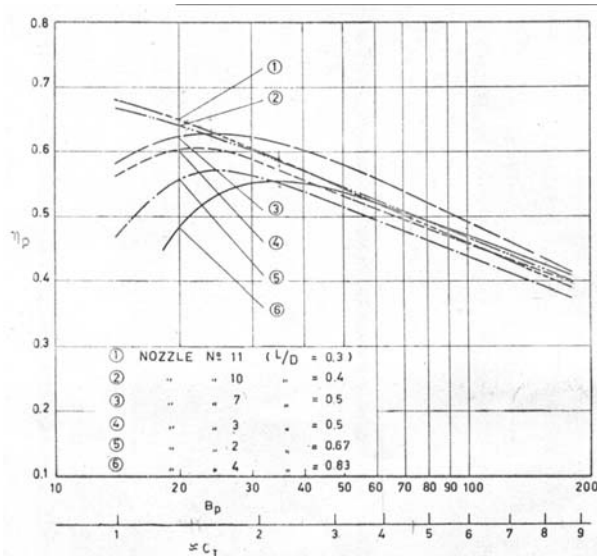


Figure 7. The effect of chord to diameter ratio

From the first series of tests, researchers concluded that there was no advantage to having nozzle sections longer than 0.5 of the diameter. Since a significant trend was not found, the next series (figure 8) used the same basic sections but the camber line was modified. The maximum camber was at 0.25 of the chord length from the leading edge instead of 0.4. This resulted in

sections 18, 19 and 20, which are even closer in resemblance to the section used by Kort. All three sections use the same parameters with the exception of maximum camber. The selected section angle of attack was 10.2° .

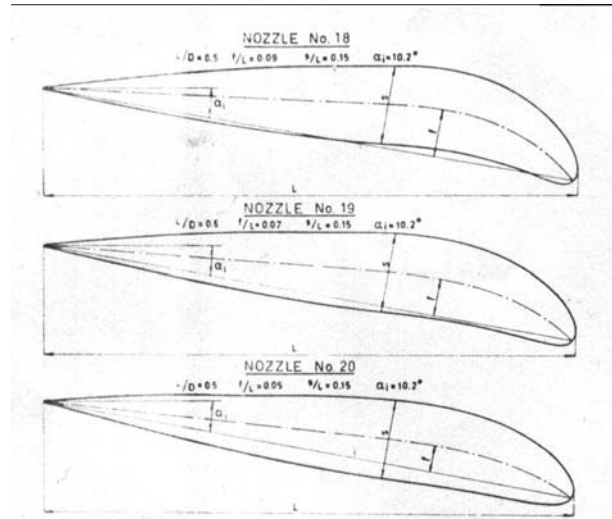


Figure 8. Second series of nozzle sections

For this nozzle series a new propeller was developed. It was modified from the Kaplan propeller used in hydroelectric turbines. These propellers are more effective with nozzles, than the B-series propellers and are widely accepted.

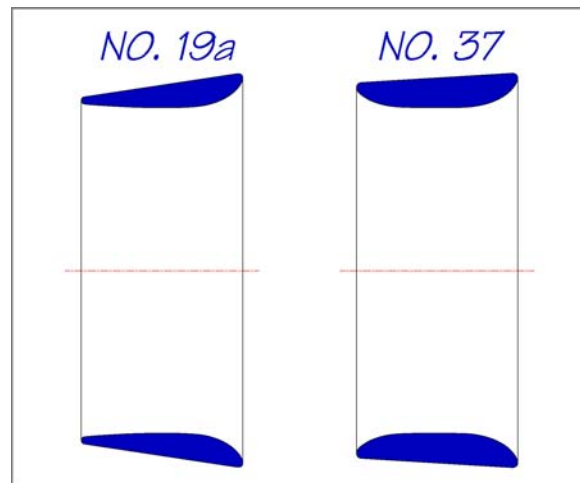


Figure 9. Nozzles no. 19a and 37

Since there was no difference in the performance of the three sections, section 19 was adopted as the standard. Modifications were made to this section by adding a trailing edge radius, straightening the outside section segment, molding a cylindrical section in the way of the propeller and creating a slight diffuser cone behind the propeller. This modified version became

what is widely known as nozzle 19a (figure 9). This section was later tested with a chord length of 0.8 and 1.0 (nozzle 22 and 24 respectively) because the chord length was more representative of the Kort nozzles of the day. Nozzle 22 and 24 had a marginally better bollard pull but was less efficient at a higher speed of advance.

Although Nozzle 19a was adopted as the standard by the industry, for ship docking work where astern performance is important, modifications were made by adding a flared section on the exit. This modification was tested as nozzle 37 (figure 9) and it had an improved astern thrust with a minor loss of thrust ahead. Test results of nozzles 19a and 37 were published and widely used to design nozzles and propellers. Many more papers were published on these two nozzles analyzing different aspects and applying different methods. Falcao de Campos presented interesting research in On the Calculation of Ducted Propeller Performance in Axisymmetric Flows (1983). A Doppler laser wake survey and paint tests were performed in a cavitation tunnel with nozzles 19a and 37, where flow separation on the outside nozzle surface was observed, even at moderate propeller loading. Also on nozzle 37 one segment was fitted with strain gauges to measure segment lift and drag forces. The results were that at higher speeds of advance and lower loading, negative lift and increased drag was measured.

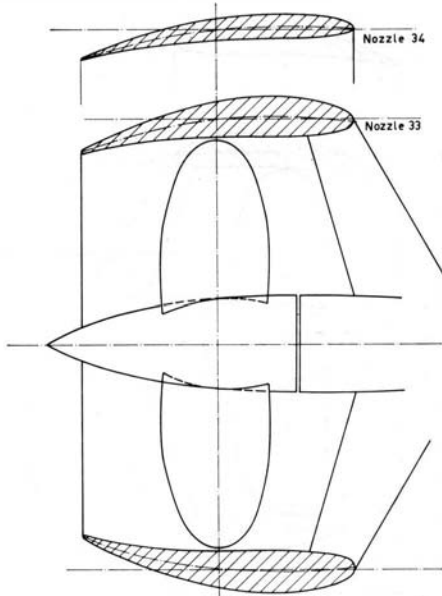


Figure 10. Decelerating nozzle no. 33 and 34

The results with the short nozzles 10 and 11 did not fit the accepted theory and no further tests were conducted on these nozzles.

Research was also conducted on decelerating nozzles, most notable nozzle 33 (figure 10).

Theoretically, decelerating nozzles have a lower efficiency than open propellers since they contract the propeller wake even more than an open propeller. From the published results it can be seen that the nozzles produce a positive thrust at a high propeller loading and low speed of advance. This causes the nozzles to operate as accelerating nozzles. It is interesting to note from the nozzles published coefficients of thrust at higher speeds that the resistance of nozzle 33 is lower than any accelerating type nozzle in the series.

In the accepted ideal nozzle theory an airfoil ring is placed around the propeller disk creating a positive or negative lift that can be represented by an equivalent anular ring vortex with a positive or negative circulation resulting in either an accelerating or decelerating nozzle. If the propeller is replaced with an actuator disk where losses due to rotation and friction are zero, momentum represented for the control volume in figure 2, quantity of the water Q passing through the disk in unit time is

$$Q = V_A(1+a)A_0$$

where A_0 is the area of the propeller disk and a is the increase in velocity at the propeller disk divided by the undisturbed velocity V_A .

