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# FIRST EXPERIMENTAL OBSERVATION OF THE AQUATIC PROPULSION CAUSED BY LOCALISED FLEXURAL WAVES IN IMMERSED STRUCTURES

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**Abstract**

The present paper reports the results of the first experimental observation of the wave-like aquatic propulsion suitable for man-inhabited marine vessels. The idea of this propulsion, first published by one of the present authors (V.V.K.) more than 10 years ago, is based on employing localised flexural elastic waves propagating along edges of wedge-like elastic structures. Such wave-supporting structures can be attached to a body of a small ship or a submarine as keels or wings and used for the propulsion. To verify the idea experimentally, the first working prototype of a small catamaran using the above-mentioned wave-like propulsion via the attached rubber keel has been build and tested. The test results have shown that the catamaran was propelled quite efficiently and could achieve the speed of about 36 cm/s, i.e. approximately one length of the vessel per second. The reported proof of the viability of the idea of wave-like propulsion as alternative to a propeller may open new opportunities for marine propulsion which can have far reaching implications.

## INTRODUCTION

This paper describes the results of the first experimental observation of the wave-like aquatic propulsion suitable for manned marine vessels and proposed by one of the present authors (V.V.K.) more than 10 years ago [1]. The idea of the propulsion in question is based on employing the unique type of localised flexural elastic waves propagating along edges of wedge-like structures immersed in water [1-4]. Such wedge-like elastic structures supporting localised flexural waves can be attached to a body of a small ship or a submarine like fish fins and used for aquatic propulsion (see Figure 1). The principle of using localised flexural waves as a source of aquatic propulsion is similar to that used in nature by some fish, e.g. stingrays, that utilise wave-like motion of their large pectoral fins (wings) for moving forward.

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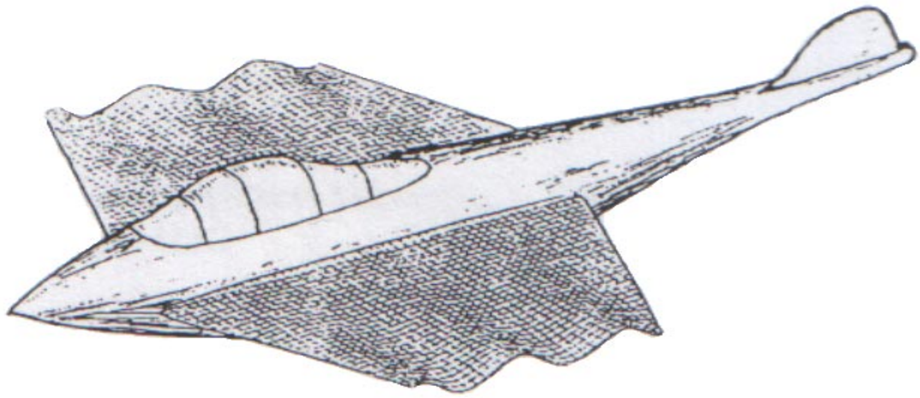

*Figure 1 - Artist's impression of the proposed use of localised elastic waves for propulsion of a small submarine [1]; the localised flexural waves propagate along the tips of the horizontal fins (wings), their energy being concentrated away from the main body.*

There is a long history of human efforts to imitate fish swimming in man-made marine craft, especially in autonomous underwater vehicles (AUV) that are now being used in a wide variety of scientific investigations and surveillance operations. Several types of fish swimming modes have been tried extensively, for example, the beating of the caudal fin or tail, which is used most extensively in nature [5-8]. However, caudal fin type of propulsion, although applicable to AUV, is unsuitable for man-inhabited marine vessels, as the main body of the vessel would be rocked in reaction to such a propulsion, making on-board conditions unsustainable.

For the above reason, the only mode of fish swimming which seems to be attractive for manned vessels is the undulatory wave-like motion seen in stingrays and skates [6]. It is this specific swimming mode used by stingrays and skates that is inspirational and the most close to the propulsion using localised waves in elastic wedges (wedge elastic waves) described in the present work. It is vitally important for the application of wedge elastic waves for propulsion of manned vessels that, in spite of the wings' vibration, the main body of the vessel remains virtually quiet because the energy of localised waves is concentrated near the wings' tips [1].

The expected main advantages of the new wave-like propulsion of marine craft over the existing ones, e.g. propellers and jets, are the following:

1. *It is quiet, which is a particularly attractive feature for surveillance operations and for applications where minimal disturbance of wildlife is important;*
2. *It is expected to be energy-efficient since it follows nature (this, however, needs to be proven both theoretically and experimentally);*
3. *It is environmentally friendly and safe for people and wildlife.*

Envisaged applications of wave like propulsion are small and medium research and pleasure man-inhabited ships and submarines. Obviously, it can be used also for

AUV propulsion, in addition to the existing methods. Another possible application is for sailing. One of the problems associated with sailing boats is that they are stranded in very calm wind conditions. This is usually overcome with outboard motors used in times of low wind. The replacement of the outboard motor by a flexible keel providing wave-like propulsion would be very beneficial as it would not affect the hydrodynamic characteristics of the hull.

