Introduction of Side-Intake Marine Impulse Thruster and Its Analysis from the Fundamentals

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ABSTRACT

The Side-Intake Marine Impulse Thruster or SI-MIT is a novel marine propulsor for general propulsion of surface or underwater vehicles. The novelty of SI-MIT is twofold. Firstly, by using piston-cylinder setups, a SI-MIT achieved a propulsive cycle that offers continuous impulsive propulsion for propelling marine vehicles. Secondly, it employed the US patent pending concept and mechanism design of the Side-Intake of water, which made it possible to accomplish the recovering stroke of the pistons in atmospheric air while for water intake. The achievement of piston's recovering stroke in air makes SI-MIT work in a cycle similar to an oar, in which an oarsman first strikes his oar to discharge water for thrust and then recovers the oar in the air, however a SI-MIT accomplished this "similar oar cycle" under water or a vehicle's waterline. The paper addressed in detail the conceptual design of SI-MIT as well as the US patent pending concept of the Side-Intake of water in SI-MIT. An evaluation of SI-MIT from efficiency, linearity and effectiveness perspectives was provided. The approach for the evaluation was based on the analysis from the fundamental principles in fluid mechanics, and supported by the facts in marine animals, laboratory findings and existing industry systems.

Keywords

Marine propeller, Water jet, Marine propulsion, Marine unsteady propulsion, Marine impulsive propulsion, Axial piston pump.

1 INTRODUCTION

For marine vehicle propulsion, propellers or impeller-driven water jets are mostly being used. Thrust generation in water requires an insertion of work on water in the aim to build up the useful water kinetic energy for thrust. Insertion of work on water for water kinetic energy increase is often achieved through the motion of a mechanical device in water, though other means such as using electromagnetic field was also found under investigation. The useful water kinetic energy for thrust generation comes from the speedup water velocity in line with the thrust direction. Marine propellers or marine impeller-driven water jets all depend on the spin of blades in water to build up the water kinetic energy. Because of the spin of blades in water, the kinetic energy built up in water is contributed not only from the speedup water velocity in line with the thrust direction but also from the swirl velocity of water associated to the spin of the blades, not to mention there is some radial velocity generation also. Water kinetic energy due to the swirl of water doesn't contribute to the generation of thrust and therefore it is an energy waste. This principle-embedded energy waste due to the spin of blades leads to the fact that such propulsors could hardly reach close to the ideal efficiency of propulsion no matter how much design optimization efforts are spent. The highly rotational water kinetic energy not only brings down the efficiency of the propulsor but also the source of blade surface cavitation and the helical vortex system in the propulsor wake that generate water noise. Quoted from Terwisga (2013), Fig. 1 provided an overview of various kinds of energy loss in a propeller. With a rough estimate, a complete elimination of rotational energy loss due to swirl in propeller could increase a propeller's efficiency by over 20%.

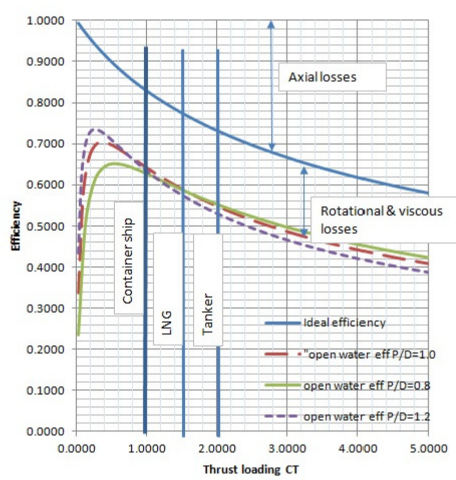

Figure 1: An overview of various kinds of energy loss for B-series propellers

Tremendous investment and research efforts have been continuously spent on various kinds of Energy Saving Devices (ESD) since the use of propellers or impeller-driven water jets for marine propulsion. Examples were contra rotating propellers, static stators upstream or downstream, Mewis duct, Grim's vane wheel, just name a few. All of them were designed with a main focus on recovering the swirl loss in propeller, but none of them is able to completely eliminate the swirl loss and their performances are very non-linear, i.e., largely affected by the flow conditions in which the ship and propeller operate.

Furthermore, the speedup of water velocity in the thrust producing axis through the spinning of the blades works on the principle of a lifting foil. A foil requires an optimal angle of attack for maximum lift, likewise, for a propeller an optimal pitch angle distribution along blade's radius in the consideration of the propeller inflow condition is required in order for propeller to work at optimal angle of attack and maintain its high efficiency at all time, though swirl loss still exists. For a given design of propeller or impeller-driven water jet, it could hardly operate in optimal pitch angle distribution at all vehicle's operational conditions, e.g., various maneuvers. In short, the hydrodynamics of a propeller system is extremely non-linear. The relation from input power to thrust power could only be established through the solution to a highly nonlinear and exquisite fluid dynamics problem. For instance, the nonlinear lifting surface theory may be applied to the solutions to such a fluid dynamics problem. Because of the highly nonlinearity of the problem, once the required exquisite flow condition breaks down, the efficiency drops greatly. That is why a propeller or an impeller-driven water jet can only reach its highest efficiency at the design condition (point). As the vehicle operates at off-design points or conditions, the efficiency of such propulsors degrades greatly. In other words, such propulsors could hardly offer the thrust power that is proportional to the input power. In real life, that fact reflects a weak or sluggish acceleration and maneuver of a marine vehicle equipped with such propulsors.

Our forefathers had long before understood that to most effectively propel and offer almost linear propulsion power to his boat one should do what oarsmen do commonly seen in boat racing. In one propulsion cycle, an oarsman gives a powerful stroke of his oar to expel or discharge water, which generates a reaction force normal to the oar surface, and then follows an effortless oar recovering stroke through the atmospheric air. Note that the force component in line with the boat motion from the normal force on the oar surface is the thrust to push the boat. In this sense, during the water-expelling stroke, the oar reaches the highest efficiency only at the moment when the oar surface is in normal to the flow. However, an oar cycle is still considered a highly efficient propulsion cycle. The reasons are that the oar's recovering stroke accomplished through air saves the most of the energy. Additional energy savings may attribute to the impulsive expelling stroke of the oar that generates large size of the reverse von Kármán vortex street in the wake.

