Design, Analysis and Development of Waterjet Propulsion System

[1]Zain Hamdani, [2]Shaheryar Abid, [3]Sheheryar Iqbal
Aeronautics and Astronautics Department, Institute of Space Technology, Islamabad 44000
[1]zainhamdani.89@gmail.com
[2]shaheryar93@live.com
[3]sheheryar15@gmail.com

Abstract-This project envisages the development of a propulsion system for a watercraft which functions by ingesting water through on board pumps and ejecting it rearwards with a surge in momentum. This type of propulsion offers paramount advantages over other types for applications in water craft designed for operation at high speed, for employment in shallow or polluted waters, for safety of life against propeller injury and for better handling at all speeds. In order to examine the performance of the designed water jet system while keeping in view the ship speed and thrust requirement, the components such as inlet, nozzle and pump are designed, analyzed and optimized iteratively. The head and flowrate requirements of the system are established by drawing the pump resistance curves. The pump resistance curves are obtained by calculating the inlet and outlet loss coefficients from empirical relations. These values of head and flow rate are used to compute the specific speed of the pump, which then determines the type of the pump.
In this case, a mixed flow pump has been employed. The power requirements of the pump determine the specifications of the power plant necessary for driving the pump. The characteristic velocities are calculated through basic design parameters such
as momentum wake fraction, jet velocity ratio and inlet velocity ratio. These characteristic velocities and flow rate are then used to calculate the dimensions of the propulsion system. The design and optimization of the system units such as the intake, the pump and the nozzle whilst ensuring cavitation free operation is a major hurdle in the design of the water jet systems with high propulsive efficiency.

Key words: Pump, nozzle, power plant, specific speed.

I. NOMENCLATURE

T:	Thrust
ρ:	Density
V_{out}:	Nozzle outlet velocity
V_{in}:	Engine inlet velocity
η_p:	Propulsive efficiency
P_{shaft}:	Power delivered by the engine through shaft
W:	Momentum wake fraction
V_{ship}:	Vehicle velocity
μ:	Jet velocity ratio
IVR:	Inlet velocity ratio
Φ:	flow coefficient
Ω:	Angular velocity
D:	Impeller diameter
Q:	Volume flow rate
Ψ:	Head coefficient
H:	Head
φ:	Nozzle loss coefficient
ε:	Inlet loss coefficient
hj:	Nozzle elevation above the waterline
Tq:	Shaft torque
η_w:	Specific speed
σ:	Cavitation number
p:	Pressure
p_v:	Vapor pressure
U_∞:	Free stream velocity

II. INTRODUCTION

Water jet propulsion systems are employed in a wide variety of water vehicles ranging from high speed pleasure craft to naval ships. They have replaced propeller based propulsion systems because of their myriad advantages over the latter ones.
The waterjet propulsion is a complex system. On the contrary, the screw propellers are simpler, lighter and more efficient than waterjet system. However, the advent of more efficient pumps, the significance of timely delivery of commercial cargos, and the need for swift and enhanced maneuverability of vessels necessitate the use of waterjet propulsion systems.
The selection of power plant used for driving the pumps depends upon the power requirements. For low power applications, i.e. <10 hp, an electric motor would suffice. For high power applications, i.e. >10 hp, gas turbine, gasoline or diesel engines are employed.
In this research paper, the complete design process of the engine has been described and illustrated. The numerical analysis approach is then used to validate the design and prototype development is carried out in order to demonstrate the concept physically.

III. BASIC THEORY AND EQUATIONS

A stern-mounted waterjet installation as used in commercial applications, can be divided into four components: the inlet, the pump, the nozzle and the steering device. Other components include the powerplant that drives the pump through a shaft and hydraulic systems for controlling the steerability of the nozzle and the bucket. The main component is the pump, which delivers the head to produce the jet at the nozzle exit. In general the stator bowl and the nozzle are integrated in one part. The ducting system upstream of the pump is called the inlet. We have used the flush mounted inlet duct for our propulsion system as this is the most commonly used inlet configuration suitable for high speed applications. Downstream of the nozzle there is a steering device, which can deflect the jet in order to create steering and reversing forces. There are also installations for the deflection of the jet possible, with only the reversing option. This can be useful for quick crash-stop maneuvers. If the waterjet has no steering device at all, it is called a booster waterjet.

