EXPERIMENTAL INVESTIGATION OF A MONO-HULL MODEL BOAT WITH WAVE-LIKE AQUATIC PROPULSION

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1 INTRODUCTION

The most common method of aquatic propulsion used in existing marine vessels is a screw propeller. It has a simple design and is capable of propelling marine craft at high speeds. However, the conventional propeller has a number of disadvantages. In particular, these are cavitation and generation of the associated under-water noise. The collapsing cavitation bubbles also cause a gradual destruction of propeller blades, which limits their service life.

For many years scientists and engineers were trying to create propulsive systems that could be alternatives to a propeller. Some of them were looking for inspiration in nature, trying to simulate fish swimming using elastic wave propagation in different submerged structures. In particular, it turned out that the wave-like motion used by stingrays resembles closely the propagation of localised flexural waves along tips of submerged elastic wedges or plates of finite width[1,2]. As a result, it has been suggested to use these waves for aquatic propulsion of small marine craft, e.g. submarines[1]. The important features of localised flexural waves for wave-like aquatic propulsion is that their energy is concentrated at the tips of the plates or wedges, which means that the main body of the craft remains isolated from their vibrations. This makes it possible to apply this type of wave motion for propulsion of manned marine craft. In comparison with a propeller, the wave-like aquatic propulsion has the following advantages: it does not generate underwater noise and it is safe for people and marine animals. The first practical realisation of this type of propulsion has been made recently using a small model catamaran employing localised flexural waves propagating in a vertical rubber plate[3,4]. Note that earlier designs of wave-like propulsion using usual (non-localised) flexural waves[5,6] caused craft body rocking in response to plate vibrations. Therefore, these designs were unsuitable for manned marine craft.

The present paper describes the design and experimental testing of a small-scale mono-hull model boat propelled by a localised flexural wave propagating along a rubber plate of finite width forming the boat's keel. Tests include measurements of boat's speed, thrust and propulsion efficiency. The model boat under consideration is fully autonomous and robotically controlled.

2 CRAFT DESIGN AND CONSTRUCTION

The first stage in the design and construction of the considered model boat, that will be also called "***B****iomimetic* ***R****obotically-operated* ***A****quatic* ***VE****hicle*" (***BRAVE***), was to define the propulsive plate excitation method. The chosen design implements a leading edge excitation mechanism. Excitation of the leading edge in this manner causes localised wave propagation throughout the length of the propulsive plate towards the trailing edge.

Ideally, the propulsive plate should have a wedge-like profile to provide isolation of the flexural wave energy from the craft's body. This however was not implemented in this investigation due to the time and cost constraints. Like in the earlier work[3,4], a wedge was therefore replaced by a plate of constant thickness, with one of its horizontal edges being clamped and another one remaining free. Plate stiffness is one of the primary factors that determines the speed of flexural wave propagation in contact with water, and as such it is a major factor which determines the maximum boat speed and efficiency. Plate thicknesses of 1mm, 1.5mm and 2mm have been used in the present work.

The hull of the model boat under consideration, the ***BRAVE***, utilised an existing plastic construction developed for a radio-controlled hobby application (see Figure 1). Utilisation of this hull provided a number of advantages. In particular, it helped to minimise construction costs and to ensure the craft's stability.

Figure 1. Hull assembly of the model boat

The propulsive rubber plate was friction fitted into the aluminium chassis slot. The propulsion system was designed to ensure that, when installed, the water level lies below any through openings such as the plate slot and the exciter bar slot. This would prevent water spilling over into the hull. The concept drawings of the propulsive plate with the exciter bar and its view under water are shown in Figures 2 and 3.