SI-MIT works with a cycle similar to an oar. SI-MIT uses multiple piston-cylinder setups to discharge water through the nozzle for a continuous and impulsive thrust. By using the US patent pending concept and mechanism design of the Side-Intake of water, SI-MIT is able to accomplish its recovering stroke in the ambient air condition but under water or the waterline of a surface vehicle. The discharging stroke of SI-MIT is, however, much more efficient than an oar stroke, because the piston surface always maintain normal to the flow or the thrust axis during the discharging stroke. The locomotion of the piston in line with the thrust axis achieves that the water kinetic energy buildup in the system only comes from the speedup water velocity in line with the thrust. That fact in SI-MIT eliminates the principle-embedded swirl loss in the conventional marine propulsors. On the other hand, generating thrust through a linear displacement of water by the piston's locomotion makes SI-MIT able to maintain a nearly constant efficiency at any working condition or vehicle speeds. This characteristic of SI-MIT is consistent with the common knowledge that the efficiency of a positive displacement pump is nearly constant and higher than an impeller-driven pump of the same power.

The paper addressed in detail the conceptual design of SI-MIT as well as the US patent pending concept of the Side-Intake of water in SI-MIT. An evaluation of SI-MIT from efficiency, linearity and effectiveness perspectives was provided. The approach for the evaluation was based on the analysis from the fundamental principles in fluid mechanics, and supported by the facts in marine animals, laboratory findings and existing industry systems.

2 PRINCIPLE OF SIDE-INTAKE FOR MIT

The concept of Side-Intake of water using piston-cylinder setups for impulsive propulsion is shown in a schematic diagram in Fig. 2. First it requires a tube for a piston to do reciprocating motion inside. The tube could be, but not limited to, a cylinder; however the author referred to such a tube as a cylinder for convenience throughout. The concept of the Side-Intake opens intake holes on the side and near the discharging end of the cylinder wall. An open-close valve must be installed to open and close the Side-Intake holes during the piston's strokes for intake and discharge respectively. The discharge end is completed with a jet nozzle. With a piston installed inside the cylinder, the system becomes a one-cylinder SI-MIT. Fig.2-(a) shows the water intake process. In this process, the valve is in fully open position and the piston takes the recovering (or back) stroke, namely the piston moves toward left as shown in the picture. Fig.2-(b) shows the process of water discharge through the jet nozzle for thrust generation. In this process, the valve is in fully closed position and the piston takes the discharge (or forward) stroke, namely the piston moves toward the right as shown in the picture.

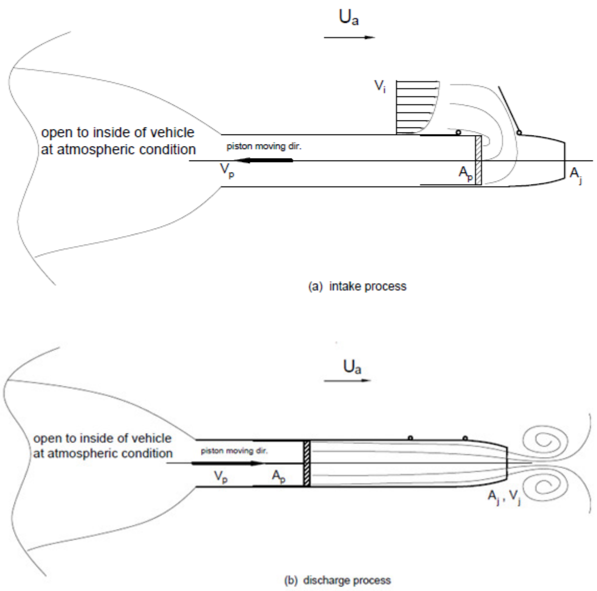

Figure 2: A schematic diagram for the process of side-intake: (a) for intake and (b) for discharge.

The principle feature for the Side-Intake concept is the separation of the inside of the cylinder to be a dry and a wet compartment by the piston at any moment during piston's motion. This feature can be explained with Fig.2-(a) and 2-(b). As shown in Fig.2-(a) and 2-(b), whether during intake or discharge, the left compartment of the cylinder separated by the piston is always dry and opens to the inside of a vehicle, which is in an atmospheric pressure condition or an ambient air pressure. On the other hand, the compartment to the right of the piston is always wet containing the water. Because the left compartment of the cylinder is always opens to ambient air condition, the piston only confronts atmospheric or ambient air during the recovering stroke for water intake, which requires a negligible energy. From the hydrodynamics point of view, this characteristic of piston's recovering stroke through air for water intake achieves the same function as an oarsman recovers his oar in the air. However, the current Side-Intake MIT achieves that function under water or a vehicle's water line.

Following the description of the above, such a SI-MIT, if with just one cylinder, will have no water intake during discharge and also no water discharge during water intake. To keep a continuous water intake and discharge, a SI-MIT shall take at least two pair of cylinders in an actual design.

3 A 4-CYLINDER SI-MIT DESIGN

There are many ways to design open-close valves to accomplish the current Side-Intake principle. A primary principle for the design of an open-close valve for the current application is of simplicity and minimum energy loss during the valve open and close process.

The current design of SI-MIT employs a novel inner-ring rotational valve for open and close actuated by an electric-magnetic actuator. Fig. 3 and 4 presented an actual design of a 4-cylinder SI-MIT (simply called SI-MIT without causing confusion in the paper).

In Fig. 3 and Fig. 4,

(1) is the jet nozzle;

(2) is the 4 cylinders;

(3) is the 4 inner ring rotational valves;

(4) is the ball bearings;

(5) is the permanent magnets installed on the wall of the inner ring rational valves;

(6) is the 4 electrical coil winding pads in the electric-magnetic actuator;

(7) is the 4 pistons;

(8) is the 4 absorbing springs, one for each piston;

(9) is the baffle cap.