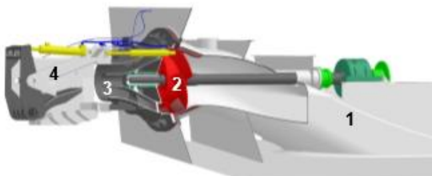

Figure 1 A waterjet layout

The thrust T of the vehicle is given by the reaction to the change of momentum of the water flow through the nozzle.

$$T = \rho Q(\mathrm{V_{out}} - \mathrm{V_{in}})$$

The propulsive efficiency is given by:

$$n_p = \frac{F v_{in}}{P_{shaft}}$$

Where F is the thrust and $P_{shaft}$is the power delivered by the shaft.

A. *Characteristic velocities*

- Mass averaged ingested velocity (Vin)
- Vehicle speed (Vship)
- Average axial inflow velocity at pump inlet (Vpump)
- Average axial outlet velocity at nozzle (Vout)

These 3 parameters relate the 4 velocities. Their values are chosen from historical trends.

- Momentum wake fraction
- Jet velocity ratio
- Inlet velocity ratio

B. *Momentum wake fraction*

The velocity deficit due to interaction of water with the “Hulls boundary layer” is expressed as the momentum wake fraction *(w), which is defined as:*

$$W = 1 - \frac{V_{in}}{V_{ship}}$$

Typical values are 0.10 – 0.14 for fast ferries.

C. *Jet velocity ratio*

$$\mu = \frac{V_{in}}{V_{out}}$$

Typical values lie in the range of 0.5 - 0.7

D. *Inlet velocity ratio*

$$IVR = \frac{V_{ship}}{V_{pump}}$$

Table 1

Stage	App. IVR
Maneuvering in harbor	<1
Sail at design speed	1.3-1.8
High speeds	>2

IV. GENERAL PUMP THEORY

A. Dimensionless performance parameters

Performance of a pump can be expressed in terms of a set of non-dimensional parameters. The performance is expressed in terms of flow rate, head and cavitation behavior. In dimensionless form, the flow rate through the pump is given as the flow coefficient ϕ:

$$\phi = \frac{Q}{\Omega\, D^3}$$

where Q is the flow rate in m3/s, **Ω** the speed of the impeller in rad/s and D the impeller diameter in m. The head coefficient ψ of a pump is defined as:

$$\psi = \frac{gH}{(\Omega\, D)^2}$$

where H is the head in m. It can be shown that geometrically similar pumps have equal values for flow and head coefficient.

The pump head is given by:

$$H_R = \frac{v_{out}^2}{2g}(1+\varphi) - \frac{v_{in}^2}{2g}(1-\varepsilon) + hj$$

where φ is the nozzle loss coefficient, ε the inlet loss coefficient and hj the nozzle elevation above the waterline.

B. Specific speed

Specific speed is a dimensionless parameter which characterizes a pump. It relates the volume flow rate of the pump to the head delivered by it.

$$n_\omega = \frac{\Omega\sqrt{Q}}{(gH)^{0.75}}$$

The value of the specific speed of a specific pump gives a good indication of its type: typical axial flow pumps have a specific speed above 2.4, whereas radial flow pumps have low values of the specific speed (typically below 1.0). Mixed-flow pumps have intermediate values for the specific speed.

Pump efficiency η_{pump} is defined as the ratio between the hydraulic power P_{hydr}, which is the product of flow rate and pressure rise, and the required shaft power P_{shaft}.

$$n_{pump} = \frac{P_{hydr}}{P_{shaft}} = \frac{\rho g H Q}{\Omega T_q}$$

where Tq is the shaft torque.

C. Cavitation

When the Vapor pressure exceeds the static pressure, the formation of bubbles at the periphery of the impeller occurs hence damaging the blades.

