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Application of guided flexural waves in immersed plates to aquatic propulsion of mono-hull marine vessels

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The present paper describes the results of the experimental investigation of a small-scale mono-hull model boat propelled by a localised flexural wave propagating along the plate of finite width forming the boat's keel. Forward propulsion of the boat was achieved through flexural wave propagation in the opposite direction, which is similar to the aquatic propulsion used in nature by stingrays. The model boat under consideration underwent a series of tests both in a Perspex water tank and in the experimental pool. In particular, the forward velocity of the boat has been measured for different frequencies and amplitudes of the flexural wave. The highest velocity achieved was 32 cm/s. The thrust and propulsive efficiency have been measured as well. The obtained value of the propulsive efficiency in the optimum regime was 51%. This indicates that efficiency of this type of aquatic propulsion is comparable to that of dolphins and sharks (around 75%) and to that of a traditional propeller (around 70%). In contrast to a propeller though, the wave-like aquatic propulsion has the following advantages: it does not generate underwater noise and it is safe for people and marine animals.

1 Introduction

It is well known that 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.

To overcome the above problems, scientists and engineers were trying for years 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 has been shown theoretically and experimentally that propagation of localised flexural waves along tips of submerged elastic wedges or 'clamped-free' plates of finite width resembles closely the wave-like motion used by stingrays for their swimming [1,2]. Therefore, it has been suggested to use these localised waves for aquatic propulsion of small marine craft, e.g. submarines [1].

The important features of using 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 main advantages: it does not generate underwater noise, and it is safe for people and marine animals.

The first practical implementation and investigation of this type of aquatic propulsion has been made recently using a small model catamaran employing localised flexural waves propagating in a vertical rubber plate [3,4].

Note in this connection that earlier designs of wave-like aquatic propulsion that were using usual (non-localised) flexural waves [5,6] caused craft body to be 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 speed as well as measurements of thrust and propulsion efficiency. The model boat under consideration is fully autonomous and robotically controlled.

2 Localised flexural waves used for aquatic propulsion

As was discussed earlier [1,3,4], ideally a propulsive plate structure should have a wedge-like quadratic profile to provide full 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 experimental 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.

One should keep in mind however that, in contrast to quadratic wedges, such 'clamped-free' plates do transmit vibrations to the main body of a vessel through the area of clamping. Therefore, although quite suitable for autonomous under-water vessels (AUV), the aforementioned 'clamped-free' rubber plates can not be recommended for applications to real manned marine vessels. For the purpose of experimental investigations on a model vessel described in this paper they, however, are perfectly acceptable. Note that all of the above-mentioned localised flexural waves in contact with water are waves propagating in the subsonic regime of wave propagation (in respect of underwater sound). As it is well known, such waves ideally do not generate sound in the surrounding water. Therefore, the associated aquatic propulsion is virtually quiet, which is an attractive feature for both man-inhabited vessels and AUV.

Figure 1 shows theoretically calculated frequency-dependent phase velocities (dispersion curves) of the lowest-order guided flexural mode in two immersed 'clamped-free' rubber strips [3,4]. Calculations have been carried out using the geometrical acoustics approach [1,2]. Both strips were of the same width $H = 150\ mm$, but had different values of thickness: $h = 1\ mm$ (solid curve) and $h = 3\ mm$ (dashed curve). For comparison, the velocities for infinite plates are shown as well - for $h = 1\ mm$ (dotted curve, which practically coincides with the solid curve) and for $h = 3\ mm$ (dash-dotted curve).

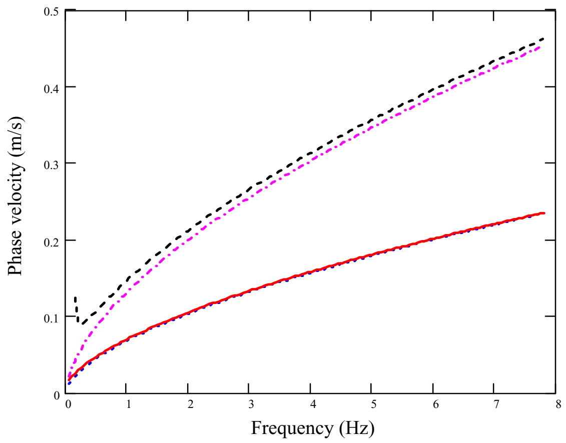

Fig.1 Calculated phase velocities of the lowest order flexural mode in two 'clamped-free' water-loaded rubber strips as functions of frequency [3,4].