The change of momentum in unit time is

$$\rho Q(V_A(1+b) - V_A)$$

where b is the increase in velocity at the sufficient distance behind divided by V_A . This is equal to thrust T of the nozzle propeller system.

$$T = \rho Q V_A b = \rho A_0 V_A^2 (1+a)b$$

For the open propeller $b = 2a$ while for the nozzle if $b < 2a$ then the nozzle is accelerating and if $b > 2a$ the nozzle is decelerating. Propeller thrust T_P is

$$T_P = V_A(1+b)A_0 V_A b$$

The kinetic energy E lost in the impeller slipstream is

$$E = \frac{1}{2} \rho V_A (1+a) A_0 (V_A b)^2$$

Ideal efficiency for the nozzle system η_i is

$$\eta_i = \frac{V_A T}{V_A T + E} = \frac{2}{1 + \sqrt{1 + \tau C_T}}$$

where,

$$C_T = \frac{T}{\frac{1}{2} \rho V_A^2 A_0}$$

$$\tau = \frac{T_P}{T}$$

Since the nozzle geometry is always fixed, nozzle thrust varies greatly with the C_T from positive at high values of C_T to negative at low values of C_T . This

representation is only meaningful for one nozzle geometry and one value of C_T . A duct that may be decelerating at low values of C_T may be accelerating at high values of C_T .

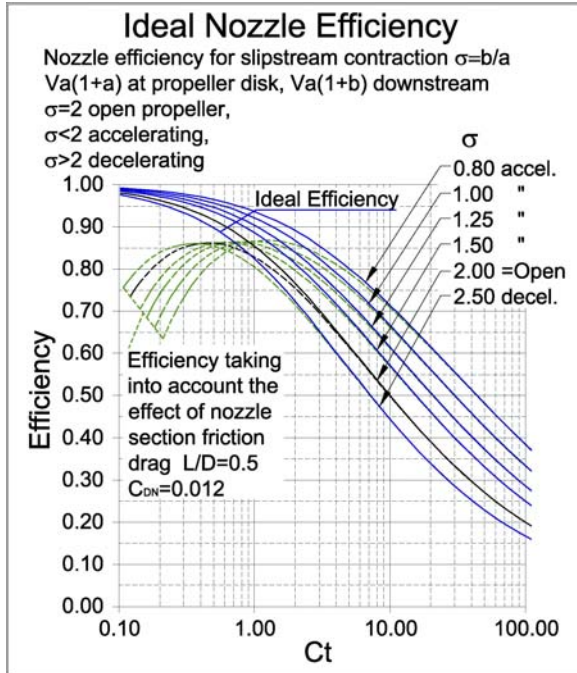


Figure 11. Ideal nozzle efficiency

For anything other than a very short chord length of the duct section, due to the three-dimensional effect of the nozzle ring, control volume through the nozzle in figure 6 can be more accurately viewed as the Venturi tube. Velocity in the Venturi tube is a function of the tubes cross section area along the length of the tube providing that there is no flow separation. It can be assumed that the velocity increase downstream will be constant relative to the increase at the propeller disk and we can designate

$$\sigma = \frac{b}{a}$$

where for the open propeller

$$\sigma = 2$$

From this duct system thrust T is

$$T = \rho Q V_A b = \rho A_0 V_A^2 (1+a) a \sigma$$

Propeller thrust T_p is

$$T_p = V_A (1+a \sigma) A_0 V_A b$$

The kinetic energy E lost is

$$E = \frac{1}{2} \rho V_A (1+a) A_0 (V_A a \sigma)^2$$

Ideal efficiency for the duct system η_i is

$$\eta_i = \frac{4}{\sqrt{\sigma(2C_T + \sigma)} - \sigma + 4}$$

For open propeller when $\sigma=2$ this reduces to

$$\eta_i = \frac{2}{1 + \sqrt{C_T + 1}}$$

The graph in figure 11 shows the effect of the factor σ on the ideal efficiency and the effect of the ducts frictional drag on the efficiency when ducts length is 0.5 propeller diameter and the coefficient of drag $C_{DN}=0.012$.

THE DEVELOPMENT OF THE HIGH EFFICIENCY NOZZLE

Expanding on the NSMB nozzle 11, new nozzle section was developed with a chord to diameter ratio of 0.3 (Figure 12). British Columbia Ferries Corporation showed interest in the nozzle and sponsored model tests in 1977, at the University of Michigan tank. Open water model tests showed an improved efficiency compared to nozzle 19a and efficiency comparable to nozzle 11, but the nozzle was not applied.

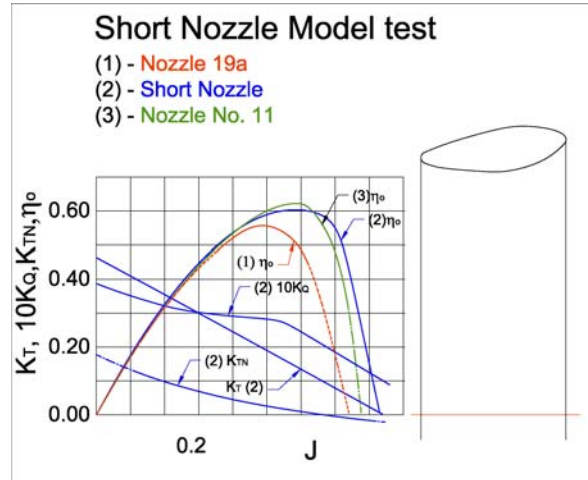


Figure 12. First short nozzle open water model test

Later while model testing Hydralift barge skegs, problems occurred with modeling the airfoil sections at the small scale. Section Reynolds number was far below the transition from laminar to turbulent flow. The profiles used for the skegs are wing sections and most wing sections suffer from laminar separation at low Reynolds numbers used in the model tests. To address the laminar separation problem it is common practice to place sand strip on the airfoil profile to create turbulent flow. This adjustment is similar to the method used in nozzle tests by NSMB to address the same problem.

However, the sand strip method is not verified to be effective in creating turbulent flow.

Applying the sand strips to the model of the airfoil section of the barge skegs did not help with the laminar separation problem. To determine what happened, a series of tests were performed, at BC Research tank, with different wing sections and different turbulence stimulators, at low Reynolds numbers. The tests showed that the use of turbulence stimulators only increased drag but did not improve the lift.

Only two informative on the subject of low Reynolds numbers wing sections were found; On wind tunnel tests of paper model airplanes (DeLaurier and Harris An Experimental Investigation of the Aerodynamic Characteristics of Stepped-Wedge Airfoils at Low Speeds (1974)) and wing sections of model airplanes (Profilpolaren für den Modellflug, Dieter Althaus, Institute für Aerdynamik und Gasdynamik der Universität Stuttgart). The graph in figure 13 shows effect of Reynolds number on section E475 and compares the NACA 0012 section with a thin cambered plate. Greater the sections chord thickness, more adversely is affected by laminar separation and transition happens at the higher Reynolds numbers. The only usable airfoil profiles under these conditions are thin cambered sections. A thin cambered section airfoil profile was successfully used during the model testing of the barge skegs. Unfortunately the section is not suitable for nozzle model tests because it has a narrow range of operating angles of attack. The flow direction in a nozzle changes with the speed of advance and load, meaning a nozzle would effective only at very narrow range of propeller loading. To achieve accurate results on the model scale, models would have to be much larger which is not practical. To avoid laminar separation, Reynolds number of the nozzle section should be above 500,000. This can be accomplished in a cavitation tunnel for higher speeds of advance or in wind tunnel but it is not achievable in selfpropulsion tests.

A way to test a nozzle section, open water or cavitation tunnel, at Reynolds number above 500,000 is needed. Selfpropulsion tests can be performed with a standard 19a nozzle and then values from the higher Reynolds number tests can be substituted. A wake survey should be done so that nozzle can be oriented into the flow. The propeller model is not as affected by the scale effects and corrections for the Reynolds number are sufficient. Laminar separation is not a problem because the blade airfoil section is very thin and the blade moves through the water at a higher speed than the nozzle.

For the new nozzles, a new skewed Kaplan type propeller was developed permitting more blade area without overlapping the blades. Experience with these propellers shows good performance and good vibration

characteristics. Also higher performance is achieved by the use of a 3-blade propeller even when the blade area ratios are up to 0.95. The blade tips are deigned to follow the nozzle profile to maintain constant tip clearance.