In the design of SI-MIT, each two piston-cylinder set is synchronized to move together. For example, one pair of the pistons takes the forward stroke to discharge water from the jet nozzle while the other pair is to take the recovering stroke to intake water from the Side-Intake openings. This can be seen in both Fig. 3 and Fig. 4. Each inner ring rotational valve has rows of ball bearings for easy rotation and two or four permanent magnet pads embedded on the ring wall at 90^o apart along its circumference. The electric-magnetic actuator installed in the centerline space of the four bundled cylinders will make the inner-ring rotational valve to turn 90^o degree to open the valve before the intake stroke takes place and turn back or another 90^o degree to close the valve before the discharge stroke takes place. The rotational motion to open and close the valve cuts across the flow, which introduces resistive energy loss. However, because the inner-ring is made thin and the cross area that cuts into the flow is small. Comparing to a gross secondary flow generation due to the entire blades spin in propeller or impeller-driven water jet, the cutting motion of the inner ring valve only excites locally a minimum secondary flow. In addition, with the use of ball bearings for easy rotation, the energy cost to open and close the valve is expected to be very small.

As indicated in Fig. 4, at this particular moment, the up- and down-cylinders have the inner-ring rotational valves in fully open position and the two pistons just start the recovering stroke for water intake, while the cylinders shown in the left and right have the inner-ring rotational valves in fully closed position and the two pistons just start the forward stroke for water discharging. Associated with Fig. 4, the pistons' positions can be seen in Fig. 3 at this same moment.

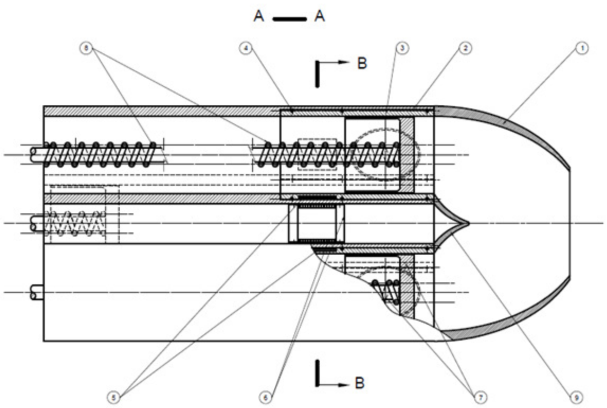

Figure 3: A side, break-away view of SI-MIT.

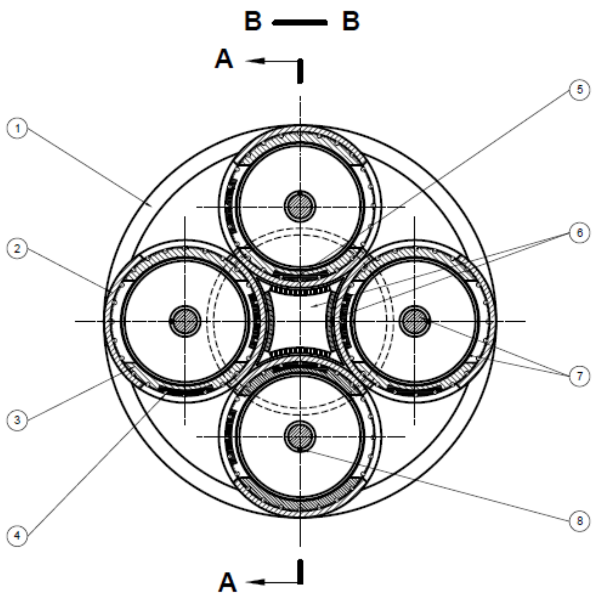

Figure 4: A front, break-away view of SI-MIT.

Each spring installed behind the piston is to absorb the potential energy from the water during the intake. SI-MIT is a general propulsion system designed for surface ships as well as submerged vehicles. Depending on its depth of submergence, the ambient pressure of a submerged vehicle is the hydrostatic pressure at the depth the vehicle operates. It is desirable to design a spring of variable stiffness based on the submerged depth of a vehicle. A simple solution to this is to employ an air pump to automatically fill the right amount of compressed air based on the submerged depth of the vehicle in the back of the piston such that at the end of the intake process the air pressure in the back of the piston is just counter balance the hydrostatic pressure of the water depth. It is proposed to have a combination of a spring and filled air in a real system design to achieve a spring system of variable stiffness depending on the vehicle's submerged depth. The air pump and its control system were omitted in Fig. 3 and 4 because they are not the main focus of the paper. A spring system is just an energy absorbing or releasing device if without considering any damping loss. The spring system used in a SI-MIT doesn't need to just store the exact amount of the potential energy of the water depth. Beyond the potential energy of the water depth, any additional energy required to compress the spring during the intake process comes from the prime mover. The energy of these two is all stored in the spring system after the completion of the intake process and quantitatively is just, $1/2kL^2$, where k is the stiffness of the spring system at the given submerged depth and L is the piston stroke length. This same amount of energy will be released from the spring system and contribute to the prime mover during the discharge stroke. The propulsion efficiency will not be affected by the spring system if the spring damping loss is neglected.

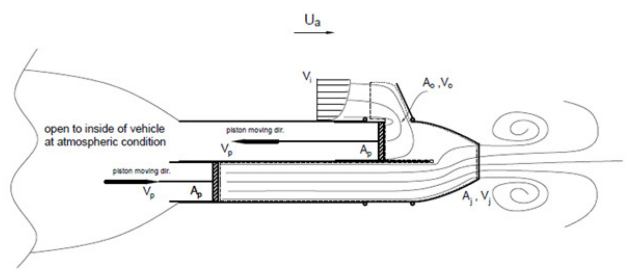

Figure 5: A schematic diagram for first principle analysis for a two-cylinder SI-MIT.