To verify the idea experimentally, we have built and tested the first working prototype of a small catamaran employing the above-mentioned wave-like propulsion via the attached rubber keel. The test results have shown that the catamaran was propelled quite efficiently and could achieve the speed of about one its body length per second (35.8 cm/s), thus demonstrating that the idea of wave-like propulsion of man-inhabited craft is viable. The reported proof of the viability of this idea as alternative to a propeller may open new opportunities for marine craft propulsion, which can have far reaching implications.

## SUITABLE TYPES OF LOCALISED FLEXURAL WAVES

The wave-like propulsion of man-inhabited marine vessels, which is the main focus of this paper, is based on employing the unique type of localised flexural waves propagating along tips of elastic wedges immersed in water. Such guided waves, that are often called water-loaded *wedge elastic waves*, have been first predicted theoretically in the same paper [1] where the idea of using these waves for aquatic propulsion has been first suggested. Further developments of the theory of water-loaded wedge waves have been published in paper [2], and their existence has been confirmed experimentally by independent researchers [3,4].

Because of their complex nature, wedge waves generally can be described only numerically even for the simplest case of wedges in vacuum which was first considered in the 1970's (see e.g. [9] and references there for more detail). This is even more so for wedges in contact with water. However, for the important case of slender wedges the situation can be simplified in both cases by using the geometrical acoustics approximation [9-11]. Using this approximation, one can obtain relatively simple and physically explicit solutions for localised guided waves propagating in wedges in contact with vacuum [9-13] as well as in wedges immersed in water [1,2,13].

For the purpose of aquatic propulsion, one can use wedge waves propagating in wedges of any shapes. The most suitable, however, appear to be quadratic wedges, which local thickness is described by the function $h(x) = \varepsilon x^2$, where $x$ is the distance from the edge and $\varepsilon$ is a constant. In such wedges, all modes of localised flexural waves are dispersive, i.e. their phase velocities depend on frequency [12,13]. This would allow an operator of a marine vessel with wave-like propulsion to change wedge wave velocity by changing frequency, which may be very convenient for efficient start of the vessel from rest. Note in this connection that from the theory of swimming of slender fish, e.g. eels, it is known that the velocity of wave-like motion of a fish body at stationary conditions should be slightly higher than the velocity of swimming [14-17]. Apart from this, the advantage of quadratic wedges is that they utilise a larger proportion of their surfaces for localised wave propagation in comparison with linear wedges, which again is beneficial for aquatic propulsion.

Although flexural waves in quadratic rubber wedges seem to be the most appropriate for aquatic propulsion of man-inhabited craft, in these first experiments it was more practical to replace them by similar type of localised flexural waves propagating in simpler structures. In particular, one of the possibilities was to use the earlier established similarity between localised wave propagation in quadratic wedges and in the geometrically simpler systems comprising thin elastic ridges embedded in an elastic half-space [12]. The latter systems are in turn similar to even more simple structures - elastic strips with one free edge and with another edge being clamped. Note that all of the above-mentioned systems are characterised by similar dispersion behaviour of localised waves caused by physical similarity in wave-guiding properties of such systems. In particular, there are different modes of flexural waves in each system, which all have minima of phase velocity at certain frequencies. Therefore, for the purpose of this work, it was decided to use 'clamped-free' rubber plates as propulsive vibrating structures. 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 AUV, the aforementioned 'clamped-free' rubber plates can not be recommended for applications to real manned marine vessels.

Calculations of the frequency-dependent phase velocities of the lowest-order flexural mode in immersed 'clamped-free' rubber strips have been carried out using the geometrical acoustics approach [1,2] for the two values of strip thickness: 1 mm and 3 mm. The width of the strip was 150 mm in both cases. It has been shown 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. For a 3 mm strip the phase velocity is slightly higher than in an infinite plate of the same thickness and has a minimum at frequency of around 0.3 Hz.

## MODEL VESSEL AND EXPERIMENTAL RIG

Although the main envisaged applications for the wave-like propulsion considered is for use on small ocean man-inhabited research submarines and AUV, at this early stage of the investigation a simpler surface-boat-type vessel (a catamaran) and the associated experimental rig have been designed and built.