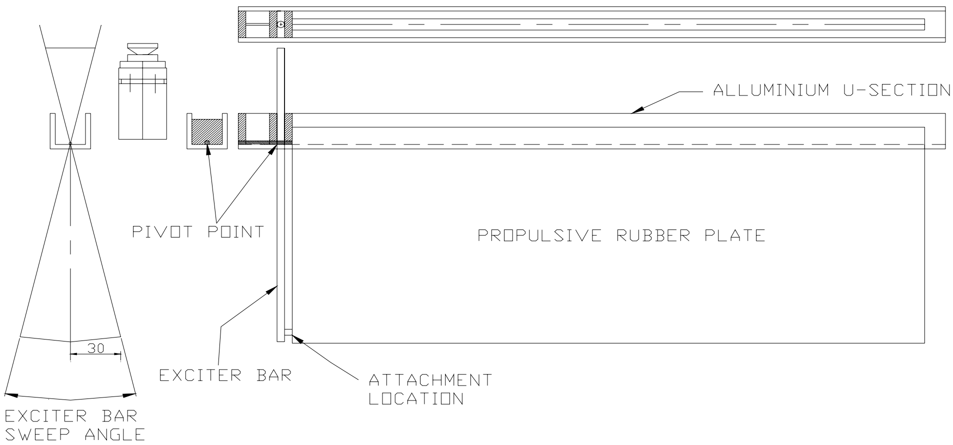

Figure 2. Concept drawings of the propulsive plate.

The exciter bar, which was driven by a servo motor, has been designed to allow maximum angle of 30^o to be achieved either side of the centre line (see Figure 2). With the exciter bar length used this gave a maximum amplitude of 33mm.

Figure 3. Under-water view of the hull and the assembled propulsive plate.

3 VALIDATION AND OPTIMISATION

Following construction of the **BRAVE**, it was necessary to validate and to optimise the propulsion system. Both the experimental pool and a Perspex test tank were used for the experiments. The following variables were investigated to ascertain the effect on propulsive effectiveness: Propulsive plate thickness, Length/width of propulsive plate, Leading edge constraints, Trailing edge constraints. Figure 4 shows the underwater view pictures taken in a Perspex tank and illustrating flexural wave propagation in the propulsive plate of 1 mm thickness at different time instants over the full period of 333 ms corresponding to the operating frequency of 3 Hz.

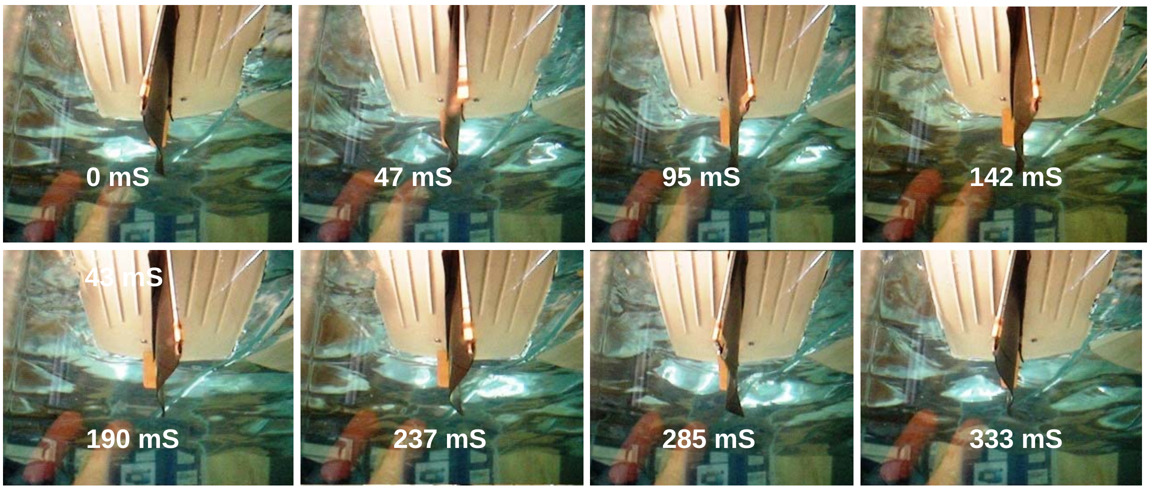

Figure 4. Wave propagation in the propulsive plate at 3 Hz and 20 mm amplitude.