4 ANALYSIS OF SI-MIT FROM FUNDAMENTALS

4.1 Efficiency and Linearity of SI-MIT

To facilitate an analysis with first principles, a schematic diagram of a SI-MIT with two cylinders that could maintain a continuous inflow and jet exit flow is shown in Fig. 5. The first principles used in the analysis are the mass, momentum and energy conservation laws in a control volume. The control volume encloses the water region from water coming into the system to water leaving out of the system at the jet exit, which is shown in the dash-dotted line in Fig. 5. Obviously, this volume is a constant at any moment of the pistons' motion. Neglecting the elevation difference between the intake and discharge as well as water viscous effect, applying the first principles to this control volume leads to,

$$Q = \rho \cdot A_p \cdot V_p = \rho \cdot A_o \cdot V_o = \rho \cdot A_j \cdot V_j \quad (1)$$

$$T = -Q \cdot (V_j - V_i) \quad (2)$$

$$W_p = Q \cdot \left(\frac{1}{2}V_j^2 - \frac{1}{2}V_i^2\right) \quad (3)$$

Note that V_j and V_i are the flow velocity in line with the thrust axis. Eqs. (1)-(3) govern the mass flow rate, the thrust generation and the required amount of mechanical work added to water from piston's locomotion. It can be seen that the piston's mechanical work on such a system is the work done on the boundary of the control volume and required only during piston's forward stroke to discharge water as shown by the down-piston in Fig.5. During the piston's recovering (the back) stroke to intake water shown by the up-piston in Fig. 5, which moves to the left, the motion of that piston requires a negligible amount of work because the left compartment at ambient pressure makes the pressure on two sides of the piston more or less equal if not considering the "added mass effect" due to the unsteady motion of the piston. The effect of unsteady motion of the piston on thrust and efficiency will be discussed in the next section.

In application, thrust and efficiency of a propulsor shall be considered as it is integrated with the vehicle it propels. Because of the thrust deduction factor, the actual thrust to push a vehicle to a given speed is,

$$T = -(1-t) \cdot Q \cdot (V_j - V_i) \quad (4)$$

The useful work is the product of vehicle's speed and the thrust, and therefore the efficiency of the propulsor is,

$$\eta = \frac{W_{useful}}{W_p} = (1-t) \cdot \frac{2U_a}{V_j + V_i} \quad (5)$$

In Eq. (5), U_a is the ambient water velocity, which is the same as the vehicle's speed but in the opposite direction when considering the vehicle is fixed. When a propulsor is integrated with the vehicle, V_i comes from the wake of the hull. Its relation with the vehicle speed is established through the wake fraction by $V_i=(1-w)U_a$. Because the area of the Side-Intake openings of the valve, A_o, is made larger than the piston's wetted-face area, from the law of mass conservation and a full account of the boundary layer ingestion, V_i is expected to be much smaller than U_a, i.e., (1-w) in SI-MIT can be much smaller than that for a conventional propeller. Considering the wake fraction, Eq. (5) turns to,

$$\eta = \frac{W_{useful}}{W_p} = \frac{1-t}{1-w} \cdot \frac{2V_i}{V_j + V_i} \quad (6)$$

The first factor on the right side of Eq. (6) is the hull efficiency and the second factor is the well-known ideal (or jet) efficiency of propulsion for propeller or water jet. Eq. (6) can be simply written as,

$$\eta = \frac{W_{useful}}{W_p} = \eta_{hull} \cdot \eta_{ideal} \quad (7)$$

Eq. (7) says that if without considering loss between the input power (or the Shaft Horsepower) and the required amount of mechanical work for thrust, the efficiency of a SI-MIT achieves ideal efficiency when considered alone and becomes the product of the hull efficiency and the ideal efficiency when integrated with the vehicle.

The propulsive coefficient is used to measure the efficiency of a marine propulsor when it propels the vehicle and all losses are considered. Its definition can be written by,

$$PC = \frac{\text{Effective Horsepower}}{\text{Shaft Horsepower}} = \eta_{hull} \cdot \eta_{ideal} \cdot \eta_{flow} \cdot \eta_{pump} \cdot \eta_{mech} \quad (8)$$

where,

$$\eta_{flow} = \frac{\text{flow kinetic energy required for thrust}}{\text{total kinetic energy added in fluid}} \quad (9)$$

$$\eta_{pump} = \frac{\text{total kinetic energy added in fluid}}{\text{mechanical work done on fluid}} \quad (10)$$

and, η_{mech} accounts for mechanical or electrical loss before power delivered to the end of the shaft connecting to the propulsor. η_{flow} is the ratio of the required flow kinetic energy for thrust, which is contributed only from the flow velocities in line with the thrust axis at the exit and the inlet, to the total fluid kinetic energy added in fluid, which is equivalent to the total fluid kinetic energy change between the exit and the inlet. For a pump, the total kinetic energy added in fluid will turn to the pressure head rise. However, the mechanical work done on fluid will not all turn to the total kinetic energy change between the exit and the inlet because of other losses including volumetric loss due to fluid leakage, viscous shear loss in fluid, and these losses are taken into account in the pump efficiency in Eq.(10). One of the major differences of SI-MIT and a conventional marine propulsor is that for SI-MIT, $\eta_{flow=1}$ because SI-MIT only generates flow velocity in the thrust axis, while for propeller or impeller-driven water jet, η_{flow} is much less than one because of swirl and other secondary flow at the exit of the propulsor.

A SI-MIT is also an axial piston pump but for large flow rate generation, because it is much more effective in the use of the space for fluid displacement than a conventional axial piston pump. However, as a pump, SI-MIT works in the same principle as an axial piston pump used in industry. Fig. 6 shows the working principle of a conventional axial piston pump. Its inlet and outlet openings are made on the same surface with a half circle shape. The piston-cylinder sets rotate with the shaft. The swash plate in the back of the piston shafts makes the pistons do reciprocating motion as the shaft rotates, and

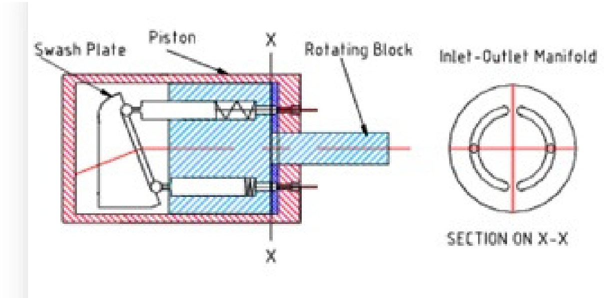

Figure 6: Working principle of an axial piston pump.