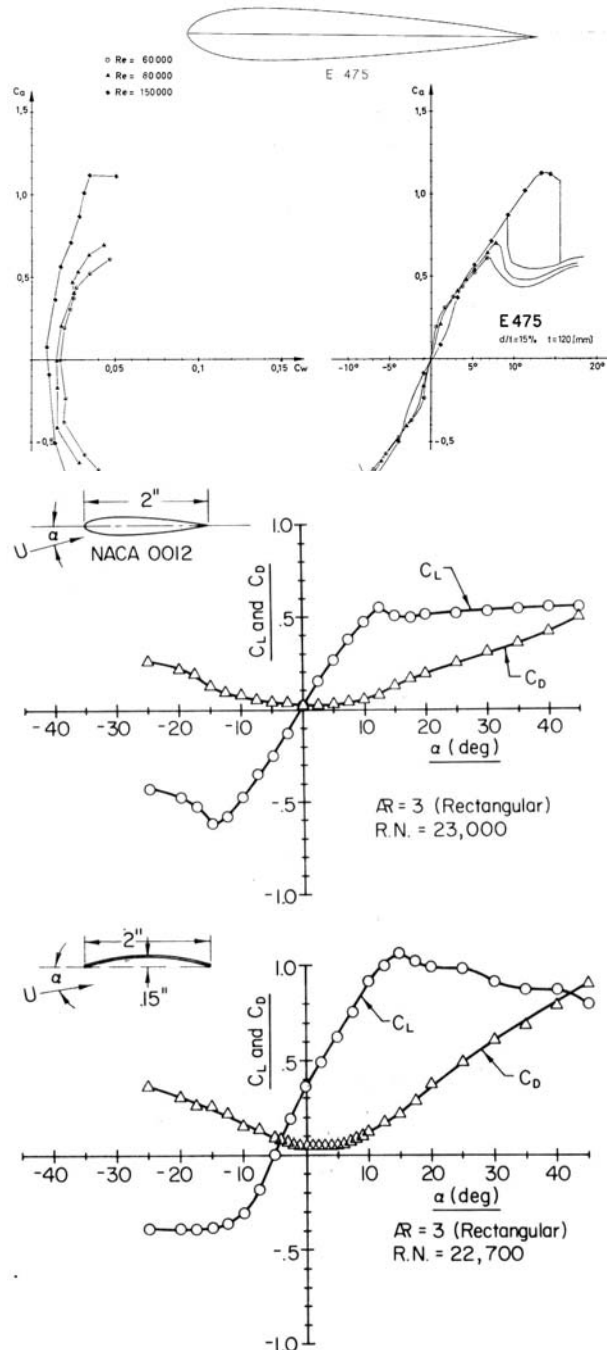


Figure 13. Low Reynolds Number wind tunnel tests

Many other studies and tests have been performed on a variety of nozzle sections, most of them relying on model tests, with inherited limitations. Some of the nozzles tested could have been more efficient at full

size; however, this efficiency cannot be shown on the model scale.

HIGH EFFICIENCY NOZZLE TESTS

While developing energy efficient tug/barge program during the last fuel shortage, there was an opportunity to perform open water and selfpropulsion tests on a model tug using an 8-inch diameter propeller. A nozzle model was made with the wing section LS(1)-421Mod (figure 15) and was compared to a nozzle 19a model. The tests were performed at the model tank of the BC Research Ocean Engineering Center. The graph in figure 14 shows the open water test results and comparisons.

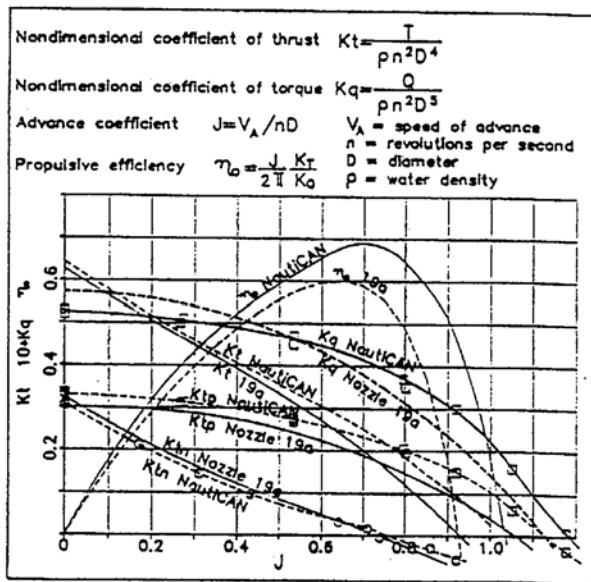


Figure 14. High efficiency nozzle model test results

Realizing it was not practical to verify the improved performance on the model scale, a decision was made to try the concept full scale. It would be too costly to make an airfoil profile nozzle with a continuous curvature on the inside and outside surface; therefore, a method of manufacturing where the nozzle was made of a 36-sided polygon was developed. The nozzle was made from 36 identical airfoil segments that were connected like LEGO pieces.

The wing section selected was LS(1)-421Mod. NACA LS(1)-417Mod and LS(1)-421Mod are low speed high lift sections optimized for maximum efficiency in turbulent flow and are suitable for the marine environment (McGhee, Robert J. and Beasley, William D. Wind-Tunnel Results for an Improved 21-Percent-Thick Low-Speed Airfoil Section. NACA Technical Memorandum 78650 1978 and Wind-Tunnel Results for Modified 17-Percent-Thick Low-Speed Airfoil Section. NACA Technical Paper 1919

November 1981). These sections have a high coefficient of lift, and a low drag over a wide range of angles (figure 15, 16).

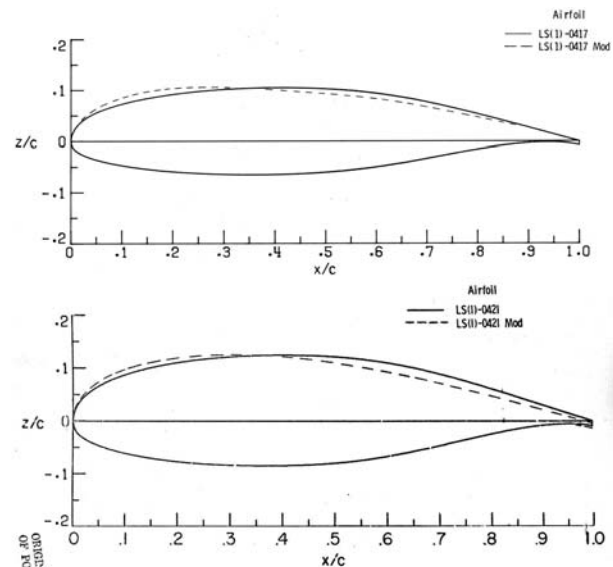


Figure 15. Wing sections optimized for turbulent flow

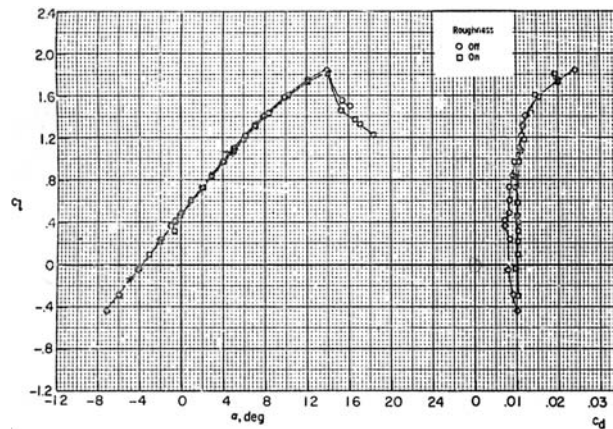


Figure 16. Properties of the LS(1)-421-Mod Wing section

Encouraged by the model tests and with an awareness of the tests limitations a 112-inch diameter nozzle was designed for the tug Larain, (figure 22). The nozzle was built using the 36-sided polygon method described above. The vessel was designed for shipberthing and bollard pull, both ahead and astern was important.



