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Large-scale ultrasonic cleaning system: Design of a multi-transducer device for boat cleaning (20 kHz)

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ABSTRACT

The present study is part of a global project which consists in the development of an automatic cleaning station for immersed boats (cockle, ninepin, etc.) in a self-service mode, associating an innovative ultrasonic device for cleaning with a specific water treatment. The originality of the process is that cleaning is performed by three transducers operating simultaneously at low frequency and moving along the surface, thanks to programmable logic controllers, and that it includes a suction to collect the dirt removed. Therefore, the time required for boat maintenance is shortened, ensuring high quality cleaning without the need for dry docks and avoiding additional pollution in the harbor areas. One of the key points was the evaluation of washing efficiency, as it is really hard to give a quantitative estimation of the dirt removed. To obtain the first design laws, feasibility tests have been carried out on dirty cockle samples and on real boat hulls with a laboratory ultrasonic device. The influence of a large number of parameters was tested such as transducer-probe distance, displacement speed and transmitted power. The obtained data allowed us to design an optimized cleaning device combining high efficiency and speed.

1. Introduction

Cleaning motor and sail boats is an expensive and lengthy operation, because it is necessary to take the boat out of the water in dry docks. Moreover, cleaning is usually performed manually and could be assisted by high pressure water. To keep the boat in good condition, one operation per year is required. In fact, before the end of the first year, the dirt layer remains thin and not very adherent. After this time, this layer becomes thick and the adhesive strength increases, while foam begins to inlay in the cockle. At this stage, only an extensive cleaning operation can save the boat, closer to an etching process consisting of sanding the surface.

On another hand, use of ultrasound is frequent in cleaning in surface treatment industries, since it is a good way to remove dirt without damaging the products [1,2]. In fact, ultrasound is known to induce cavitation phenomena in liquid media, and some of the bubbles generated collapse asymmetrically near the surface [3,4]. It induces a mechanical cleaning effect due to the high velocity fluid jet delivered while the bubbles collapse. This had already been observed on a microscopic scale, while irradiating a sample during the activation step before an electroless coating. Evidence of cleaning the palladium surface by removing agglomerates of colloidal palladium has been shown [5]. Additionally, the ultrasonic wave also induces a stirring effect of the liquid media, which is helpful in cleaning operations.

In these conditions, ultrasound appears to be an interesting tool for designing a new device, as it is possible to remove the thin dirty layer created in less than one year while keeping the boat in the water [6]. It could therefore be a faster, easier and cheaper way of performing maintenance, with a total operation time of 2 h at most (compared with two days' downtime for a classic cleaning operation). Moreover, this new type of process is able to collect the waste and direct it toward a specific water treatment, thus reducing the negative impact on yachting activity environment. In fact, waste is not only made up of bio-organisms, but also by other pollutants present in the sea water or in its neighborhood, and linked to the dirt layer. This is particularly true if an anti-fouling paint is present, as it is the case for most of the less than 15 m long boats. The ultrasound process should remove the superficial layer of this paint, including pollutant heavy metals, and ensure their treatment before releasing them. Finally, the cleaning station including this ultrasonic process could be designed to run in a self-service mode, which will be very easy to use by ship owners.

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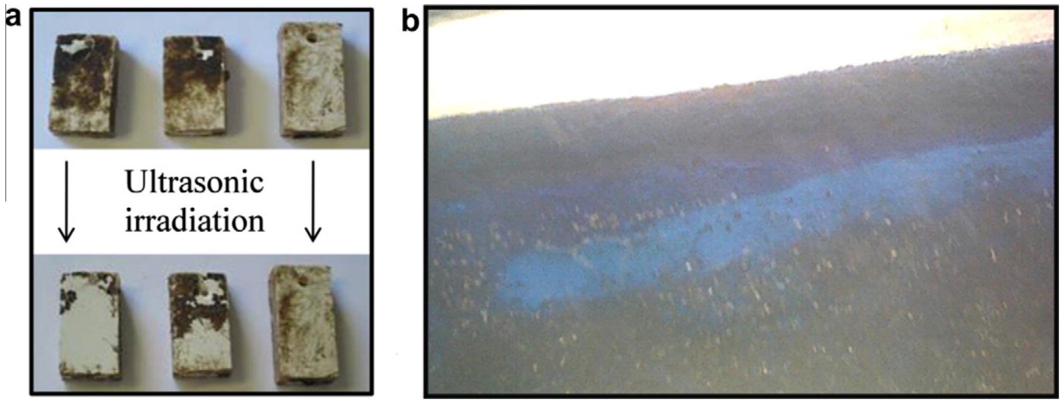

Fig. 1. Results from first cleaning tests: a. Cleaning test on dirty polymer samples; b. cleaning test on a real boat hull.