results in one cylinder intakes fluid while the other discharges fluid through the two half circle openings respectively. SI-MIT and axial piston pump are the same in that both systems keep ambient air pressure in the back of the pistons so that the recovering stroke is effortless, and both systems have springs for an energy absorbing and releasing. It is well recognized that an axial piston pump can easily achieve an efficiency of 90%, i.e., η_{pump}=90%. Further, being a positive displacement pump, its efficiency is basically a constant as it works in different load conditions. In other words, an axial piston pump is a linear system or a linear performer. In terms of efficiency and linearity, SI-MIT shall behave the same as a conventional axial piston pump. However, SI-MIT is different from a conventional axial piston pump in two accounts: (1) a conventional axial piston pump has inlet and outlet openings made on the same plane, which makes it applicable to a pump, but not applicable to net momentum generation as required for a marine propulsor; (2) because of the design of a conventional axial piston pump, the piston-cylinder sets are not able to take the maximum space of the system, which greatly reduces its effectiveness to generate flow rate. Because of these two reasons, a conventional axial piston pump is often used as a pump in applications where high pressure and low flow rate are required. In order to generate thrust efficiently in marine propulsion, a propulsor is required to generate flow rate in the most effective way. A comparison of the design to a conventional axial piston pump, it is not difficult to realize that SI-MIT is essentially an axial piston pump, but for applications of large flow rate and linear momentum generation. Looking back to Eq. (8) and neglecting the mechanical efficiency for a moment, the propulsive coefficient for SI-MIT can be expressed as,

$$PC_{SI-MIT} = \eta_{hull} \cdot \eta_{ideal} \cdot \eta_{pump} \qquad (11)$$

where η_{pump} is a constant and its value is expected to be above 90%. η_{ideal} is determined by the ratio of the areas of inlet and outlet openings and also a constant. η_{hull} accounts for the coupling effect of the ship hull and SI-MIT, and it may vary a little depending on the vehicle's speeds. However, this nonlinearity doesn't come from SI-MIT itself.

Through the first principle analysis for SI-MIT and its working principle comparison to axial piston pump used in industry, one can realize that SI-MIT belongs to axial piston pump but for large flow rate and linear momentum generation, and therefore SI-MIT is ideal for marine propulsors. As a marine propulsor, the efficiency of SI-MIT in open water is determined by,

$$\eta_{SI-MIT} = \eta_{ideal} \cdot \eta_{pump} \qquad (12)$$

Again, η_{pump} is basically a constant and its value shall be close to the efficiency of a conventional axial piston pump. The high efficiency and linear characteristics of SI-MIT can been seen from Eq.(12). For comparison, it is worthwhile to point out that the nonlinear characteristics of a propeller or impeller-driven water jet reside in η_{flow} and η_{pump}. Both terms are nonlinear functions because of the existence of swirl in flow and the working principle of propeller or impeller-driven water jet, which is basically governed by the non-linear lifting surface theory.

It was acknowledged that the analysis above neglects the energy cost in the open and close of the open-close valve for water intake and discharge and it shall be accounted for into the pump efficiency. To achieve high pump efficiency, a nontrivial question is to design an open-close valve that costs least energy. An inner-ring rotational valve is thus proposed and discussed in Section 3. The inner-ring valve is expected to cost relatively small amount of energy during the open and close processes. Remember that a conventional axial piston pump has a similar energy cost during the switching from intake to discharge of the cylinder through the rotation of the cylinders. However, its efficiency is still recognized to be the highest among any other types of positive or negative displacement pumps.

The first principle analysis above is valid only for steady state or quasi-steady state flow within the control volume from the inlet to the exit of SI-MIT. In reality, the piston motion is unsteady. Recent studies have proven that the water jet generated from an unsteady piston motion is able to form vortex rings in the jet exit flow, which through entraining the ambient flow mass and being accelerated results in an additional increase of the axial water momentum. Because of this reason, the vortex rings generated from the water jet of unsteady piston motion will contribute to an additional thrust and therefore give a further increase of the propulsion efficiency, which is not taken into account in Eqs. (1) to (3). A brief discussion on vortex ring and its effect on SI-MIT was given in Section 4.3.

4.2 Effectiveness of SI-MIT

Effectiveness of a power machine is about the power density question. For a propulsor, it is ideally to have the most compact system to generate a given thrust power without scarifying its efficiency. Eq.(2) is a general equation to calculate thrust within a propulsor system between its inlet and exit. There are two ways to increase thrust. One way is to increase the difference of the inlet and exit velocities, which is equivalent to increase the load on the propulsor. That way is not good in that it will increase the linear slip loss, and therefore reduce efficiency through a reduction of the ideal (or jet) efficiency term in Eq.(7). An ideal way to increase thrust is by increasing the flow rate, because flow rate doesn't directly appear in the efficiency equation and assuming that η_{flow} and η_{pump} also not a function of the flow rate. As shown in Fig. 7, in fact for propeller and impeller-driven water jet, the relation of efficiency and flow rate is a bell-shape curve, but for SI-MIT, efficiency is basically independent from flow rate because SI-MIT is a linear performer.

If one doesn't like to see reduction of efficiency in a propeller or impeller-driven water jet, then to increase flow rate means to increase the size of the propulsor. The effectiveness question is then to answer: among the same size of propulsors, which propulsor can produce the most flow rate without scarifying efficiency. The capacity coefficient, which is defined as, $C_Q=Q/nD^3$, where n is the RPM of a propeller or impeller-driven water jet, and D is the diameter of the propulsor, can be used to compare the effectiveness of two propulsors. It is well-known that axial-flow pumps are the most effective system for generating flow rate, and therefore often chosen for water jet propulsors. A propeller actually can also be viewed as an axial-flow pump. Because of the nonlinear behave, the relation between the capacity coefficient and the efficiency in propeller or impeller-driven water jet has no straight way to determine, but comes from the result depending on the design skill level and model tests. Fig. 7 quoted from White (1986) provided pump curves for a typical axial-flow pump. A rough estimate for C_Q at the best efficiency point is around 0.55 for a typical axial-flow pump. There are tremendous investment and research work on designing the best axial-flow pump jet for marine propulsor. Through a literature search and to the best knowledge of the author, it was found that ONR AxWJ-2 pump jet was able to achieve $C_{Q,ONR}$ =0.77 at its highest pump efficiency of 0.89. The

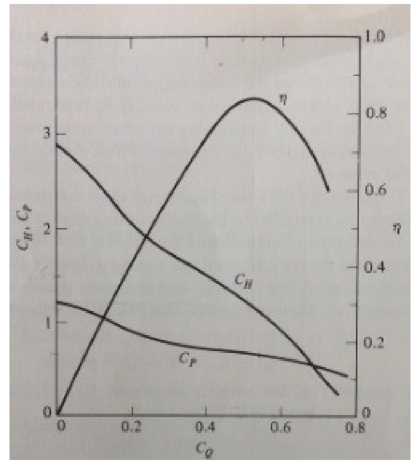

Figure 7: A typical axial-flow pump curve (White (1986)).