The waterjet pump needs a certain level of the pressure at the suction side of the pump in order to prevent cavitation. This required pressure is expressed as the required net positive suction head (NPSHR).

The required net positive suction head should be less than the available net positive suction head.

Cavitation number is defined as:

$$\sigma = \frac{p - p_v}{1/2\, \rho U_\infty^2}$$

Where p is the static pressure at the pump inlet and p_v is the vapour pressure. When "$\sigma \leq 0$", cavitation starts. This implies that high cavitation numbers give less risk for cavitation.

D. Nozzle

A converging nozzle is used to eject the water at high velocities according to the continuity relation. This imparts momentum thrust to the whole system. A steerable nozzle is used for swift maneuverability of the vehicle.

V. DESIGN METHODOLOGY

The design of the water jet propulsion system involves the calculation of the inlet and outlet velocities based on the historical values of jet velocity ratio, inlet velocity ratio and momentum wake fraction. Using these values, the required flow rate is calculated. The pump resistance curves are plotted by projecting the variation in system head and pump head through major and minor head losses. Using the computed values of head and flow rate, the specific speed of the pump is calculated and the type of pump suited to our application is established. Hence, the detailed design of the inlet, pump and outlet is carried out.

VI. PUMP RESISTANCE CURVES

The inlet and outlet loss coefficients were calculated and they were then used to calculate the corresponding head losses. The pump curves were plotted through which the design operating point of the pump was obtained.

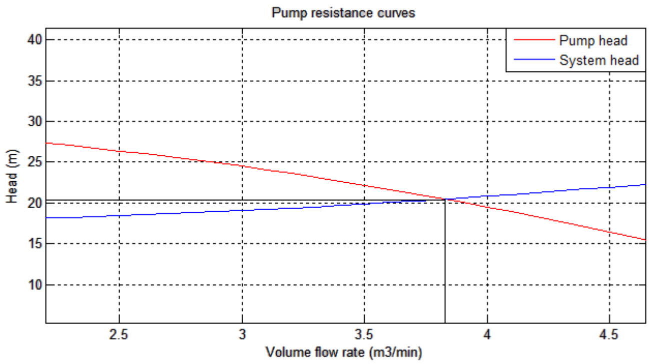

Figure 2: Pump resistance curve

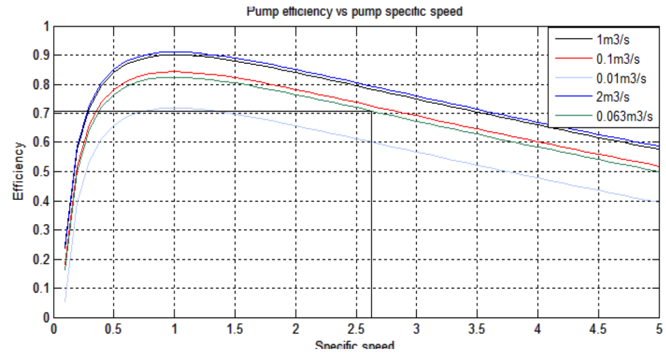

Figure 4: Pump efficiency vs specific speed

VII. LIMITATIONS IN SPECIFIC SPEED

By using an empirical relation between specific speed, jet velocity ratio and ship speed, taking Inlet loss $\varepsilon = 0.20$, outlet loss $\varphi = 0.02$, wake fraction $w = 0.12$, jet velocity ratio, μ=0.6, the following curve was obtained. It gives us the specific speed against the ship speed and helps determine the pump specific speed.