2. Experimental section

2.1. Preliminary tests: Feasibility

At the beginning of this project, feasibility tests were performed with 20 kHz Vibracell equipment (1500 W power and 25 mm titanium circular emission). Vibration frequency was chosen in order to use high powers and amplitude waves. The first time, static cleaning tests were conducted on dirty cockle samples in order to test their efficiency in removing an organic coat on resin ("gel coat") surfaces. Only two parameters were studied: irradiation time and the distance between the ultrasonic device and the sample. The most difficult part was to appreciate cleaning quality because it appears that simple measurements yielded a better appreciation than visual observation.

Some results are presented on Fig. 1a. On the top left, dirty samples are produced, and on the bottom, the same samples can be seen again after ultrasound treatment. To summarize, only the extreme conditions are presented i.e. three different times of ultrasound irradiation (10, 30 and 60 s from left to right) and three distances (1, 2 and 5 cm from left to right) were used.

The first sample is almost clean, which proves that ultrasound is able to clean a boat hull. The second sample is partially clean and the third one is dirty, as though ultrasound treatment produces no improvement. This shows the limits of this process. In fact, the ultrasound wave is attenuated with distance in the water, so the end of the horn has to be close to the surface to ensure good efficiency. The acoustic transmission of low frequency ultrasound has been extensively studied by tomography techniques to give cavitation bubble distribution [7], as well as with the help of Particle Image Velocimetry to appreciate convective flow in the close zone of the transducers [8]. Nevertheless, quantification of all phenomena induced by ultrasound (cavitation and convection) is not trivial, and a unique parameter has been calculated: equivalent flow velocity [9]. A systematic study in the transducer vicinity leads to the same conclusions i.e. that the power necessary for cleaning decreases drastically with distance, and that after a few millimeters, efficiency is not sufficient to allow cleaning effects [10]. The third sample clearly illustrates this phenomenon: there is not enough cleaning effect at long distances, even with a long irradiation time.

To confirm these encouraging results, real tests have been performed on a boat in the harbor of downtown Marseille. To this end, a prototype consisting of a waterproof chamber has been built to protect the transducers and avoid energy losses in water the length of the ultrasonic horn. One of the results is shown on Fig. 1b in the form of a picture of the cockle after ultrasound treatment at a distance of 2 mm. The cockle painted in blue[1] is covered by green dirt, and reappears in the form of a light blue line as the result of ultrasound treatment. Another test with larger distances is not as good as the previous one. These dynamic studies were also useful in that they gave the range of magnitude of displacement speed limitation for the wave guide to maintain an efficient process, and in the meantime also revealed some technical difficulties to overcome to attain the objective. In fact, all specifications for higher power transducers with larger emitting surfaces included in a special waterproof device have been recorded, to aid complete equipment design.

2.2. Design

The preliminary tests allowed us to determine the main parameters to consider for an efficient ultrasound cleaning process: (i) the distance between ultrasound emitting surface and boat hull should always remain as short as possible, (ii) many pieces of practical information, (iii) the upper limit of the displacement speed ensured a sufficient degree of cleanliness. The appropriate operating speed seems to be kept at less than 5 cm s^{-1} depending on surface dirty level. This parameter is the most important in determining the number of transducers and the transducer geometry required to be able to clean an entire 15 m long boat in less than 2 h. Already, it is possible to propose that two devices operate simultaneously on both sides of the boat. Furthermore, the area cleaned is almost the same as the emitting area. Consequently, the diameter of the wave guide needs to be enlarged in order to clean a wider surface at the same time. Finally, each cleaning device should include three ultrasonic horns and an aspiration collecting the waste and directing it toward a water treatment plant (Fig. 2a). The three ultrasonic horns are placed in a triangular position to ensure a wider surface cleaned for a linear displacement (row by row) while taking up as little space as possible. A brush around the ultrasonic horns is used to keep the dirt in the vicinity of the aspiration device and help remove the smooth dirt detached from the surface by the ultrasound. Both devices will be placed on both sides of the boat, moving automatically all along the hull as shown in Fig. 2b.