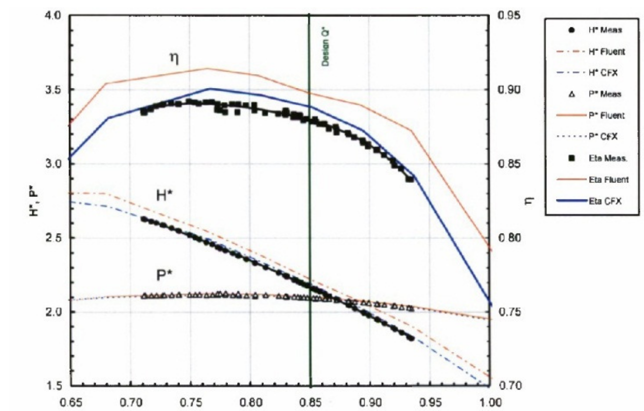

Figure 8: ONR AxWJ-2 measured and CFD calculated pump curves.

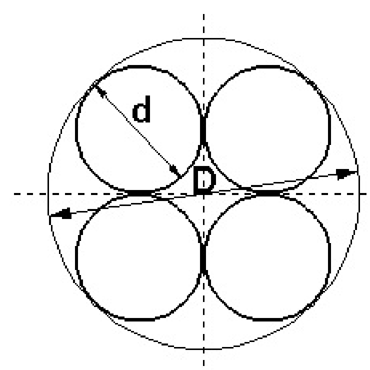

Figure 9: relation of cylinder and system diameters in SI-MIT.

data is read from Fig. 8, which was presented in Chesnakas, et al. (2009). The way SI-MIT generates thrust is straightforward. It is just a linear displacement of water through a piston linear stroke motion. Therefore, its capacity coefficient is constant and easily determined. Fig. 9 shows the relation of the diameter of each cylinder, d, and the system diameter, D, in SI-MIT. Mathematically,

$$d = D/(1+\sqrt{2}) \tag{13}$$

A simple algebraic operation can find that the capacity coefficient for SI-MIT is,

$$C_{\mathrm{Q,SI-MIT}} = \frac{Q}{nD^3} = 0.071 \cdot \lambda \cdot \pi \tag{14}$$

where n is Cycles Per Minute (CPM) of the piston reciprocating motion, a parameter comparable to RPM in propellers, and $\lambda = L/d$ is the stroke to diameter ratio of the piston-cylinder set. To show SI-MIT is a more effective system than ONR AxWJ-2 pump jet, the ratio of $C_{Q,SI-MIT}$ to $C_{Q,ONR}$ is calculated,

$$\frac{C_{\mathrm{Q,SI-MIT}}}{C_{Q,ONR}} = 0.29 \cdot \lambda \tag{15}$$

This relation shows that under the condition that SI-MIT runs at CPR the same as the RPM of ONR AxWJ-2, a designer just needs to choose $\lambda \geq 3.45$ in the design of a SI-MIT, and he can ensure the SI-MIT system will be more effective or more compact than ONR AxWJ-2. Further, because SI-MIT capacity coefficient is more or less a constant, the designers can always choose higher working CPR to make the system more compact if cavitation is under check. In the next section, it showed that a λ around 4 is just the formation number to generate maximum vortex ring in unsteady jet flow, which will further enhance propulsive efficiency for SI-MIT.

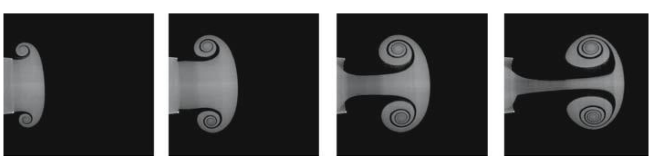

Figure 10: Vortex ring formation in the wake of a starting jet from the work by Olcay and Krueger (2008).

4.3 Water Jet from Unsteady Piston Motion

Piston motion naturally employs a non-constant velocity profile or a velocity program, which is from velocity zero at the start of discharge to its peak and then back to zero at the end of discharge. The velocity program of the piston motion in turn creates an impulsive water jet or a starting jet at the jet exit. It is a well known phenomenon that vortex rings will be generated when forcing fluid impulsively out of a nozzle into ambient fluid. Piston-cylinder arrangement is, thus, commonly used in experiments by researchers to generate starting jets and study vortex ring dynamics. Fig.10 taken from the work by Olcay and Krueger (2008) gives a typical view of a vortex ring formation and evolution as a column of water in the cylinder is ejected out by the piston to the ambient water.