One can see that for a strip of 1 mm thickness the dispersion curves for a finite strip are almost indistinguishable from the dispersion curves for an infinite plate of the same thickness. Note that in the case under consideration the calculated phase velocities of flexural waves in immersed 'clamped-free' rubber strips are very low, from about 2 to 45 cm/s, depending on frequency (these are much lower than wave velocities in the same strips and plates in vacuum). Such low wave velocities have been specifically chosen to provide several wavelengths of flexural waves on the length of the propulsive fin, which was required to emulate the 'rajiform' wave-like motion associated with stingrays.

3 Design and construction of the model boat

The first stage in the design and construction of the considered model boat, that will be also referred to as "***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.

As was described in the previous section, the propulsive plate material and thickness are the primary factors that determine the speed of flexural wave propagation in contact with water, and as such they are major factors which determines the maximum boat speed and efficiency. The choice of material in the present work was rubber, and the values of plate thickness of 1mm, 1.5mm and 2mm have been used.

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

The concept drawings of the propulsive plate with the exciter bar and its view under water are shown in Figs. 2 and 3.

The propulsive rubber plate was friction fitted into the aluminium chassis slot. Note that 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 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 Fig.2). With the exciter bar length used this gave a maximum amplitude of 33mm.

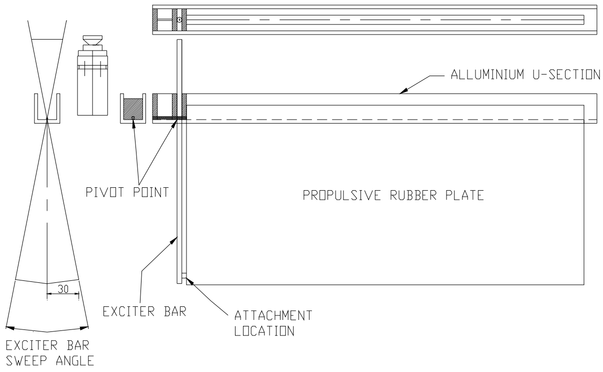

Fig.2 Concept drawings of the propulsive plate.

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.

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

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 Figs. 4 and 5), and indirectly (in motion) – using measured steady state velocities of the craft and measured drag as a function of the craft velocity. A comparison of the results of these two methods of thrust measurement is discussed in the next section.

Fig.4 Spring gauge attachment

Fig.5 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 (Fig.6). This process was repeated for a number of different speeds.

The results of the drug measurements at different speeds are shown in Fig.7. As expected, the results can be approximated by a parabolic curve, the value of the coefficient being equal to 0.0036.

Fig.6 Drag measurement test

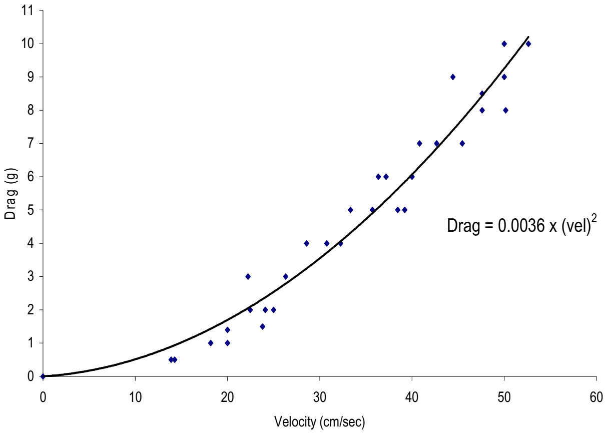

Fig.7 Craft’s drag as a function of its velocity

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 m course allowing an average speed for the boat to be calculated. Figure 8 shows the measured craft velocity.

As one can see from Fig.8, as both the frequency and amplitude increase, the velocity increases as well. The decrease in velocity at around 2.4 -2.8 Hz may be due to the plate being excited near its natural frequency. One could expect that in this condition, a standing wave is created in the plate, which is displacing water at 90 degrees to the plate, rather than the desired propagating wave [3,4]. However, as the above-mentioned plate flexural wave is of large amplitude and hence highly nonlinear, this interpretation of the observed minima as effects of plate natural frequencies should be taken with some caution.

