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HIGH EFFICIENCY HUBLESS RING PROPELLER FOR UNDERWATER VEHICLES

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Abstract - Harbor Branch Oceanographic Institution, Inc. (HBOI) has developed a unique new electric propulsion device that maximizes thrust at significantly lower power and weight than other conventional propulsors used for undersea vehicles. Appropriate applications for the Electric Ring Propeller (ERP) include AUVs, UUVs, manned submersibles, swimmer delivery vehicles, diver propulsion devices, acoustic targets (e.g., Mk 30), surface ship maneuvering thrusters and recreational water craft. Because the propeller blades are attached and supported by a rotating ring at its circumference, there is no center hub. This facilitates towed arrays, fiber-optic links and other systems to be deployed directly through the center of the thruster. A number of prototypes with voltages ranging from 24 VDC - 120 VDC have been built and tested, exhibiting performance of 0.1 lb. of thrust per watt. With syntactic foam nozzles, the thruster and its control circuitry can be packaged in a compact, near-neutral buoyancy package.

I. INTRODUCTION

In 1973 Harbor Branch initiated the design of an ROV capable of underwater operation in the 6 knot Florida current immediately offshore of Ft. Pierce, Florida, the home port of Harbor Branch. This required a small diameter cable with limited power handling capabilities. Thoughts turned to high efficiency equipment, and particularly to thrusters. The ROV was completed utilizing an electro hydraulic system, and was successfully deployed to 3000 ft. for several years.

In addition, Harbor Branch presently owns and operates three manned submersibles, two capable of routine operation to 3,000 ft. These submersibles depend on battery power, requiring careful consideration of operating efficiency to maximize bottom time. The thrusters are powered by brush-type, DC electric motors, requiring pressure proof housings and seals for the rotating shafts. The 3,000 ft. submersibles each have nine separate units which are simply replaced as they encounter problems, usually from leakage around the shaft.

In an attempt to develop a highly efficient thruster for ROVs and submersibles, an internal invention disclosure was made (in 1976) describing a propulsion unit which was the same size and power, but had a brushless electric motor built around the outside of the propeller itself. The stator was "potted" to protect it from the water so no protective enclosure or "can" was necessary. The connection to the propeller itself was magnetic and no shaft was necessary. Unfortunately a suitable motor could not be found at that time and the project was discontinued.

In 1992 a chance meeting with a motor design engineer at an electronics symposium brought the project back to life. Fisher Electric Motor Technology had built some motors using new technology which fit the thruster requirements of high torque and low speed, and featured high efficiency and low weight as well. By 1994 a prototype thruster had been built and tested.

The original concept was based on our experience with conventional underwater propulsion units, both hydraulic and electric. Dubbed the "ERP" for Electric Ring Propeller, it was to be simple, efficient, and easily maintained. The design applied torque to a propeller where the power is used, at the periphery. Bearings were water lubricated and easily replaced. Propeller blades were individually molded and replaceable. Maximum use was made of plastics for corrosion resistance.

Perhaps more noticeable are the things that are absent from the design. There is no propeller hub, no shaft, no gear box and no shaft seal. No structure is necessary within the area of the propeller and all thrust and torque loads are borne outside the propeller disk by the nozzle structure.

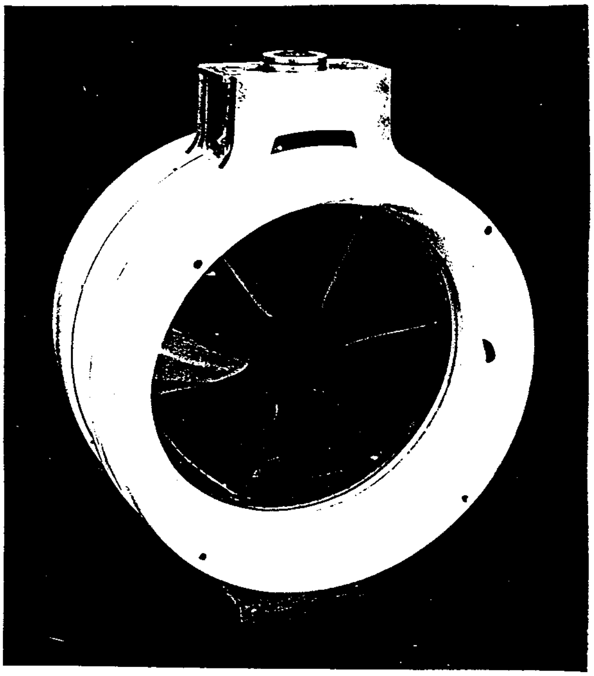

Figure 1. Prototype ERP

There are really only five major parts to the ERP. The frame and stator with point of attachment, the rotor containing the propeller blades, two end plates and bearing assembly which hold the rotor in position, and the controller which makes it operate. These can be treated separately in some detail.