Recently, there are increasing interests in the study of vortex ring formation in impulsive jet flow in relation to impulse, thrust and propulsive efficiency and its application to marine vehicle propulsion. One early research in this direction was reported in Gharib, et al. (1998). Using a piston-cylinder device to study vortex ring formation in starting jets generated from various short to long of the piston stroke to diameter ratio (L/d), Gharib, et al. (1998) observed that for L/d sufficiently less than 4, there is only a single vortex ring in the jet flow, while for L/d larger than 4, the jet flow will generate a pinched-off leading vortex ring followed by a trailing jet. After the leading vortex pinches off, the on-going trailing jet just behaves like a steady jet flow. The L/d ratio can also be viewed as a non-dimensional time scale for completing one piston stroke. Their observation concluded that when this non-dimensional time scale is around the neighborhood of 4, referred to as the 'formation number' in the paper, a pinch-off of the leading vortex ring from a trailing jet will occur, indicating that the vortex ring can no longer absorb any more vorticities emanating from the jet flow. In other words, the leading vortex ring contains the maximum circulation a vortex ring is able to acquire. Again using the piston-cylinder device, Krueger and Gharib (2003) further studied the relative contributions of the leading vortex ring and the trailing jet to the total impulse provided by the impulsive jet flow at various L/d ratios. Note that thrust of an impulsive or unsteady jet is the time average of the total impulse. The experiment results from Krueger and Gharib (2003) showed that the thrust contributed from the vortex ring is much higher than the thrust contributed from the trailing jet, which represents a steady jet mode, and the maximum thrust of an impulsive jet can be achieved at a L/d ratio just after the leading vortex pinches off or equal to the formation number. According to Krueger and Gharib (2003), the fact that vortex rings contributes to an increase of thrust or total impulse over a steady jet for a given average piston velocity is attributed to ambient flow mass entrainment into the vortex ring and an acceleration of the vortex ring due to the over-pressure at the jet exit. The existence of an over-pressure at the jet exit is the result of the pulsed-motion of the piston.

An example of relying fully on the impulse from vortex rings for thrust generation to maneuver an underwater vehicle was found in a synthetic jet design in Krieg and Mohseni (2008). Their synthetic jet design relied on a plunger movement in a cylindrical water cavity to discharge and intake water from the same nozzle opening. From steady jet analysis point of view, the water discharge and intake from the same opening shall result in no net change of momentum flux crossing the opening. However, the device did create a net positive momentum flux because of the impulse supplied by the vortex ring in the jet exit flow. The synthetic jet was thus also called a vortex ring thruster (VRT) in the paper. VRT reported in Krieg and Mohseni (2008) proved that vortex ring generated from impulsive jet is able to add additional thrust to the conventional marine propulsion system that only relies on the linear momentum flux change between the system's inlet and exit.

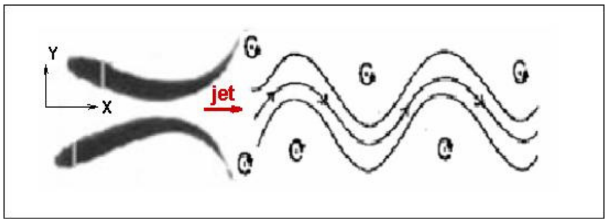

Figure 11: Impulsive jet generated by fish caudal fin.

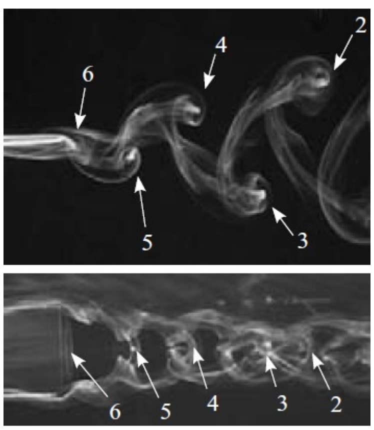

Figure 12: 3-D reverse von Kármán vortex street (Buchholz and Smits (2006))

Nature provided the most compelling evidence that over millions of years' natural selection most of the fast moving biological animals choose impulsive mode to fly or swimming. On the aquatic animal side, examples are various kinds of fish and squid. Fig. 11 describes a 2-D view of the impulsive jet generated from an alternating impulsive flapping of the caudal fin of a fish. The jet is featured with reverse von Kármán vortex street that generates impulsive thrust for fish. The alternating impulsive flapping of caudal fin also controls the direction of the jet for fish to have an easy and fast maneuver. Many researches were done on fish swimming, e.g., Drucker and Lauder (1999). DPIV observation in fish jet wake from Drucker and Lauder (1999) inferred that the alternating impulsive flapping of the caudal fin of a fish actually generates a system of vortex rings chained together with each ring oriented in the local mean jet flow. Buchholz and Smits (2006) studied the vortex structures in the wake of a pitching panel of low-aspect-ratio. Fig. 12 taken from Buchholz and Smiths gave a visual look of a system of chain vortex rings, a 3-D reverse von Kármán vortex street, in the wake of the pitching panel. A squid ingests surrounding fluid into a large mantle cavity. It then uses its body muscle to eject the fluid out through a nozzle called the siphon in an impulsive manner. By a comparison, it is not difficult to realize that the way of SI-MIT to generate impulsive thrust is more like that of a squid. Examples of human being naturally employing impulsive thrust were found in competitive sports, such as swimming and boat racing.

From the natural evidence of aquatic animal swim and the fundamental research finding that optimum vortex ring at the formation number generated from an impulsive jet can greatly increase propulsive efficiency, researches on using impulsive jet as a general marine propulsion system received ever greater attention around the world. Ruiz et al. (2011) designed and built an impulsive jet system to be installed in a laboratory-scale submarine vehicle so as to accomplish a self-propelled vehicle with impulsive propulsion. The goal of their research was to study the propulsion efficiency of impulsive jets under vehicle's self-propelled condition. Openings were made as water jet inlet on the submarine hull along its circumference at about the mid body, and the end of the hull left open to water as a jet nozzle. A propeller was installed inside the aft-mid body of the submarine hull to generate water flow for thrust. The impulsive jet flow at the nozzle exit was achieved by a periodic close and open of the inlet openings through a rotating shell mounted on the hull. When the openings were constantly open, the system worked in a steady jet mode, which was the same as an impeller-driven water jet. When the openings were periodically open and close during the spin of the propeller to drive the flow, the system worked in an impulsive jet mode. The experiment results from Ruiz et al. (2011) showed that the impulsive jet was able to increase propulsive efficiency by over 50% greater than that of the steady jet through an optimum use of vortex ring. Their analysis model also pointed out that a substantial propulsion efficiency enhancement from the impulsive jet by more than 50% over a steady jet were the results of two primary mechanisms: (1) ambient fluid entrainment into the forming vortex ring; (2) the added mass generated by the downstream acceleration of the vortex ring due to the over-pressure created by the pulsing jet flow at the nozzle exit. These findings were in agreement with the analysis from Krueger and Gharib (2003). However, it should point out that their propulsion system whether operated in the impulsive jet mode or in the steady jet mode there always was swirl loss because of the use of propeller and the baseline efficiency of their propulsive system in steady jet mode was not provided in the paper.