Figure 17. Manufacturing segmented nozzle

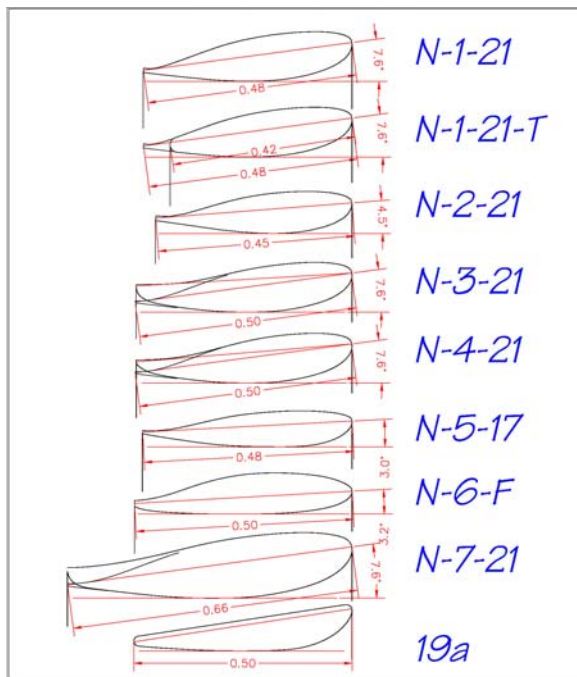


Figure 18. Full scale test nozzle section series

Assuming that a continuously curved inner surface would permit a greater angle of diffusion than 3.5° and considering the NSMB series results, where a less negative angle of entry resulted in greater efficiency, nozzle N-1-21 (figure 18) was designed with a chord length of 0.48 and a chord angle of 7.6°.

To improve astern performance, the section was truncated with the radius on the trailing edge to 0.42 chord length resulting in nozzle N-1-21-T (figure 18).

M.V. *Larain* is a single screw diesel electric tugboat built in 1958 by Gulf Point Shipbuilding. Its 120" x 99" 3-bladed open propeller is powered by a 750-RPM D.C. electric motor through a 4.1:1 reduction gear. Sea trials consisting of bollard pull, speed trials and maneuvering trials were recorded by BC Research before and after the installation of the nozzle. The electric power to the motor, motor RPM, vessel speed over the measured mile, and pull on the line were measured (figure 19 and 21). According to the tests, bollard pull increased 68% and free running speed increased 0.45 knots after the installation of the nozzles.

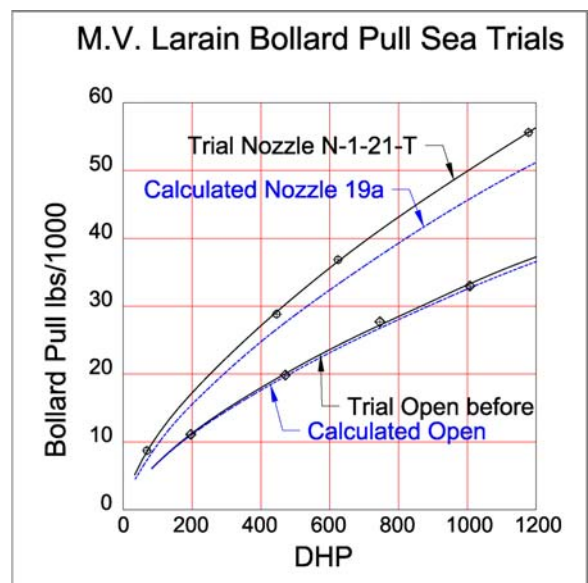


Figure 19. Bollard pull trial on the M.V. *Larain*

Encouraged by the positive results and by the great interest of the local towboat and fishing industry, a decision was made to modify the nozzle section for different applications, nozzle N-1-21 for tugboats towing barges and N-2-21 for fishing vessels where speed is important. Nozzle N-2-21 had a chord length of 0.45 and a chord angle of 4.5°.

From the sea trials and operator reports it could not be established if there was any difference in performance between the two nozzles. All the tested nozzles improved free running speed compared to an open propeller between 0.5 and 2.0 knots. On applications where Kort nozzles were replaced by high-efficiency nozzles, bollard pull increased 3-4% and speed increased 0.75 to 1.0 knots.

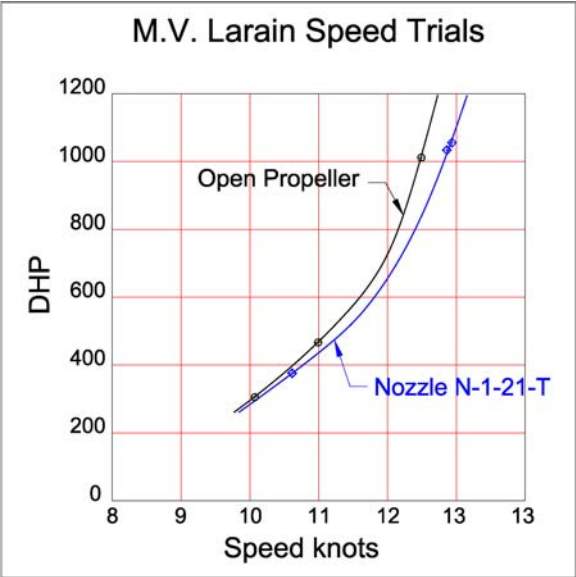


Figure 20. Speed trials on the M.V. *Larain*

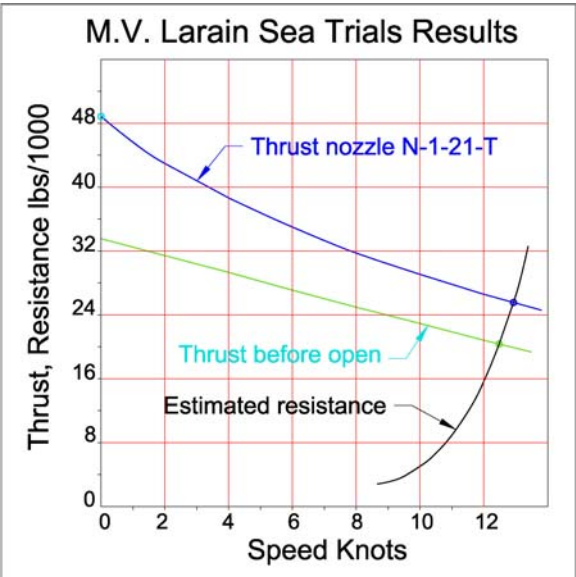


Figure 21. M.V. *Larain* before and after comparison

With the results of the first model tests at B.C. Research and the full size sea trial results, the BC Ferry Corporation was once again approached and plans were made for model testing. The aim of the project was to eliminate a vibration problem with the additional benefit of improving the efficiency.

A program of testing multiple combinations of nozzles and vessels was developed. The objective of the tests was to investigate the possibility of adding a deck and stretching the Burnaby class ferry, while using the existing engines and propellers. The existing engines are operated at 320 RPM and 3000 SHP. The same engines are capable of operating at 400 RPM and 3840 SHP. Using the existing KeMaWa5-blade C.P.

propellers with new blades and the existing engines would add up to great savings. However, in the possible case of excessive cavitation, a configuration as used on the Vancouver class was also considered. This consisted of repowering with 2 x 4500 SHP engines and reduction gears operating at 255 RPM and 4-blade C.P. propellers (figure 23).