4 THRUST AND DRAG MEASUREMENTS

Flexural-wave-generated thrust of the ***BRAVE*** was measured both directly (in static position) - using a spring gauge attached to the stern (see Figures 5 and 6), and indirectly (in motion) – using measured steady state velocities of the craft and measured drag as a function of the craft velocity.

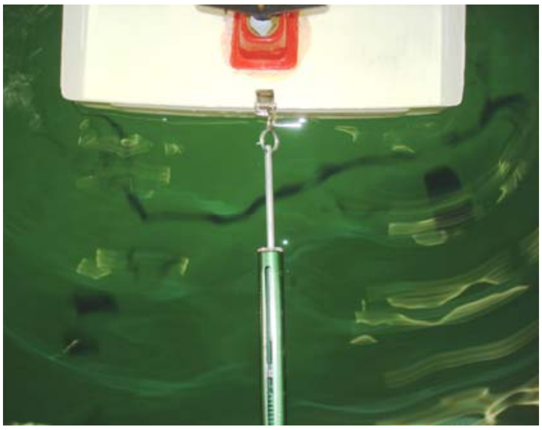

Figure 5. Spring gauge attachment

Figure 6. Static thrust test in progress

To measure drag, the craft was towed at constant velocity, and the tension in the tow cable was measured using the spring gauge (Figure 7). This process was repeated for a number of different speeds. The results of the drug measurements at different speeds are shown in Figure 8. As expected, the results can be approximated by a parabolic curve, the value of the coefficient being equal to 0.0036.

Figure 7. Drag measurement test

The technique used for data collection involved towing and timing the craft along a straight 3m course whilst maintaining a specific tow cable tension. Runs were repeated a number of times to allow for inaccuracies in the timing and tension measurements. A best fit line was drawn through the data points (see Figure 8).

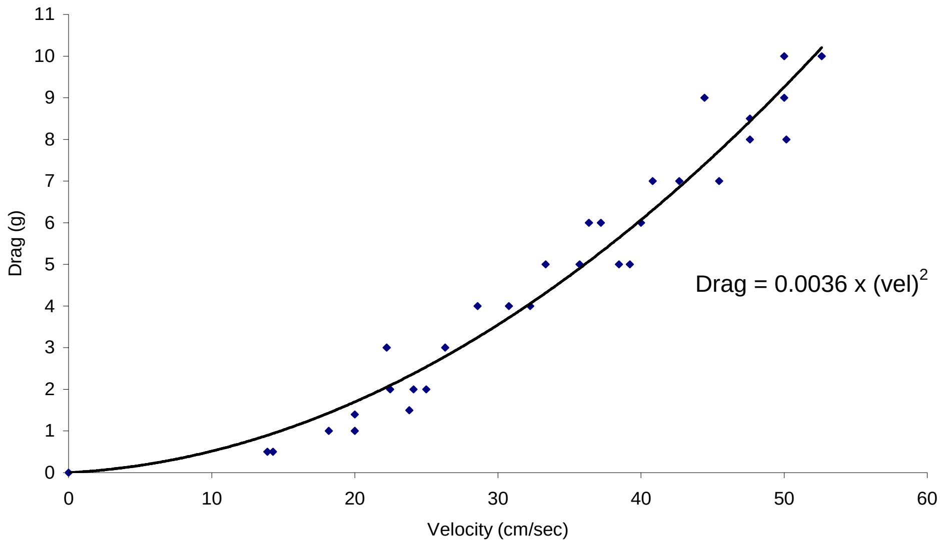

Figure 8 Craft's drag as a function of its velocity

5 SWIMMING SPEED AND OTHER IMPORTANT PARAMETERS

5.1 Steady State Velocity of Swimming

This was measured by allowing the ***BRAVE*** to accelerate to a steady state velocity. A stopwatch was used to measure the time taken to traverse a 3 metre course allowing an average speed for the boat to be calculated. Figure 9 shows the measured craft velocity.