The basic rig comprised the central propulsive plate (fin) mounted on the two supporting pylons (30 cm each) positioned at 90 degrees to the fin. The pylons could then either be clamped above a water tank to study water flows generated by the vibrating propulsive fin or their ends could be attached to a pair of pontoons to form a catamaran. The propulsive rubber plates were clamped along one edge and were free on the other three sides, thus forming the aforementioned ‘clamped-free’ strips of finite length. Assuming that frequencies of wave excitation are in the range 2 - 10 Hz, the thickness of the basic rubber plate was chosen as 1 mm. The width (span) and the length (chord) of the propulsive rubber plate were chosen as 150 mm and 250 mm respectively. The plates were excited at the tip by given flexural displacements of a mechanical pivoted arm that was attached to the leading edge of the propelling plate and driven by the electric motor. The motor was connected to the exciting pivoted arm via an additional mechanical arm and a disk with a set of 12 drilled holes placed at different distances from the centre of rotation. The drilled holes allowed for a change in amplitudes of the plate excitation by changing the pivotal position of the additional mechanical arm. These holes were designated by the symbols D1 - D12, from innermost to outermost ones, each of them being associated with the specific increased value of the displacement amplitude of the plate tip.

The experimental testing took place in two stages. The first stage had been carried out in a water tank, where the rig (the propulsive part of the model vessel) did not move. This testing in an enclosed and controlled environment allowed for easier and more accurate observations of the water-loaded flexural waves generated in an immersed propulsive fin and of the resulting water flows associated with the propulsion. The second stage took place in open water, with the rig mounted on a catamaran and moving due to the effect of the wave-like propulsion.

A 12-24 V dc motor with a gearbox was chosen to power the craft. The gearbox ratio could be adjusted between 4:1 and 4096:1. In particular, using a 64:1 gear ratio gave a suitable maximum rotational speed of roughly 300 rpm (or 5 Hz) at the maximum rated voltage of 24 V.

The open-water stage of testing incorporated the same basic propulsive test rig as the water-tank testing, with the addition of buoyancy aids (pontoons) to the sides of the rig to assemble a catamaran craft. Two Styrofoam pontoons were designed to maintain the fully immersed water depth of the fin. The rig was weighed, and the pontoons were sized accordingly. With the motor mass offset from centre in both the longitudinal and lateral directions, the right-hand pontoon needed to be longer than the left-hand (50 cm and 35 cm respectively), with both pontoons extending forward of the main deck. This configuration ensured a level deck of the vessel.

## EXPERIMENTAL RESULTS

During the testing in a water tank the propulsive fin was placed vertically in the centre of the container and fully immersed. The flow speeds were measured by timing the movement of the small pieces of cork floated in water over a set distance.

The main part of the testing in a water tank included observation of the behaviour of the fin as a source of propulsion over a range of amplitudes and frequencies. The frequency (in Hz) was equal to a number of motor revolutions per second. The actual observed frequency depended on the loading and on the input electric power. The speed of the water flow generated by flexural waves propagating along the propulsive fin was measured for different values of the input electric power and frequency.

Naturally, the best operating setting for the propulsive system under consideration would be the one corresponding to the maximum efficiency of propulsion. Using the measured values of the input electric power $P_{in} = I \cdot V$ and of the flow speed $v$ in a water tank, it was possible to estimate the relative propulsive efficiency of the fin at the various test conditions. In particular, it has been found that there is the maximum relative efficiency at around 3.8 Hz, with the amplitude setting D6 ($W_0$ = 2.8 cm). The frequency at which the maximum efficiency occurs corresponds to the input voltage of 23 V. To achieve the desired maximum efficiency the system would have to be pulling 5 W of electric power. For the open water testing, this was provided by the set of lead acid batteries. These were very heavy and required to be off the craft, with a wire feed.

The open-water testing was carried out in the experimental pool. Two sets of tests were performed. The first was a timed run over a distance of 3m, the craft starting form rest. This was designed to measure averaged speeds of the craft over this distance. The second set of tests was again a timed run over a distance of 2m, but with an initial speed achieved after passing the added 'acceleration' distance of 2m, an ample space to reach what appeared to be a stationary speed. This set of tests was obviously designed to measure stationary speeds.