Figure 22. M.V. *Larain* nozzle installation



Figure 23. *Queen of Burnaby* model nozzles

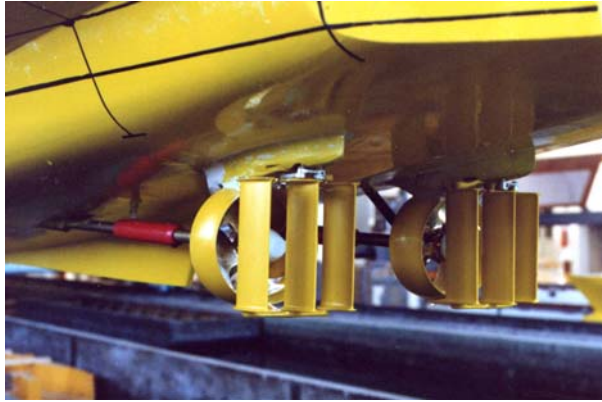


Figure 24. Ferry model with nozzles and rudders

These two possible configurations of the vessel prompted the construction of two 5-blade model nozzles for the 84-inch diameter propellers and two 4-blade model nozzles for the 102-inch diameter propellers. Both sets of models were to the scale of 1:17 for the selfpropulsion tests (figure 23). Since the models were too small and to avoid laminar separation, two additional 9.84-inch model propellers and one nozzle were built for the open water and cavitation tunnel tests, where higher Reynolds Numbers could be achieved (figure 25).

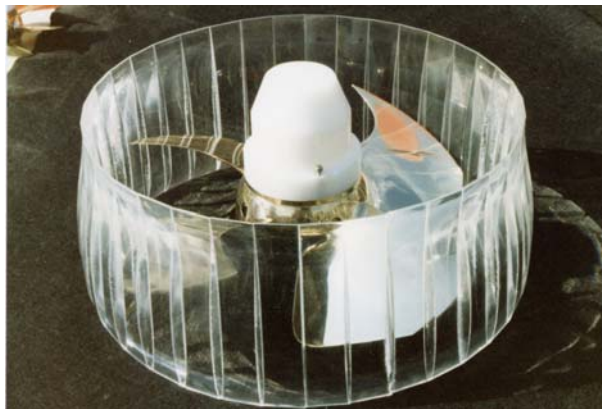


Figure 25. Nozzle model for cavitation tunnel tests

To address the concern of a possible reduction in maneuverability, a model of the existing rudders and two additional types of rudders were built: a set of Schilling type and high aspect ratio triple rudders per nozzle (figure 24).

For this application where an operating speed of 18 knots was required, a new nozzle N-5-17 (figure 18) was developed. NACA section LS(1)-417Mod with 0.17 chord thickness, 0.48 chord length and 3.0° chord angle was selected.

Model tests were performed at the Vienna Ship Model Basin. To overcome the problems with scale effects, a comprehensive testing program was developed. Open water tests were performed with the

new nozzle and nozzle 19a, at Reynolds numbers up to 150,000 and showed that there was little difference in performance. Another test was performed in the cavitation tunnel (figure 26 - 28) with the larger model. Reynolds numbers of over 500,000 were achieved and have demonstrated improved efficiency, with the nozzle N-5-17 (figure 27).

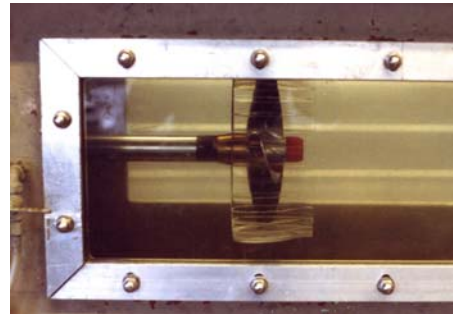


Figure 26. High Reynolds Number model test

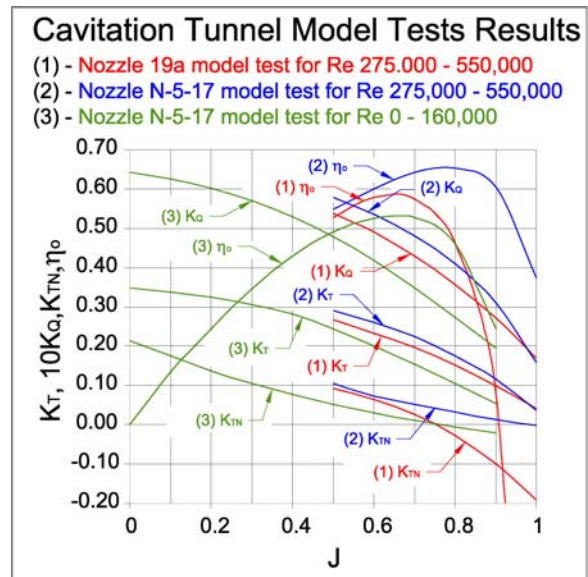


Figure 27. Reynolds number effect on nozzle model tests

The resistance of nozzle N-5-17 and 19a in the open water tests was also measured without a propeller. While at a Reynolds number of about 150,000 both nozzles had a coefficient of drag of about 0.17, at a Reynolds number of 580,000 the N-5-17 nozzles coefficient of drag decreased to 0.01 while the drag of nozzle 19a stayed about the same. The results can be verified from the NSMB series K_T - K_Q - K_{TN} design charts. At the point where propeller thrust $K_T=0$, a negative value of K_{TN} represents drag. An increase in drag at a low Reynolds number for nozzle N-5-17 is caused by scale effects and laminar separation while the drag for nozzle 19a is caused by not optimal wing section design operating at a -10.2° chord angle. This is

the reason why a full-scale performance of the 19a nozzles can be predicted so accurately using model test data. According to the test results, the efficiency with nozzle N-5-17, was predicted to be 12% higher than with an open propeller.

Unfortunately, the full size sea trials were disappointing. A top speed of 16.8 knots was achieved rather than the 18 knots predicted. This was compared to a top speed of 17.5 knots with the open propeller. At speeds above 16 knots, the ferry developed unusual low frequency vertical oscillations at a frequency much lower than the blade of the shaft revolution. A solution was not recognized at the time; therefore, the nozzles were removed. At speeds of up to 16 knots there was a dramatic absence of noise and vibration compared to the open propeller, even during crash stops. Also, acceleration and stopping were greatly enhanced by the nozzle.

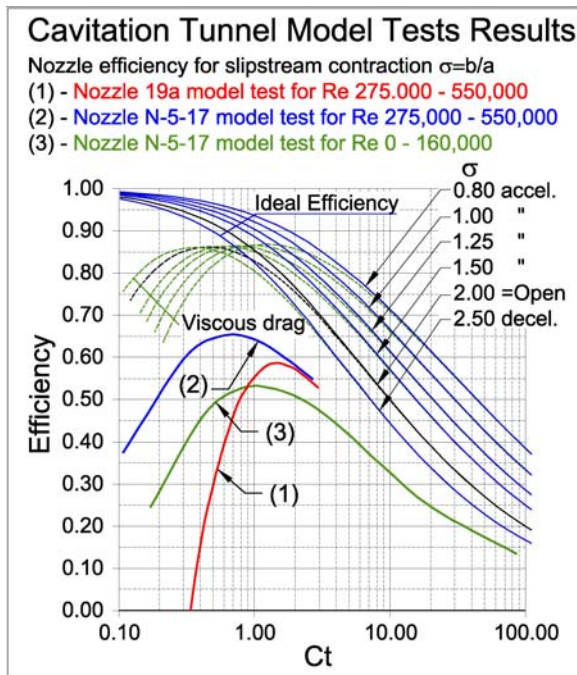


Figure 28. Reynolds number effect on the nozzle model tests

Considering that the oscillations were speed dependent, rather than engine or propeller revolution dependent, a possible conclusion is that the problem was caused by the nozzles orientation being installed concentric to the shaft axis and at the angle to the flow, about 6° . From the model tests of azimuthing thrusters (Results of Open Water Tests with Ducted and Non-Ducted Propellers with Angle of Attack from 0 to 360 Deg., by E. Mueller) with nozzles operating at the angle of attack to the flow, there is considerable loss of thrust and strong vertical force proportional to the angle of

attack and the speed of advance. This force F_z is function of the total momentum and angle to the flow θ .

$$F_z = (V_A(1+a))^2 A_0 \sin(\theta)$$

This nozzle has a high diffuser angle and at this angle could suffer unsteady flow separation causing the hull oscillation and resulting in increased drag.