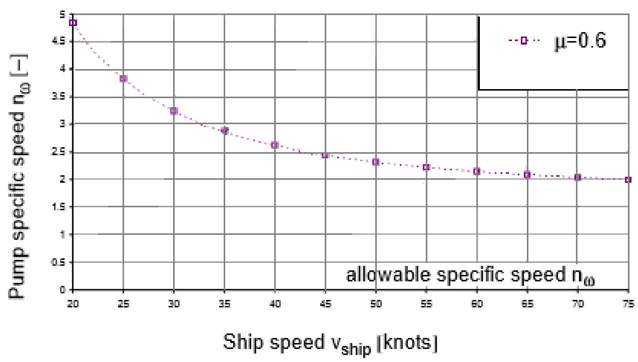

Figure 3: Specific speed vs ship speed

VIII. PUMP EFFICIENCY AND SPECIFIC SPEED

The pump efficiency and specific speed vary as the flow rate varies and the trend is shown below. From this curve, the overall efficiency of the pump at the specified specific speed and flow rate is determined.

IX. LIMITATION OF POWER DENSITY

Power density is an important criterion that ensures highly loaded and compact blades. Higher the power density, greater would be blade loading and hence, smaller would be the impeller diameter.

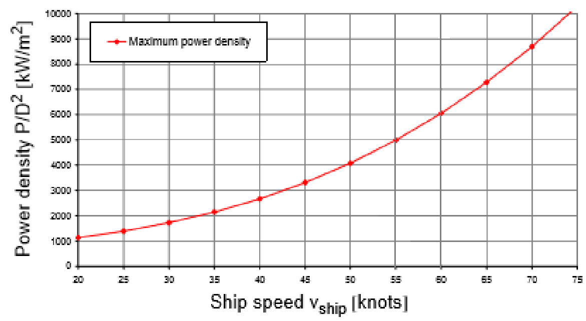

Figure 5: Power density

The value of power density chosen against the ship speed is used to compute the impeller diameter which in turn determines the geometry of the pump.

X. RESULTS

The conceptual and actual design of the waterjet propulsion system along with the numerical analysis and validation of the design is a laborious task. Analysis of the complete waterjet assembly could not be carried out owing to insufficient computational resources. The results of the analysis of the inlet are illustrated below:

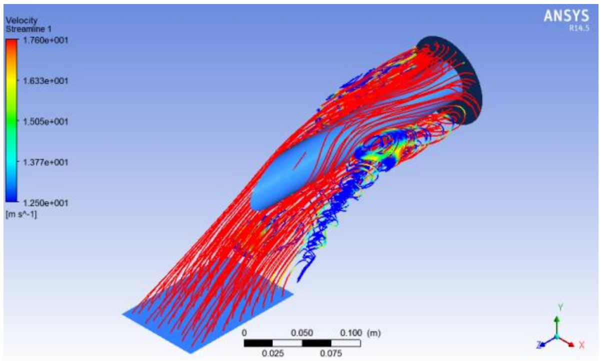

Figure 6

The vorticity and non-uniformity of the flow along the bend in the inlet takes several diameters of the cylindrical pipe to settle but the rotating shaft plays its part in lending the flow its lost uniformity hence stabilizing the flow.
The results of the CFD analysis of the flow through the pump are displayed below:

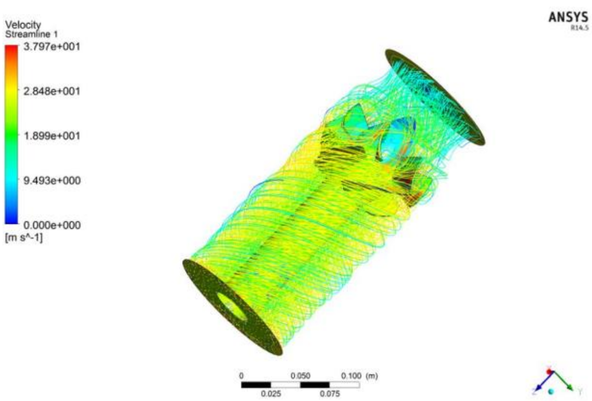

Figure 7

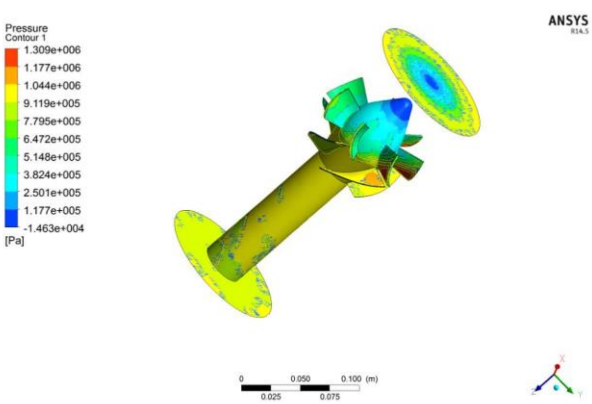

Figure 8

The increase in pressure from root to tip and leading edge to trailing edge can be observed through the pressure contour which manifests an adverse pressure gradient along the chord of the rotor blades.

The velocity streamlines and pressure contour for the converging nozzle are shown below:

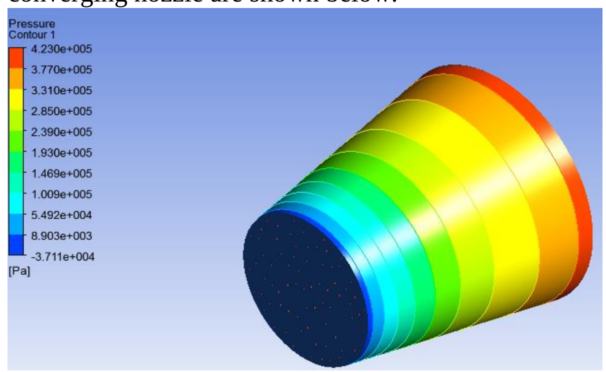

Figure 9

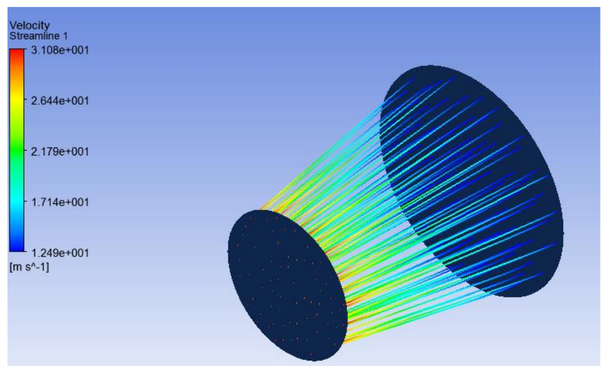

Figure 10

The variation in pressure and velocity as per venturi effect can be registered and the outlet conditions at the nozzle can be established adequately.

XI. CONCLUSION

The analysis validates the theoretical design and the smooth contour verifies the accuracy of the design. The developed prototype's specifications were on par with the theoretical design and it achieved the anticipated target i.e. a cruise velocity of 20 m/s. The employed power plant was a 1300 cc electronic fuel injection gasoline engine which delivered 72 hp and 5250 RPM to the mixed flow pump which is pretty close to the calculated angular velocity of the designed pump i.e. 5300. The torque delivered by the power plant was 75 lb.ft.

XII. RECOMMENDATIONS

The designed water jet propulsion system carries great prospects for application in submarines, torpedoes, ferries, yachts and jet capsules etc. The greatest advantage of a jet engine equipped water craft is that it can operate in flood inundated areas and carry out rescue operations in shallow and contaminated water with minimal risk of injuries and cavitation. It also offers greater efficiency at high speeds than its counterpart i.e. propeller driven engine.

XIII. REFERENCES

[1] Ramseye, David, 'Manufacture of Saltpetre, Raising Water, Propelling Vessels, &c.', English patent no. 50, 1630

[2] Roy, S.M., 'The evolution of the modern waterjet marine propulsion unit', Proceedings RINA Waterjet Propulsion conference, London, 1994

[3] Warren, N.F., & Sims, N.,'Waterjet propulsion, a shipbuilder's view', Proceedings RINA Waterjet Propulsion conference, London, 1994

[4] Terwisga, T.J.C. van,'Waterjet hull interaction', PhD thesis, Delft, 1996 *m* · 1.6 References Numerical analysis of a waterjet propulsion system 13