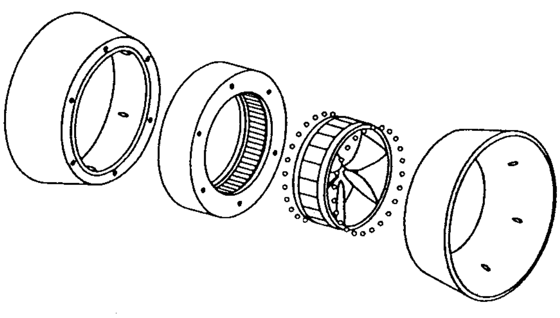

Figure 2. Exploded View

II. HARDWARE DESCRIPTION

Frame and Stator

There are two equally important functions which the frame must fulfill. It is the housing which contains the stator portion of the electric motor. It must be designed to pass the thrust generated by the propeller to the vessel and include a means of dissipating any heat generated during operation. Thrust is passed from the rotor through the bearings to the end plates which must then be secured to the frame. These are design considerations which apply mainly to strength and rigidity.

There are several ways to dissipate heat generated in the stator windings and pole laminations. The simplest, used in our prototypes, is to use a heat conducting frame material such as aluminum. The stator could be directly cooled by water flow around the rotor. A cooling system such as this would permit an all plastic construction for reduced weight in deep submergence applications.

Rotor

The rotor can be thought of as a very large diameter hollow motor shaft. In a permanent magnet motor it carries only permanent magnets and a flux return path on its peripheral surface. In this case it is a peripheral ring to which propeller blades are attached. The initial prototype was literally a propeller, complete with hub, welded into the ring at the blade tips. On both ends of this cylindrical ring is a bearing race. At rest, the bearing holds the powerful rotor magnets in close proximity to the steel pole pieces of the stator, and when spinning, transfers the axial thrust from the blades through the end caps to the vessel. The rotor itself contains no electrical elements. Its connection to the motor is entirely magnetic.

End Plates

The end plates are the demountable portion of the unit which permit assembly and maintenance. They hold the fixed portion of the bearing assembly and must transfer all of the thrust load to the vessel. In our prototypes this was done through he main frame. Hydrodynamic nozzle shapes may be part of this end plate or attached to it.

Controller

This part of the motor does require protection from the surrounding pressure at depth. The electronic assemblies are delicate and must remain dry and some components are subject to crushing under high pressure. The circuitry also generates heat and means must be provided for dissipation. The conventional solution is to build the circuitry into a water and pressure proof "can" which will dissipate heat directly to the water. This container can be attached directly to the unit or located nearby and connected by cable. Similarly, the circuitry may be located remotely, inside the host vessel or in a common electronics housing. For some applications, the controller may be built into an end plate and protected by an envelope of syntactic foam or other rigid plastic. This is considered a throw-away solution to make rapid repair on site.

III. DESIGN DETAILS

There are features of the ERP which require a more complete explanation as follows:

Motor

The motor is a three phase, WYE connected, 34 pole design. It has three Hall effect switches to signal the controller the movement of the permanent magnets in the rotor. The controller is a more or less conventional H bridge design with a current limiting circuit and a 10 kHz chopping frequency on the lower switches of the H bridge. We have built prototypes with design voltages of 28, 60 and 120 DC. Nominal horsepower for the various designs range from 1/2 to 2 hp.

Commutation

The hall effect switches can be mounted directly on the face of a pole piece in close proximity to the main rotor magnets in which case they are sealed with the stator during construction and cannot be adjusted. An alternative is to mount an auxiliary timing magnetic strip on the rotor and seal the hall effect switches in an auxiliary structure facing the timing strip. In any case, the switches and their auxiliary wiring must be sealed against seawater. There are other ways to commutate these motors, including one method with no sensing system at all.

Bearings

The bearings serve two important functions. They hold the rotor in the correct relationship to the stator while allowing it to turn. They also transmit the thrust from the race on the edge of the rotor to its opposite half on the end plate, then through bracketry to the host vehicle. Deep groove ball thrust bearings fill this roll very nicely with great simplicity. Since the major radial load occurs when the rotor is at rest, the side loading on the deep grooves is enough to maintain design clearances. In operation axial (thrust) loads force the rotating balls more firmly into the center of the grooves. Bearings are designed with replaceable plastic balls and races, all bathed in ambient water.