This would account for the shortfall in efficiency of the nozzle. However, there has not been an opportunity to test this theory. The problem was not recognized on the model selfpropulsion tests because of the already high nozzle drag at the low Reynolds numbers. Flowlines tested on the model would have showed the problem. Installing the nozzle aligned to the flow at the angle of 6° to the shaft should have had the nozzle operating as predicted by the model tests.

The orientation of the nozzle operating at higher speeds has a great deal of influence on the performance and it has to be taken into account when designing high speed applications. High lateral forces on the nozzles operating at the angle to the flow are a reason why vessels with nozzles are difficult to turn.

A further nozzle section modification was designed for the tug *Barbara Foss*, (figure 29) which was being converted from the open propeller barge towing application to shipberthing. *Barbara Foss* had 2x 2150 SHP and 5-blade 110" diameter propellers replaced by high-efficiency nozzles and 108" 3-blade propellers. Ahead and astern pulls are very important and it was decided to modify section N-1-21. The nozzle chord length was rounded to 0.50 of diameter and the trailing edge curve was added to form a nozzle N-3-21 (figure 18). The nozzles were built using the same segmented construction method as all the other nozzles in the series.

Results of the sea trials were completely unexpected. The small change in the section profile near the trailing edge caused a dramatic change in performance. The predicted bollard pull of 133,000 lb was achieved with only 80% power. This bollard pull was acceptable however; the turbochargers were unable to operate while free running due to insufficient load to the engines. The propeller pitch was already 4% higher than with an equivalent nozzle 19a and had to be increased by additional 8% for a total of 12% more than an equivalent nozzle 19a. This resulted in bollard pull increase to 142,600 (appendix 1). Also the astern pull of 103,600 lb is considerably greater than what would be achieved with nozzle 37.

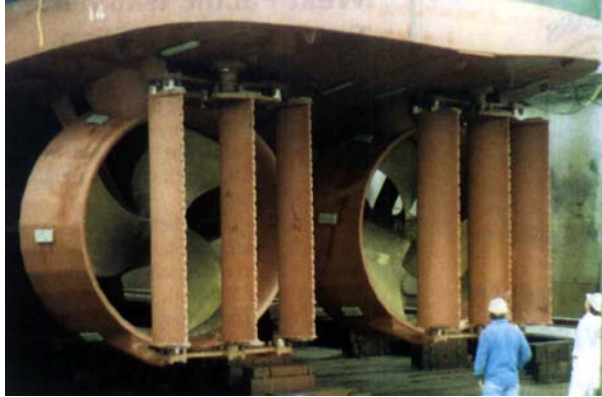


Figure 29. *Barbra Foss* with nozzle N-3-21

This performance was repeated on the sister ships *Jeffrey Foss*, *Phillip Foss*, *Moana Halo* and many other vessels. Since there was no speed penalty compared to nozzles N-1-21 and N-2-21, nozzle N-3-21 was adopted as the standard for all low and medium speed applications

From the flow momentum arising from the increase in propeller pitch, it is evident that nozzle N-3-21 is more “accelerating” than nozzle 19a and the other nozzles tested, (figure 30) resulting in greater efficiency. The nozzle was not only successful in preventing flow contraction but expanded the flow. This increased the momentum of flow and therefore efficiency. It is interesting that the same effect was not observed with sections N-2-21 and N-5-17, which had a reduced chord angle and a greater diffuser angle.

For Z-drives that do not operate in astern mode, nozzle N-3-21 was modified slightly at the tail end resulting in the nozzle N-4-21 without performance loss

The numbers of the segmented N-4-21 nozzles were built for Z-drives with equal success. One Z-drive manufacturer did not like this method for aesthetic reasons and contracted a conventional nozzle manufacturer to build the nozzles in a conventional way by spinning a single cylindrical plate with the rollers. This method did not produce an accurate enough section and did not perform same as the segmented nozzle. Propellers had to be pitched down to that of nozzle N-1-21 at a great expense. With this method of manufacturing the nozzle profile was approximated with a leading edge pipe and it had a flat section in the way of the propeller that was unreachable by the rollers. Additionally the section profile inside the nozzle could not be accurately produced due to the limitations of this method deviating up to $\pm 0.3\%$ of propeller diameter from the designed profile. This prevented flow from expanding and resulted in lower efficiency. The outside surface was even less accurate and may have increased nozzle drag.

Since the first successful application in 1987 a large number of vessels have been fitted with high

efficiency nozzles. One highlight worth mentioning is the installation of nozzles N-4-21 on the cable laying ship *C/S Agile* (figure 31). The nozzles and new CP blades have improved the vessels speed from 10.5 to 12.5 knots. In every situation where trials are possible, improved efficiency is demonstrated. However, most of these applications are still for low speed vessels like tugboats, fishing boats, and passagemaker yachts.

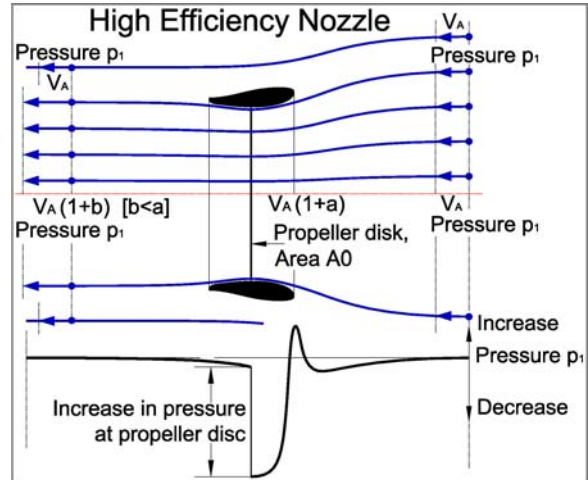


Figure 30. Propeller momentum theory – High efficiency nozzle with expanding flow



Figure 31. *C/S Agile* with nozzle N-4-21



Figure 32. *F/V Harmony* with a 23 knot operating speed



Figure 33. F/V *Harmony* with an integrated N-6-F nozzle propulsion and steering unit

One exception is F/V *Harmony* (figure 32), a 47' semi-planing hull fitted with an integrated unit consisting of 32" N-6-F nozzle, stators, and triple rudders. This nozzle operates at the load factor C_T of about 1.0. From momentum theory, the area of the flow at the distance ahead is $A_0(1+a)$ or about 1.20 of the propeller area. This was used for the entry area of the nozzle. The outside surface of the nozzle is designed for minimum resistance and to avoid flow separation. The vessel cruises at 23 knots. This speed compares favourably to the same hull powered by an open propeller. The unit was designed for a shaft angle of 6°. At these high speeds, it is important that the nozzle is aligned into the flow and the propeller axis was at an angle of 6° to the nozzle axis. This resulted in greater propeller tip clearance and some performance loss. When the unit was installed (figure 33), it was inclined together with the shaft an extra 2° resulting in an additional penalty. One big advantage of this boat compared to boats with the open propeller is seen when the boat is carrying a full load. The open propeller boat loses speed while the nozzle-equipped boat maintains the same high speed.

An earlier attempt at higher speed with the 47' aluminium shallow water shrimper (figure 34), with 600 SHP, was partially successful. The builder tried three different jet drives, but the boat could not achieve planing speeds. A full tunnel propulsion and steering unit using 27" nozzle section N-5-17 was developed, while the hull was lengthened 4 feet. The light vessel speed increased from 11 knots to 17. At the point when the vessel started planing at 17 knots using only 60% power, the tunnel vented through the nozzle mounted flush on the transom causing water in the tunnel to drop losing thrust. The problem could be solved by extending the tunnel aft and sealing the rudders to prevent venting. The owner accepted the boat as is on account that it will save fuel. Fully loaded and in shallow water, where planing was delayed, speed increased to 20 knots from 7 knots with a jet drive.