The wave guides use as ultrasonic horns (TA6 V titanium alloy) have been especially designed to satisfy the specific conditions of use and all the requirements of the cleaning station: the wave amplitude as great as possible to improve efficiency but with low overheating and high reliability. In the meantime, the transducers

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

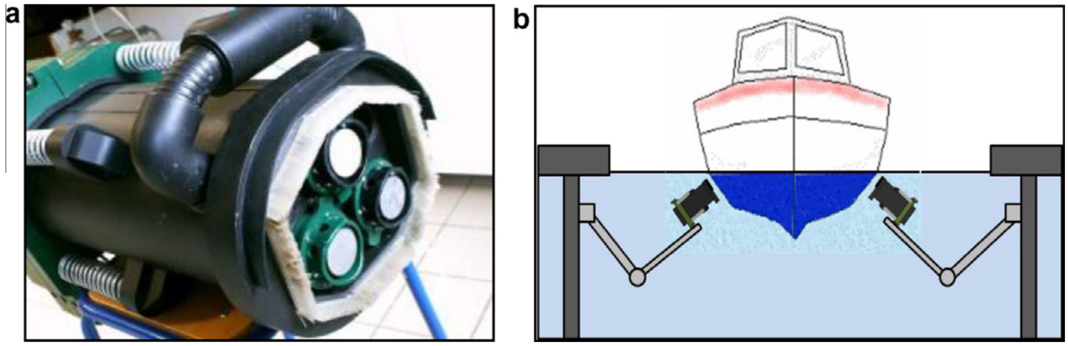

Fig. 2. Cleaning tool: a. Photograph; b. cleaning station with two devices.

need to be protected from water, to avoid electrical issues and to limit energy loss. To be able to resonate at 20 kHz, the dimensions of the different parts of the wave guide have been calculated using specific software (Atila®). The resonating condition has a direct effect on the axial dimensions of the different pieces of the vibrating device, thus accounting for the large size of the tool. Electrical generators are supplied by Martin Walters (1000 W) equipment with automatic control of power input.

To assist in tool design, tests have been performed at every step, both for technical features and for cleaning efficiency in order to optimize the operating parameters. This had led to successive drawings of all the component parts of the tool. It consists in calorimetric measurements [11] and sonochemiluminescence pictures [7,8], as well as cleaning efficiency evaluation on static and dynamic experimental set-ups.

Dynamic cleaning tests were performed in a long tank, equipped with a system able to move the ultrasonic horn perpendicularly to cockle sample at variable speeds. A PMMA tank has also been built 1.2 m long, 30 cm wide and 20 cm high and thus able to receive hull samples of 1 m long. This makes it possible to simulate the displacement of the wave guide along a boat hull on a laboratory scale.

2.3. Characterization and optimization

2.3.1. Characterization

2.3.1.1. Calorimetric measurements. The temperature of the water exposed to the acoustic field increases gradually with time, irrespective of wave amplitude. The energy yield of our specific devices is measured by comparing the transmitted power measured by calorimetric measurements and the electric power delivered by the power supply [11,12]. This determination was systematically conducted to characterize new design of ultrasonic wave guides.

For our cleaning application, it is important that three ultrasonic devices could run together with as little destructive interaction as possible. This was confirmed by calorimetric measurements by running ultrasonic horns individually or simultaneously in a confined zone (Fig. 3).

The results prove there are no significant destructive interactions between the waves of two or more ultrasonic set-ups running close to each other. In fact, the transmitted power for two transducers is nearly the same as twice the transmitted power of one device. This can be explained by the fact that ultrasound beam is mainly directive and that very little of the total amount of transmitted energy spreads around the emitting surface. So, even if there are some destructive interactions between some transversal or reflected waves, this is not important enough to have an impact on the global calorimetric measurements. In the same way, cleaning efficiency will not be reduced when we use two or three devices together, since these potential minor interactions will not destroy the major part of the directive ultrasound beam where almost all the energy is concentrated.