As one can see from Figure 9, as both the frequency and amplitude increase, the velocity increases as well. The decrease in velocity at around 2.4 -2.8Hz may be due to the plate being excited near its natural frequency. In this condition, a standing wave is created displacing water at 90 degrees to the plate, rather than the desired propagating wave[3,4].

5.2 Thrust Produced

Thrust is directly related to the craft steady state velocity described above. The drag curve shown in Figure 8 was used to convert the velocity (see Figure 9) to the thrust force being produced by the propulsive plate for that condition. The results for the thrust determined in this way are shown in Figure 10. Note that these results behave very similarly to the measured steady state velocities shown in Figure 9. In particular, the thrust force generally increases as frequency increases. This is due to the higher flexural wave velocity which is achieved at higher frequencies[3,4]. It should be remembered though that a higher thrust force does not necessarily imply a higher efficiency.

Comparison has been made to the direct measurements of thrust produced for the same frequencies and amplitudes at static condition (see Figures 5 and 6). In particular, Figure 11 shows the results of the 'static' thrust measurements taken for the 28mm amplitude setting; these results are compared with the 'dynamic' thrust values determined as it was described above. It can be seen that at frequencies above about 4 Hz the 'static' thrust is higher than the 'dynamic' one. This can be explained by the fact that drag measurements at the tow test (see Figure 7) were performed with the propulsion system turned off. However, when the propulsion system was actuated for the craft speed measurements, the plate was obviously oscillating, which could result in an increase in the drag force. Therefore, the 'dynamic' thrust values calculated using the measured craft velocities are likely to be underestimated, thus explaining the apparent difference between the 'static' and 'dynamic' thrust values.