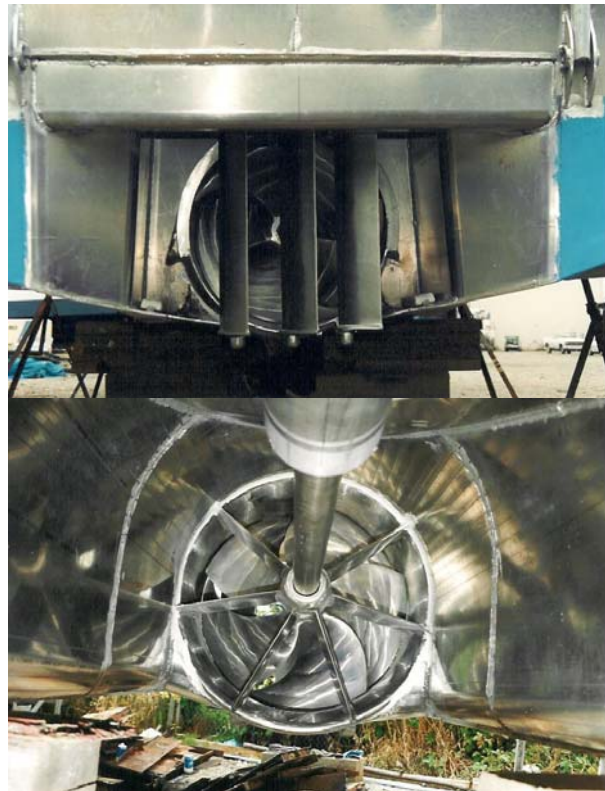


Figure 34. Shallow draft tunnel with a propulsion and steering unit installed

HIGH EFFICIENCY NOZZLES WITH PRE-SWIRL STATORS

High efficiency nozzles have further been improved by adding pre-swirl stators ahead of the propeller. The stator blades replace conventional struts to support the stern bearings or to support the nozzle in the case of Z-drives (figure 35). Stators increase the propeller thrust by removing rotational losses in the propeller wake. Gains in efficiency are comparable to a contra-rotating propeller without the added complexity.

Pre-swirl stators induce just the right amount of inflow rotation in the opposite direction of the propeller rotation. The propeller rotation then straightens this flow, which produces extra thrust. In trials, on *Daniel Foss*, bollard pull increased to 93,000 lb from 90,000 lb after stators were added.

Tug Philips Dunlap (figure 36) with 120" N-4-21 nozzles, stators and rudders achieved an unprecedented bollard pull of 178,000 lb and a free running speed of 15.5 knots (appendix. 1).

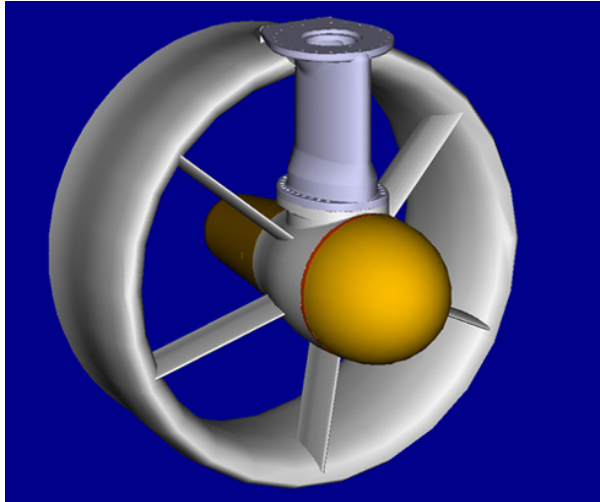


Figure 35. Z-drive with nozzle N-4-21 and stators

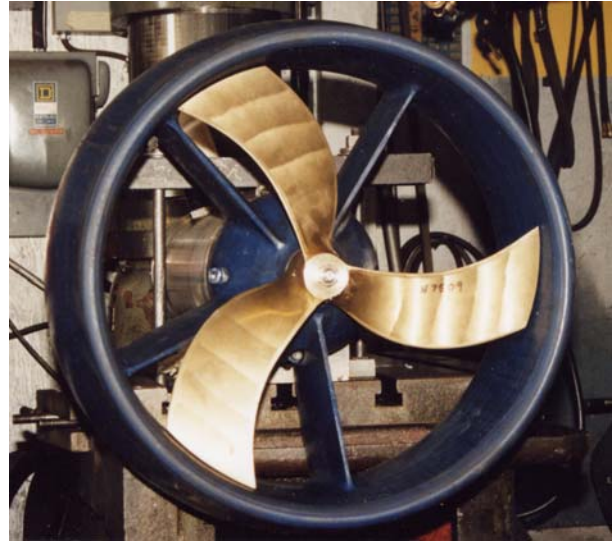


Figure 38. Electric thrusters for tourist submarine



Figure 36. *Phyllis Dunlap* with high efficiency nozzles and stators



Figure 37. Passagemaker yacht *Karvi 47* with nozzle and stators

High efficiency nozzles with stators were also fitted to passagemaker yachts (figure 37) to increase the yacht range and to the electric thrusters used on tourist submarines to extend the batteries life (figure 38). High efficiency nozzles with pre-swirl stators are ideally suited for large cargo ships where an increase in propulsive efficiency by 10-25% is possible. At the same time stators increase the strength and integrity of large nozzles. The vessel safety will also improve by reducing stopping distance.

NOZZLES WITH HIGH ASPECT RATIO TRIPLE RUDDERS

Nozzle equipped vessels resist turning because of the momentum of water flow through the nozzle. Vessels fitted with nozzles usually compromise their maneuverability. To solve this problem, the high performance triple rudders system was developed.



Figure 39. *Island Monarch* with triple rudders fitted to a conventional nozzle

By using differential linkage and unique geometry, the entire propeller outflow is deflected up to 60

degrees to the side with very little loss of thrust and without loading of the engine. This deflection makes it possible for even large vessels and barge trains to make tight turns.



Figure 40. *Neva Straights* fitted with a high efficiency nozzle and rudders for barge pushing

Twin screw vessels equipped with triple rudders are able to "walk" sideways at a speed of up to four knots and even greater maneuverability is achieved when twin screw vessels have separate steering gears.

Triple rudders are best suited for vessels towing, pushing, ship berthing, large ships operating in confined waters, or vessels performing other demanding applications.

The triple rudders, nozzles, and propellers can be assembled and installed as an integrated propulsion/steering unit (figure 41). This solid unit has proven to be durable even in strenuous shallow water and ice conditions.

A recent installation of triple Rudders on the tug *Island Monarch* (figure 39) has proven to be extremely effective. The vessel is fitted with an Intercon system and it is pushing a new oil barge. Existing tugs nozzles are modified Kort type Nozzles.



Figure 41. Integrated Propulsion and steering unit

SHALLOW DRAFT APPLICATIONS OF HIGH EFFICIENCY NOZZLES

The first riverboat application of High Efficiency nozzles was on the pushboat *Lanti* (figure 42). It needed new nozzles to replace worn out Kort nozzles while keeping the same rudders and flanking rudders. The original Kort nozzles chord length was 0.8 and therefore, nozzle N-7-21 was selected with LS(1)421Mod wing section with 0.66 chord length and 7.6° chord angle. The trailing edge was modified the same as the nozzle N-3-21. The tug operated on a river in Western Africa and has reported a towing speed increase from 10 MPH to over 11 MPH.



Figure 42. Pushboat *Lanti* with high efficiency nozzles

Another application has been for the McKenzie River on the Canadian North. In the past 3 years five river pushboats were fitted with high efficiency nozzle sections N-3-21 resulting in a greatly improved performance and a reduction in vibration and cavitation (figure 43 and 44).



Figure 43. NTCL pushboat *Marjory*

The most significant breakthrough was achieved when high efficiency nozzles were integrated with triple rudders. The most recent refit to the quad screw pusher-towing tug, *Edgar Kotokak* included new engines, integrated nozzles, and triple rudders (figure 45). This refit has provided an entirely new approach to shallow draft river transportation. It is proven so successful that sistership *Henry Christoffersen* is undergoing the same conversion.