2.3.1.2. Sonochemiluminescence of luminol. To visualize the possible interaction of the acoustic activity of two probes operating simultaneously and close to each other, pictures of sonochemiluminescence [13] were recorded as shown in Fig. 4. On this picture,

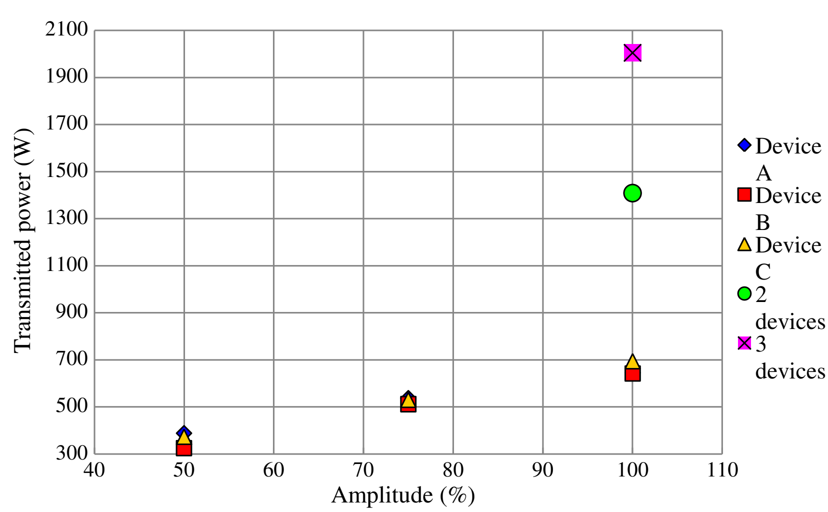

Fig. 3. Transmitted power versus amplitude for single or multi devices.

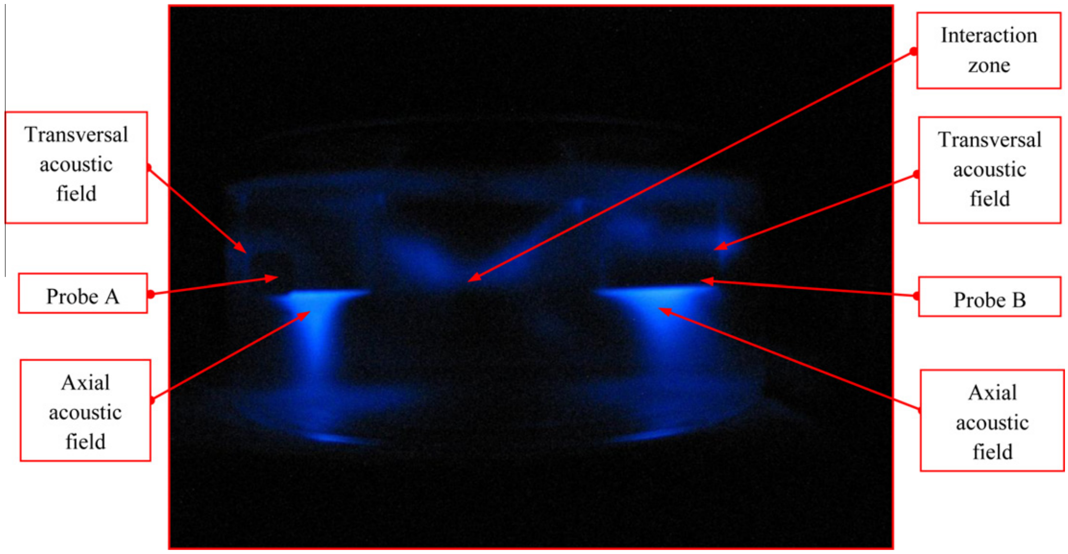

Fig. 4. Photography of sonochemiluminescence for two devices running together.

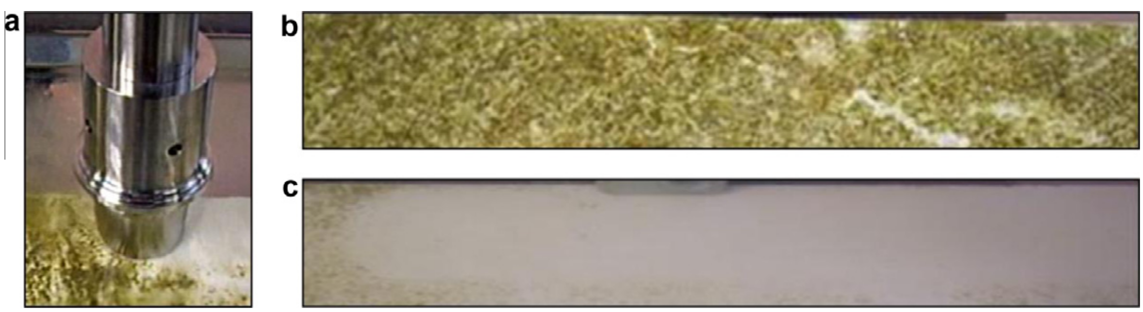

Fig. 5. Dynamic cleaning test of a dirty sample: a. Ultrasonic device cleaning the sample; b. dirty sample before cleaning test; c. dirty sample after cleaning test.