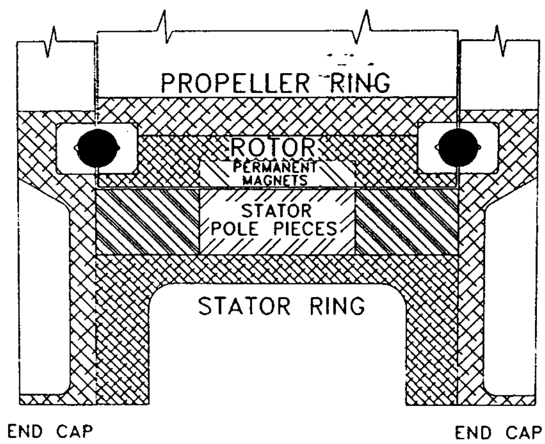

Figure 3. Cross Section

Races

The grooves in the plastic races are deep enough so that only a few thousandths of an inch separate their adjacent faces, enough space for water but not enough clearance for larger particles of sand or detritus. Grooves are filled almost to capacity and no provision is made for a cage. The balls themselves are Teflon or UHMWPE and will rub together without harm should they touch. The races are also abrasion resistant but need not have a slippery surface (a tough urethane is preferred).

Definite water circulation has been demonstrated through the bearings. Grooves in the mating surfaces between the main frame and the end caps permit circulation right through the nozzle structure. The rotor and blades, when in motion, cause a high and a low pressure effect at the propeller disk. Dye tests showed water exiting from the grooves on the high pressure side and entering the grooves on the low pressure side. The balls rolling in the bearing grooves tend to push water out by centrifugal action, somewhat confusing the pressure effects, but there remains adequate circulation through the bearings to flush away any small particles. In high power density applications, the circulation can easily be enhanced to provide direct cooling of the stator in proportion to the thrust being created.

Bearing tests were conducted to help in material choices for our prototypes and to study the effects of loading on bearing drag. The early tests quickly illustrated the need for "slippery" balls. Glass balls, for example, quickly became pitted and rough, and further testing ate up the races. Bearing drag remained less than 10% of applied torque at our low (300) rpm test speeds. When sand was added to the test container wear increased but not as much as expected. In one trial, 0.375 inch urethane balls running in UHMWPE races wore less than 0.006" in 48 hours running in a stirred mixture of 40 gallons of water and 25 pounds of sand.

One unusual turn of events will have future impact on bearing design for some applications. After one severe abrasion test a thin trail of embedded sand particles was noticed at the very bottom of the bearing grooves. This was removed by cutting a narrow "V" shaped groove at the bottom of the race. New balls were added and the test continued. The wear decreased dramatically. It was theorized that a particle in the path of an oncoming ball now had a very short escape route in the pressure wave assumed in front of the ball. It could either move out of the race or into the "V."

Propeller Blades

The ERP is a radical departure from conventional practice and introduces an entirely new set of conditions to build on. The ERP is a "tunnel thruster" or a "nozzle thruster" or whatever you choose to call it. Torque is applied at the propeller tips where it is used. The blade mounting is a solid ring which rotates and transfers thrust directly to the nozzle itself. There is no hub. There is no shaft. Instead, there is a hole at the center of the blade set. There is unobstructed flow through the entire area of the propeller disk, reducing the velocity required for a given amount of thrust.

The blades themselves are thinner and more of a foil shape for their entire length. Since they are fastened at the tip where more torque is absorbed and more thrust generated, there is less lever arm for these loads to work through, less structure is necessary to maintain rigidity and alignment. The "tip vortex" occurs at the center, adjacent to the hole, where velocity through the water is low. For vehicles whose task may include towing arrays of sensors, transducers, antennas, etc., the design can include a wine bottle shaped hollow cone from the stern of the vehicle or vessel through the center of the ERP through which tools may be deployed without regard to propeller arc.

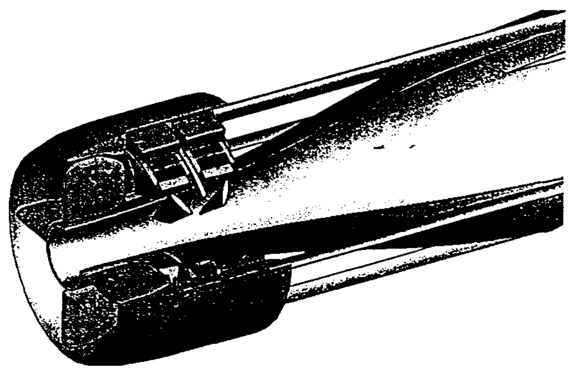

Figure 4. Counter-Rotating

The prototypes built at Harbor Branch have bi-directional replaceable molded plastic propeller blades, with the exception of the first unit. The more traditional unidirectional propeller is designed to deliver maximum thrust in one direction only, with reverse being far less efficient. Counter-rotating propeller sets work very well in this application, and the ERP lends itself to this service. Two units can easily be mounted one behind the other. As they have separate motors and no shafts it is a simple matter to control the units so that both share the load. The type control system used at harbor Branch controls input power to the motor, not rpm as some controllers do. The individual motors are free to rotate at whatever speed is necessary to absorb the allotted power. Such paired units can also be mounted to a hollow cone and controlled by a single command signal. Interestingly, the cone can be gimbaled to a vehicle and control both attitude and azimuth without the use of control fins.