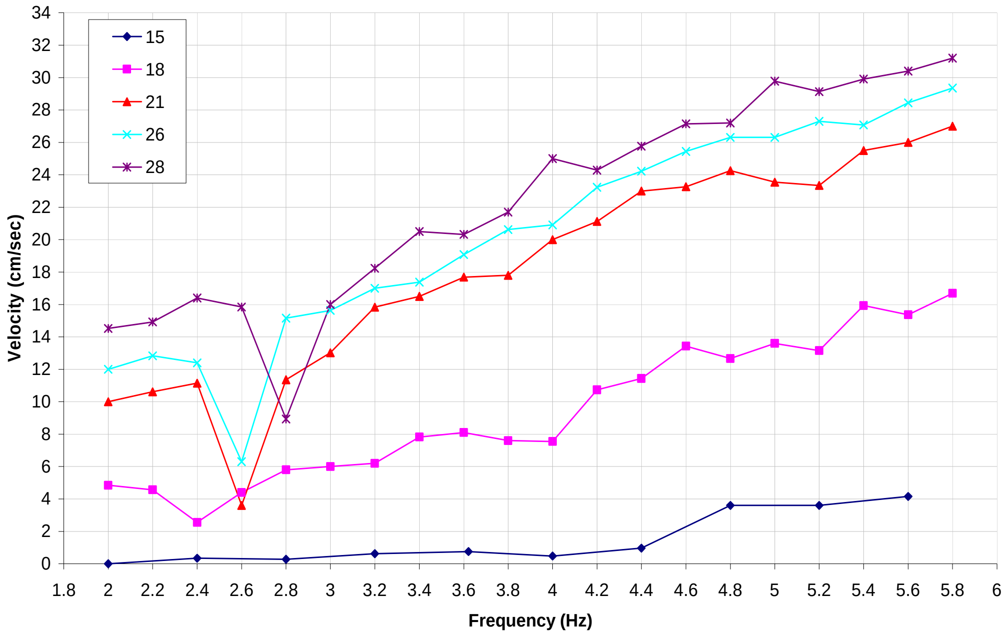

Figure 9. Steady state craft velocity as a function of frequency and amplitude

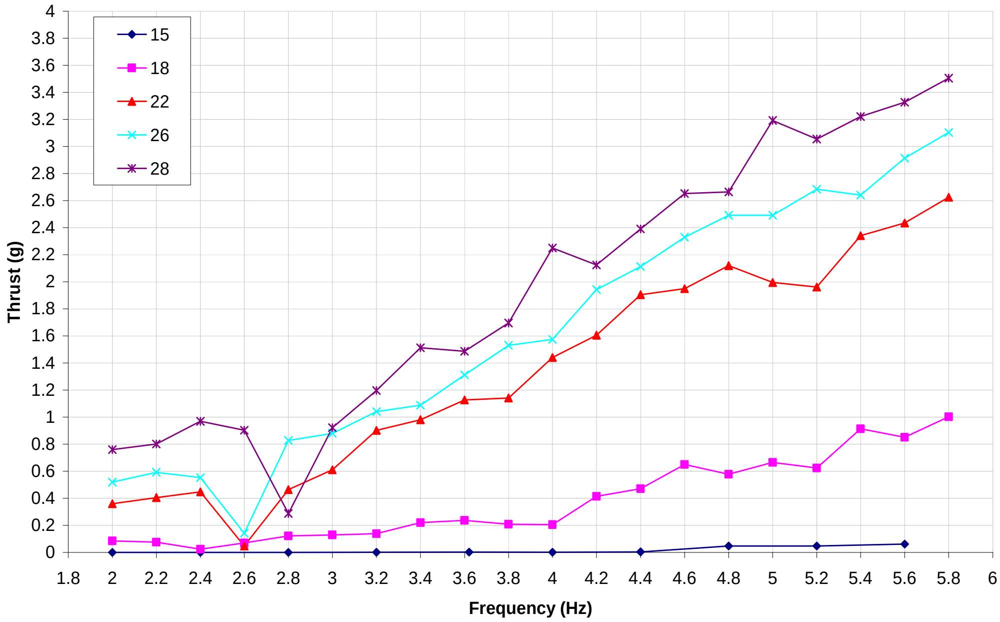

Figure 10. Variation of thrust with frequency and amplitude

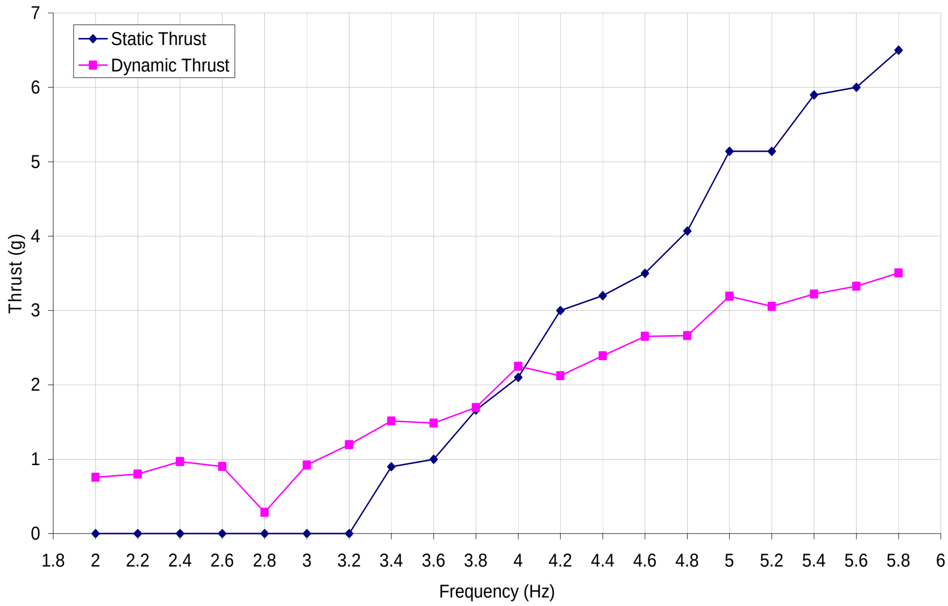

Figure 11. ‘Static’ and ‘dynamic’ thrusts at 28mm amplitude

5.3 Strouhal Number

Strouhal number, St, is a non-dimensional figure which is often used to characterise the propulsion efficiency. For example, while dolphins, sharks and bony fish move at their preferred speed, the ratio of their tail frequency f and amplitude W_0 to the swimming speed U, which constitutes the Strouhal Number, $St = f\,W_0/U$, falls between 0.2 and 0.4[7]. Strouhal number in the present work was calculated from the steady state boat velocity with the corresponding frequency and amplitude for that condition. The results show that St for the ***BRAVE*** is almost independent of frequency across a wide frequency range, where it takes values roughly between 0.4 and 1. The configuration which operates closest to the above-mentioned ‘natural’ maximum efficiency range, St = 0.2 – 0.4, is the 4.4Hz frequency and the 21 mm amplitude, which corresponds to St = 0.402.

5.4 Flexural Wavelength and Velocity

The wavelength of the flexural wave motion was measured in the Perspex test tank by inspecting photos taken using a high-speed camera. At 4.4Hz, roughly 2.8 wavelengths were present in the plate. This gave the wave speed as 39 cm/sec. Comparing this wave speed to the steady state boat velocity at this condition gives the wave speed to swimming speed ratio of 39/23 = 1.65. This is in line with the theoretical result of Lighthill for the swimming of slender fish[8], according to which for the most efficient regime the wave speed to swimming speed ratio should be equal to 5/4 (or 1.25).

5.5 Propulsion Efficiency

The efficiency of the wave-like propulsion has been calculated as the ratio of the measured values of useful work (P_{OUT}) to the electrical energy supplied to the servo motor (P_{IN}). It should be noted that the propulsion efficiency does not take into account the losses generated in the actual actuation system and is a measure of the ‘true’ efficiency of the wave-like propulsion only. In order to calculate the power inputted just into propulsion, it was necessary to measure the power consumption when running in air (which is required to overcome the actuation losses) and when in water. The difference between these two values gives the power inputted into propulsion. The electric power input to the propulsive plate in the optimal regime has been calculated as:

$$P_{IN} = V \cdot I = 5.9 \cdot 1.5 \cdot 10^{-3} = 8.85\ mW .$$

Here 5.9 V is the voltage of the batteries, and 1.5 mA is the measured difference between electric currents consumed by the craft running in water and in the air. The useful power output has been calculated as the product of the drag force and steady state craft velocity:

$$P_{OUT} = Thrust \cdot Steady\, state\ craft\, velocity = \left(2 \cdot 10^{-3} \cdot 9.81\right) \cdot 0.23 = 4.5\ mW$$

Thus the propulsion efficiency has been determined as:

$$\eta_{System} = P_{OUT} / P_{IN} = (4.5/8.85) \cdot 100 = 51\,\%$$

The calculated value of 51% indicates that the efficiency of this type of aquatic propulsion is comparable to that of a propeller (around 70%) and to that of dolphins and sharks (around 75%).

6 CONCLUSIONS

The results from the testing performed on the model boat ***BRAVE*** have confirmed that wave-like propulsion using localised flexural waves is an attractive method of propulsion for mono-hull aquatic craft. Unlike conventional propulsion methods, such as a propeller, wave-like propulsion does not generate underwater noise and is safe for people and marine animals.

It has been found that increasing both frequency and amplitude results in an increase in thrust brought about by the associated increase in flexural wave propagation velocity. It should be noted however that the highest propulsive thrust does not necessarily correlate to the highest propulsive efficiency, and an optimum frequency and amplitude of wave motion must be found.

The efficiency of the wave-like propulsion system for the ***BRAVE*** was found to be 51% when operating at the optimum Strouhal number of 0.402. This is comparable to the 70% efficiency found for propellers, and 75% efficiency for dolphins and sharks. It is anticipated that with further research and technological advances it would be possible to achieve and perhaps even exceed the efficiencies of conventional propulsion methods. However, the efficiency should not be considered as the most important feature of wave-like aquatic propulsion. The other benefits, such as elimination of underwater noise, absence of cavitation and environmentally friendly operation, make this type of aquatic propulsion very attractive for many practical applications.

7 REFERENCES

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