transducer A was running with an amplitude of 50% and transducer B with an amplitude of 80%. The difference in power is clearly visible with the size of the luminescent cone under each emitting surface. The other important information is the transversal acoustic activity around the immersed part of the wave guide, together with the interaction between these two transversal acoustic fields. However, this transversal acoustic activity seems to be very small compared to axial activity and is too far away from the major axial luminescent cone to disturb it. The only consequence of this transversal activity is a slight loss of energy which slightly decreases the part of the total transmitted power useful for the cleaning process.

The important characteristic of our ultrasonic devices revealed by these two global characterization methods is the fact that it is able to deliver a high quantity of energy and produce high acoustic activity, which will be beneficial for the boat cleaning operation.

2.3.2. Cleaning parameter optimization

The most important feature of our ultrasonic devices is its cleaning efficiency in order to build the boat cleaning station. So, cleaning tests on dirty samples were necessary to evaluate its efficiency and to determine the limits of the process.

2.3.3. Dirty samples

Dynamic tests on dirty samples give information about the cleaning efficiency of the ultrasonic device. Influence of distance between the emitting surface and the cockle sample, of speed motion or of amplitude of the ultrasonic wave can also be chosen further to these studies.

Fig. 5 clearly shows the good efficiency of the process, since the sonicated zone 5c is properly cleaned after one run in dynamic mode with a 2 $cm\,s^{-1}$ speed. The major problem with this test is the difficulty to get samples. In fact, it takes considerable time, several weeks to a few months, to obtain a dirty coat in marine water, which finally constitutes a limit of the test.

2.3.4. Painted samples

To compensate for the restricted number of samples, a substitute is needed. Cockle samples coated with antifouling painting appear interesting, because the first layer in contact with the water is easy to remove in quite the same conditions as biological dirt. Moreover, it is attractive because painting etching could be a further application.

2.3.4.1. Auto polishing painting. This includes a copolymer binder soluble in water and eroding gradually layer per layer in contact with water during ship movement. This is done by creating a conversion layer on its surface. A black painting was used on a white cockle sample, and the conversion layer appears in a kind of dark grey. When this layer is removed, the painting appears black again for a few seconds, before a new conversion layer is formed. This painting is interesting because we can conduct both dynamic, with the conversion layer, and static etching tests.

The first test was a cleaning test in dynamic mode, and the conversion layer and craps that could be attached on it were removed, without distorting the base of the painting which will regenerate the conversion layer within a short time. We then decided to con-

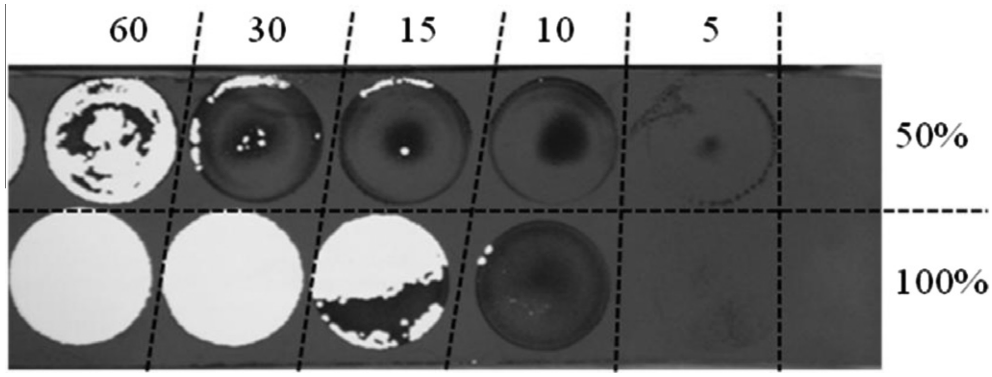

Fig. 6. Static cleaning and etching test on auto-polishing painting with two wave amplitudes (50% and 100%) and five sonication times (5–60 s).