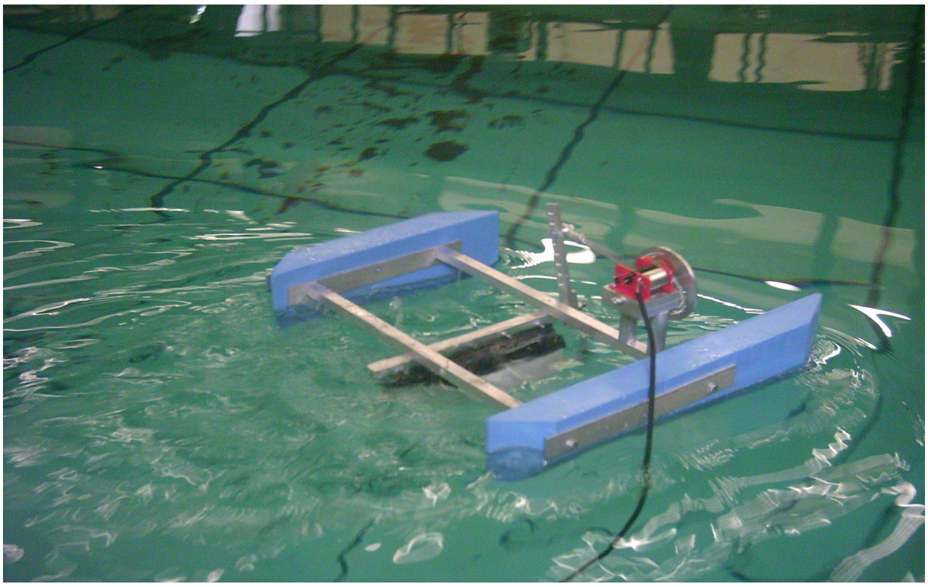

*Figure 2 - View of the moving catamaran with the wave propulsive system during its testing in open water.*

When powered from the external batteries via a flexible cable, the catamaran demonstrated fast acceleration from rest to stationary speeds (see Figure 2). The achieved speeds were in the range 22.9 – 35.8 cm/s, which was high enough in terms of the craft lengths per second. The amplitude settings used in the tests were D4 ($W_0$ = 2.2 cm), D6 ($W_0$ = 2.8 cm) and D8 ($W_0$ = 3.2 cm). The obtained results demonstrate that the wave-like aquatic propulsion considered is viable and efficient.

The qualitative comparison of the measured craft speeds in open water with the predicted phase velocities in clamped-free plates has shown that the achieved speeds were comparable with the calculated wave speeds in the propulsive plates at the operating frequencies, around 3.8 Hz. As expected, the results on propulsion efficiency obtained from the in-tank testing agreed with those observed in the open-water test. For example, at the open-water test condition of 22 volts (corresponding to operating frequency of 3.8 Hz), the most efficient amplitude setting was D6, then D8, and then D4, which was in agreement with the in-tank testing.

Absolute measurements of the propulsive efficiency and comparison of the efficiency of the proposed type of wave propulsion with the efficiency of a propeller were beyond the scope of this paper concerned primarily with the feasibility studies. To make such measurements and the comparison meaningful one would require to optimise the mechanical design of the model vessel. In the current design, which employs the motor disk and mechanical arms for flexural wave generation, a substantial amount of energy is being lost due to friction at the mechanical arm contact points. This reduces substantially the energy efficiency of the system.

It makes sense, however, to evaluate the potential efficiency of the proposed wave propulsion indirectly, using the non-dimensional Strouhal number $St = f\, W_0/U$, where $f$ is the undulating wave frequency, $W_0$ is the wave amplitude, and $U$ is the stationary speed achieved by the vessel. It is known that the Strouhal number can be used to characterise the propulsive efficiency of fish regardless of the energy consumption used to achieve the actual values of $f$, $W_0$, and $U$ (see e.g. [19]). It is also known that propulsive efficiency is the highest for $St$ within the interval $0.2 < St < 0.4$. In particular, this is true for such efficient swimmers as dolphins, sharks and bony fish, which all swim at $0.2 < St < 0.4$.

Note in this connection that the value of $St$ for the proposed wave-like propulsion in the regime corresponding to its maximum relative efficiency ($f = 3.8$ Hz, $W_0 = 2.8$ cm, and $U = 35.8$ cm/s) can be calculated as $St = 3.8\ 2.8/\ 35.8 = 0.297$. The remarkable fact is that this value of $St$ is also in the 'high efficiency range' $0.2 < St < 0.4$, which may imply that the proposed wave like propulsion is potentially as efficient as the propulsion of dolphins and sharks!

## CONCLUSIONS

The most important conclusion resulting from this work is that localised wedge or plate flexural elastic waves can indeed be used to generate wave-like aquatic propulsion and to propel a small marine craft. To propel a manned craft one should use propulsive fins made of quadratic elastic wedges that keep the wave vibration energy away from the main body of the vessel.

Although the current experimental rig used a rather complex mechanical construction to achieve the localised flexural wave excitation, it is expected that further investigations could lead to the development of a simpler and more efficient marine craft. In particular, this could include the use of electro-active bending polymers (EAP) to directly generate flexural waves at a leading edge in a plate or wedge. This would reduce or even eliminate any moving parts from a wave propulsion rig, giving it another advantage over a conventional propeller.

Further work is required to investigate the efficiency of wave propulsion in comparison with its main rival, a propeller. However, even if the efficiency of wave-like propulsion cannot be developed to surpass that of a propeller, there is still an unexplored niche for it. Namely, wave-like propulsion may have no rivals in cases where quiet and safe operation is paramount, in particular in the cases of small manned research submarines and autonomous underwater vehicles (AUV).

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