5.2 Thrust produced

Thrust is directly related to the craft steady state velocity described above. Namely, for this condition thrust is equal to the drag. Therefore, the drag curve shown in Fig.7 was used to convert the measured steady state velocity of swimming (see Fig.8) 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 Fig.9.

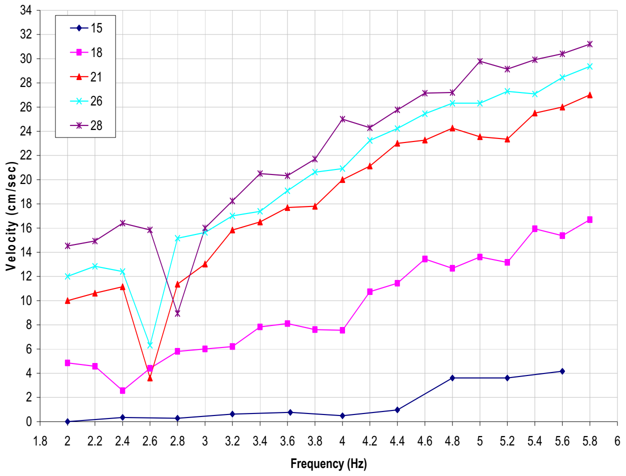

Fig.8 Steady state craft velocity as a function of frequency and amplitude

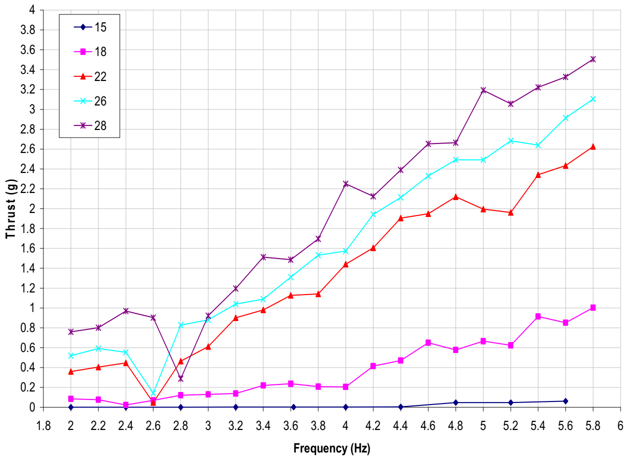

Fig.9 Variation of thrust with frequency and amplitude

Note that the obtained thrust values behave very similarly to the measured steady state velocities shown in Fig.8. In particular, the thrust force generally increases as frequency increases. This is due to the higher flexural wave velocity that 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 Figs. 4 and 5). In particular, Fig.10 shows the results of such '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 Fig.6) 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.

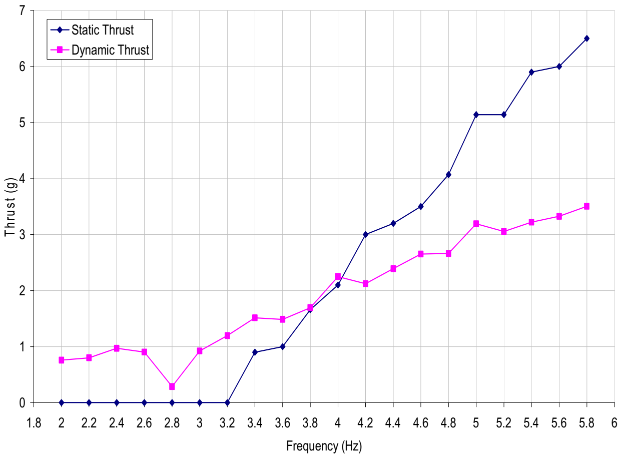

Fig.10 'Static' and 'dynamic' thrusts at 28mm amplitude

5.3 Strouhal number

Strouhal number, St, is a non-dimensional figure that is frequently used in hydrodynamics. In particular, it is often employed 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 (see [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 value of 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 under consideration has been determined 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 determined in this work does not take into account the power losses occured in the actual actuation system. It is thus a measure of the 'true' efficiency of the wave-like propulsion only. In order to determine 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.

Thus, 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 thrust 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 η has been calculated using the above-mentioned values as:

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

The obtained value of 51% indicates that the efficiency of this type of aquatic propulsion is comparable to that of a screw propeller (around 70%) and to that of such effective swimmers as 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 aquatic 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 typical 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.

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