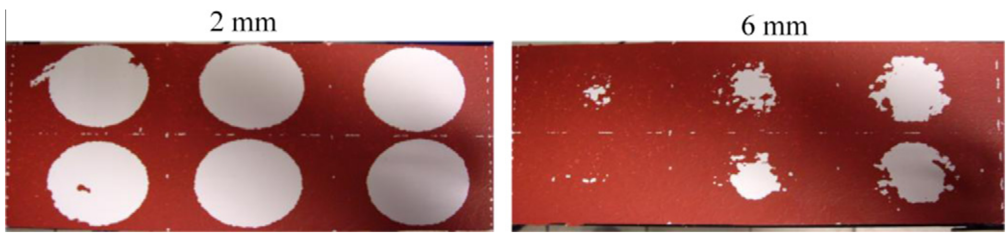

Fig. 7. Hard matrix sample after etching tests.

duct some static tests to evaluate the etching power of our devices and efficiency with irradiation time. Distance to the sample and wave amplitude were fixed, and irradiation time was changed from one spot to another. The results are shown in Fig. 6. Unfortunately, the conversion layer is regenerated very quickly and thus the results shown in the picture are not totally representative of the real effect. But we can still see clearly the influence of wave amplitude and irradiation time on the etching results. In fact, with 50% wave amplitude, only the conversion layer is attacked up to 15 s of sonication. The etching phenomenon then begins in the middle and at the edges and spreads to the rest of the surface directly exposed to the ultrasound beam. One minute is not enough to have a fully etched surface. However, with full wave amplitude, 30 s are enough to perform a complete etch, and the minimum time should be around 20 s. In the meantime, only the conversion layer is removed for a cleaning time of less than 10 s, even with the higher wave amplitude. This confirms the dynamic results as motion speed was 2 cm s^{-1} which corresponds to an irradiation time of about 2 s for a point placed in the middle of the ultrasonic device, whereas in static tests, 5 s only attack the conversion layer which is regenerated very quickly (almost finished when the picture was taken).

These tests prove the importance of wave amplitude as a parameter for the cleaning operation and the etching potential. It also shows the influence of sonication time on efficiency and explains why motion speed cannot be too high because the cleaning effect is not instantaneous.

2.3.4.2. Hard matrix painting. This kind of painting includes a binder which does not dissolve in water, and contains "micro-organism killer components" which diffuse into the water. Consequently, there is no conversion layer, and this coating can be used only for etching tests.

Information expected from these tests is to know whether a hard-matrix painting will be resistant to cleaning, and whether complete etching for a renovation is possible with our ultrasonic tool, even with a longer irradiation time. The painting we used is red, and the cockle sample is white.

Fig. 7 shows part of the results obtained with this painting. Three parameters were studied: the distance between the horn and the painted sample, the wave amplitude and the sonication time. The upper line tests were carried out at 80% of wave amplitude, and the down line tests at 95%. On this picture, there are four (two distance, two wave amplitude) batches of three tests (three sonication times). For each batch, sonication time was 30 s on the left, 1 min on the middle and 2 min on the right.

Distance has a major influence on results, because hard matrix painting is all etched for a distance of 2 mm although it is not even cleaned with 2 min of sonication at a distance of 6 mm. It confirms that distance is an important parameter as the previous tests on antifouling painting or for feasibility have showed. Wave amplitude has no influence in this case. Different times of ultrasound irradiation give only significant results at 6 mm, but this is not as important as distance. In fact, if the distance is too great, the time to etch is far too long to be a viable option for the cleaning station. Finally, higher wave amplitudes give good results without damaging antifouling painting and the cockle, especially in dynamic mode.

Cleaning, the etching test and characterization helped us to choose the important parameters and their optimum values, such as motion speed or distance to the boat hull. Moreover, wave guide geometry was optimized, and the waterproof chambers and the cleaning tool designed to satisfy these better values and to solve some problems such as major overheating or tightness issues.

3. Conclusion

Preliminary tests had proven that ultrasonic boat cleaning is possible. A new wave guide was then designed, as well as a waterproof chamber and a cleaning tool. The ultrasonic device has been studied to optimize the cleaning parameters. Thanks to the data obtained with all cleaning, etching and characterization experiments, all the components of the cleaning tool are ready for a test in real conditions. Thanks to a manual set-up built in our laboratory, an in-situ test had been successfully performed on a 15 m boat in the Mediterranean Sea last summer. Moreover, our ultrasound cleaning process may or may not be associated with the use of antifouling painting. This will continue to be the choice of the boat owner, because the cleaning effects do not affect the painting itself.

Finally, characterization of ultrasound activity in disturbed flow will be investigated, to evaluate the influence of tool displacement or water aspiration on process efficiency.

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