IV. TESTING

During the course of the project, designs were completed, prototype units built and testing performed. Component testing was performed early, including bearing tests and electronic development. Testing continued on a dynamometer where performance could be evaluated, temperatures measured, etc. Thrust tests were performed from a small barge located in the Harbor Branch ship channel. The center of the thruster was six feet below water level and thrust was measured six feet above by means of a lever and a spring scale. Input power was measured at the battery power supply. Rpm was measured in early tests on the dynamometer and "inferred" during thrust tests. In flow observations in a tank with windows, a strobe tachometer measured rpm. Later units were built with a connection in the controller which allowed engineers to calculate rpm by measuring pulse rates on an oscilloscope.

The original propeller, hub and all, was "borrowed" from one of the spare 28-volt thrusters used on the JOHNSON SEA LINK manned submersible. It was a Kaplan type 4 blade 14" diameter aluminum prop with 14" pitch. The prototype ERP was 1 hp at a nominal 400 rpm, 28-volt DC. The initial testing was disappointing because the propeller would not absorb the full one horsepower before reaching its top speed. It was later discovered that the JSL thrusters actually contained 24-V motors and their geared down rpm was actually 462, not the 400 calculated from name plate ratings. The propeller was left in place and testing continued in order to note changes in performance which might occur as the hub was removed and the blade shape thinned and smoothed. Slight improvement was noted until area was diminished

A six bladed propeller was fashioned from an next exhaust fan and installed with a 25-inch pitch. Total blade area was kept equal to the 4-blade. Thrust was quite linear vs. input power at 0.1 pound per watt of input power.

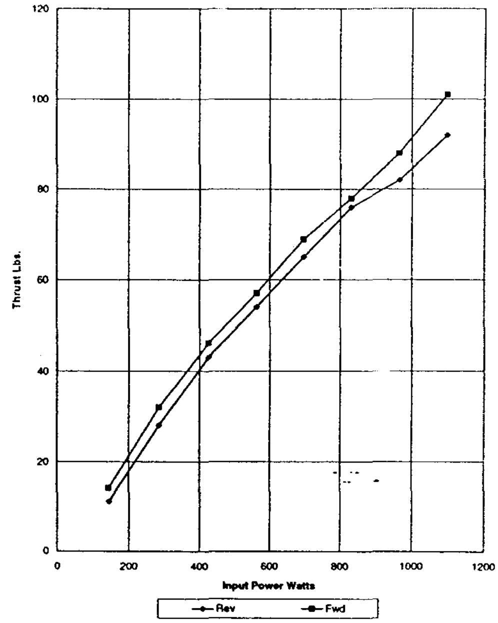

Figure 5. Thrust Watts

Later units used molded plastic blades which could be bolted in place. All were molded from a single aluminum blade pattern fashioned in the HBOI machine shop. Changes were made from that original, but always in the direction of smaller area. The 0.1 pound per watt figure was not exceeded.

V. CONCLUSIONS

Further development of the basic concept presented by the ERP will yield quieter more efficient propulsion systems. Blade refinement coupled with the low speed nozzled configuration will decrease radiated noise while delivering more thrust. More powerful versions of the ERP will be built in the future; and due to the unique relationship between the motor and the propeller, it may prove to be more efficient than conventional electric propulsion in all sizes (Figure 6 compares the ERP efficiency with two contemporary conventional thrusters).

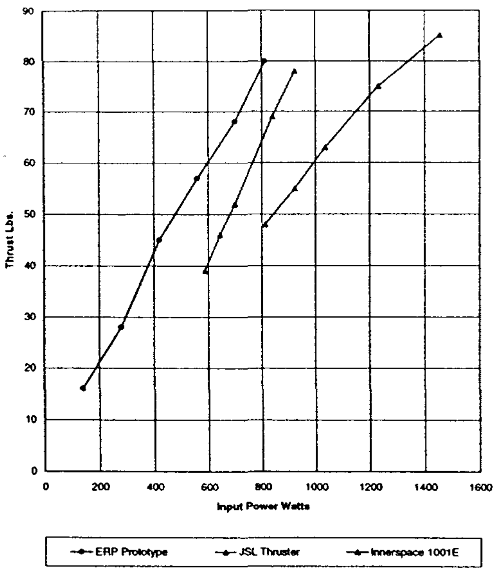

Figure 6. Comparison Graph

VI. ACKNOWLEDGEMENTS

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