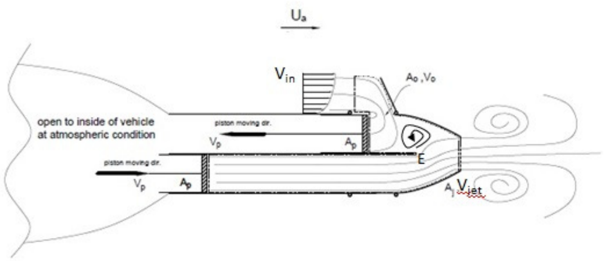

Figure 13: A sketch of flow structure in SI-MIT

All the recent studies proved that impulsive jet or unsteady jet created from a typical piston-cylinder setup can have a substantial increase of thrust over a steady jet with the same power input especially when the impulsive jet operates around the formation number to generate pinched-off vortex rings. This additional thrust or efficiency increase is related to the vortex ring dynamics in the jet wake generated from the impulsive motion of the device, which is not quantified in the steady-state flow analysis for a system from inlet to exit.

Finally, it may be of interest to give a speculation of the flow structure within SI-MIT. The detail flow structure within the system contributes to the pump efficiency, and may be determined through advanced CFD methods or the DPIV flow visualization. Looking back of the working principle of SI-MIT as shown in Fig. 13, the inflow and the outflow takes place at the same time and therefore continuing flow is maintained through the SI-MIT system. The inflow and the outflow are separated by the cylinder wall except that at the end of the cylinder as indicated by the E point in Fig. 13, the two flows may merge. However, because of the Kutta condition the two opposite flows will not turn around the sharp edge (the E point) at the end of the cylinder. Instead, the two opposite flows in the vicinity of the E point leads to shear flow that introduces a vortex similar to the starting vortex at an airfoil trailing edge. A speculation is that this vortex will only generate thrust because it shall always rotate in the same direction as the vortex ring and it shall enhance the vortex ring formation once it is ejected into the jet wake. However, this argument will remain a speculation without the confirmation from laboratory observations or advanced CFD simulations.

5 CONCLUSIONS AND FUTURE WORK

SI-MIT is a piston water jet propulsor characterized by the principle feature of the Side-Intake of water. The principle feature of the Side-Intake of water is the separation of the cylinder into a dry and wet compartment at any time piston moves, and therefore achieves a negligible energy requirement for water intake because the piston just encounters the ambient pressure during the recovering stroke. The US patent pending concept and mechanism design of the Side-Intake of water makes a practical application of marine impulsive propulsion with piston water jet become feasible from its laboratory studies.

SI-MIT can be applied to either surface or underwater vehicles as a general thrust provider. The system can also turn to be a VRT automatically when the system works in the closed mode of the open-close valves for vehicle low-speed maneuvering or positioning. The prime mover to drive the piston's motion can either come from the marine engines or linear motors. Although it will be not difficult to design a standardized mechanical drive for using marine engines to drive SI-MIT, the author prefers the use of linear motors similar to solenoids to power each of the cylinders. The use of linear motors also eliminates the needs of the rods connecting the pistons and makes the system more compact. SI-MIT with linear motors as the prime mover will offer an ideal propulsion system to a fully electrical powered ship or underwater vehicle.

It is necessary to give a summary of the performance advantages of SI-MIT. They were summarized below: (1) SI-MIT is essentially an axial piston pump specially designed for marine propulsors which require large flow rate and linear momentum generation; (2) the system eliminates the swirl loss as well as the loss from the recovering stroke of the piston motion so that the system has potential to unlimitedly attain the ideal efficiency through design optimization; (3) the system uses piston-cylinder setup for thrust, which is a natural and simplest device to generate and manipulate vortex rings for the maximum thrust enhancement from the vortex ring impulse. The thrust enhancement from the vortex ring impulse makes the system possibly reach super efficiency, a term here referred to as the efficiency higher than the ideal efficiency of propulsion; (4) the system is a linear thruster, referring to that the thrust power is able to maintain more or less a linear relation to the input power even when the vehicle operational condition changes. This is because the work done by the piston motion is in proportional to the linear displacement of water, leading to a linear momentum flux increase or thrust generation; (5) Analysis also showed that SI-MIT is the most compact marine propulsor among the existing marine propulsors.

Future work includes: (1) targeting to propel a model surface or submerged vehicle, design and build a prototype of SI-MIT; (2) test the prototype SI-MIT in open water condition to verify its performances and compare them with those from the propeller of similar size; (3) conduct self-propelled model tests for the vehicle as it is integrated with the prototype SI-MIT; (4) CFD simulations for the SI-MIT flow including its internal, external and unsteady vortex wake flow. CFD simulations are expected to be of challenge, because it is required to simulate multiple moving bodies interacting with the flow and capture accurately the unsteady vortex systems.

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DISCUSSION

Question from Dr. Yan Xiang-kaeding

Very interesting presentation and topic! I wonder how the efficiency of such impulsive system will be comparing to the traditional propulsion system. Especially for which speed would it be suitable? Since as one can see in the nature, that the creatures using the mass flow impulse to move forward, no doubt they are very efficient but normally have low speed.

Authors' Closure

I appreciated that Dr. Yan raised this question. As we know non-dimensional parameters are usually used in the marine propulsor design such as the advance coefficient (J_s), thrust coefficient (K_T)…. Respective parameters for SI-MIT can be derived, for instances, $J_s = U_a / V_p$ and $K_T = T/(2A_p \rho V_p^2)$, so that propulsor performances between the traditional and the impulsive can be compared in similar design conditions. It was acknowledged that most of the experiment study on the piston cylinder jet flow is at relatively low Reynolds number (1.0E4 on the high side). For practical marine applications, Reynolds numbers shall be much higher. However, the vortex ring dynamics is mainly an inviscid process, though the Reynolds number will affect the formation number somewhat as the experiment work revealed. The author looks forward to more research work on piston water jets at high Reynolds number to be carried out as interests in impulsive jets for practical marine propulsion become intense.