Figure 44. NTCL pushboat *Nanakput*

Edgar Kotokak is a 153-foot long vessel, with a 3'-9" draft and is one of four quad screw shallow draft tugs that operate mostly on the Mackenzie River in Canada's Northwest Territories, with some work in the Beaufort Sea when the ice breaks up. Two of the tugs have type 22 Kort nozzles, the usual profile for shallow draft applications, and the other, *Henry Christoffersen* is undergoing the conversion to a high efficiency propulsion-steering system.

The total engine power on the *Edgar Kotokak* increased from 4500 hp to 5640 hp, and the bollard pull trials showed obvious improvement from 60,000 lbs to over 100,000 lbs (figure 46). The trials' data shows that the high efficiency nozzles produce more thrust at the same horsepower, almost 60% over the open propeller and 10% over the Kort nozzle at 4400 hp.



Figure 45. Pushboat *Edgar Kotokak* starboard side with integrated nozzles and steering units

Speed trials had to be halted at 14 knots when the bow began to submerge compared to the two Kort Nozzle vessels that only achieve 12 knots. After the first season the operator reported saving a day and a half on an 1100 mile trip with loaded barges down the river. He also saved was three days worth of fuel.

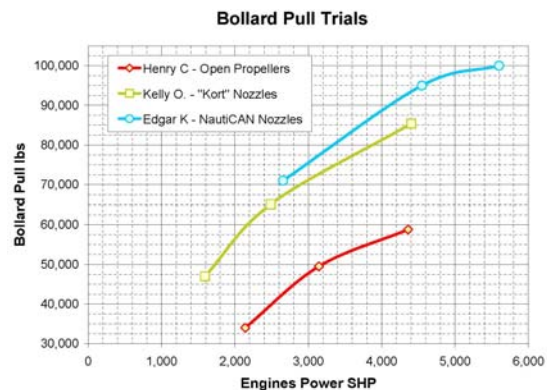


Figure 46. *Edgar Kotokak* bollard pull trials

Tugs typically push two rows of three barges about 700' long by 165' wide tow. The savings in fuel and time comes from the efficiency of the nozzles but even more from the effectiveness of the rudders. When turning corners down stream it is common practice to drive one side ahead using the rudders and other side astern, burning fuel. The Mississippi boats are fitted with the flanking rudders specifically for that purpose. There are also rapids at four locations along the river where the tug has to stop and tie off some of the barges. To achieve this, 180° turn must be made upstream. The other vessels, with conventional rudders, have to start turning the tow 1/2 to 1/4 mile before, running one side ahead and the other astern. With the *Edgar Kotokak* the turn is made instantly when needed using only rudders.

This installation is the first shallow draft application of the triple rudders and the first application of the integrated nozzle-steering unit. In the case that new vessels will be built, the propulsion unit will also incorporate the stators.

WORLDWIDE APPLICATIONS

In 1997 a license was given to a company in the Netherlands to manufacture and market nozzle N-3-21 in Europe. They have built hundreds of these nozzles and most of them are used on the rivers in Europe.

On one application, trials were performed for Dutch river authorities where two sister ship tug/cargo vessels were tied in the same tow and trials then performed one vessel at the time. One was equipped with an N-3-21 nozzle and other with an Optima nozzle, which is a modified nozzle 37 and marketed as high performance. The results were that N-3-21 performed at 15.6 km/h while nozzle 37 only reached 14.3 km/h (figure 47).

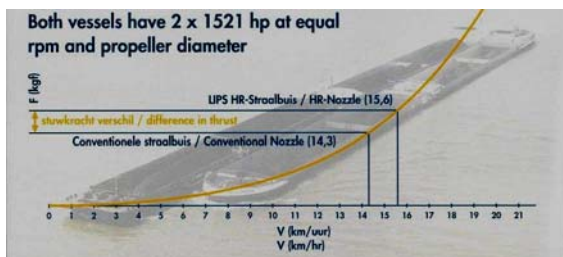


Figure 47. N-2-21 nozzles achieved 15.6 km/h versus a 37 type nozzle at 14.3 km/h

CONCLUSION

For many decades the full potential of nozzles was not utilized. After many years of research, nozzle performance fell short of what was theoretically predicted. Most of the research was performed on scale

models where the influence of laminar separation at the low Reynolds Number was not correctly taken into account.

It has been shown here that the model scale nozzle does not perform at higher speeds of advance to the full theoretical potential, regardless of the wing profile used. At full size, nozzle performance depends on the section profile used and is capable of operating efficiently at speeds that up to now were thought to be unattainable.

It is also shown that a small change in the nozzle profile can dramatically improve performance or equally degrade the performance.

Incorporating stators improves the nozzle efficiency and high aspect ratio triple rudders greatly improve the vessels effectiveness and safety. Nozzles can be manufactured as integrated units with the triple rudders, stators, and bearings, which saves a great deal of shipyard time.

High efficiency nozzles with stators are ideally suited for Z-drives and Azipods to improve efficiency, tracking and maneuverability at higher speeds while reducing vibrations. However there is a great reluctance from the manufactures to change. Nozzles with stators are also ideal for submarines and SWAT vessels with submerged cylindrical hulls to improve performance and provide protection for the propellers and large ships with stern bulb or cone. Also nozzles will improve tracking and reduce pitching.

On applications of high efficiency nozzles with stators and triple rudders for large tankers and other large ships, performance improvements of 15-25% are possible, while reducing vibrations and improving safety. A tanker with the nozzles will stop in much shorter distance.

More research is needed to maximize nozzle performance by testing in a large cross-section high speed cavitation tunnel or in wind tunnel were full size Reynolds numbers could be achieved and in full scale trials.

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Discussion by J.B.Hadler – Webb Institute

“The Development and Application of High Efficiency Nozzles and Rudders” by Josip Gruzling

I would like to open my comments by complimenting the author on an interesting paper that enhances our knowledge of the hydrodynamic of ducted propellers and focuses on some of the problems of scale effects on model testing of such devices.

In my research work at Webb Institute I am constrained to the use of small models where turbulence stimulation is essential. A few years ago, in conjunction with my students, I ran tests on 5 ft models of a number of Series 60 parent hull forms. I tried trip wires, sand strips, various sizes and spacing of studs and Hama triangles (Reference 1). I compared the results with those produced with 20 ft models at DTMB. I found that only studs of a certain size and spacing and the Hama triangles stimulated the requisite amount of turbulence (Reference 2). The studs have the disadvantage that they produced parasitic drag, which has to be estimated, whereas the Hama triangles, which are designed to be within the boundary layer, produce minimal parasitic drag. As a consequence of this experience, and further testing on other models where we knew the results from other towing tanks, we now use exclusively this form of stimulation. Our work up to this point has been limited to drag. In the case of foils it is also necessary to consider the scaling problem on lift. I would like to bring to the attention of the author a paper by Lewandowski (Reference 3) where he used Hama triangles to stimulate turbulence on lifting foils.

I would also like to comment on the unusual method of construction of the full scale nozzle using segmental sections, followed with a question. The use of 36 separate sections attached like “legos” means that the structure must be very rigid particularly on the inner face where the pressure pulses from the propeller are acting. I had the experience a few years ago on the repair of a 19a nozzle on a product carrier where the inner surface of the nozzle was failing due to the pressure pulses from blade passage. It turned out there were insufficient stiffeners within the nozzle structure. A segmental construction should preclude such a problem arising. I would like to know if this method of construction is more expensive than that employed in the manufacturing of a conventional 19a nozzle. Also have you noted any hydrodynamic problems arising from propeller-nozzle interaction with the segmental section nozzle?

In closing I would like to thank the author for presenting to the profession the results of their research and the subsequent development of an enhanced performance propeller-nozzle system.

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