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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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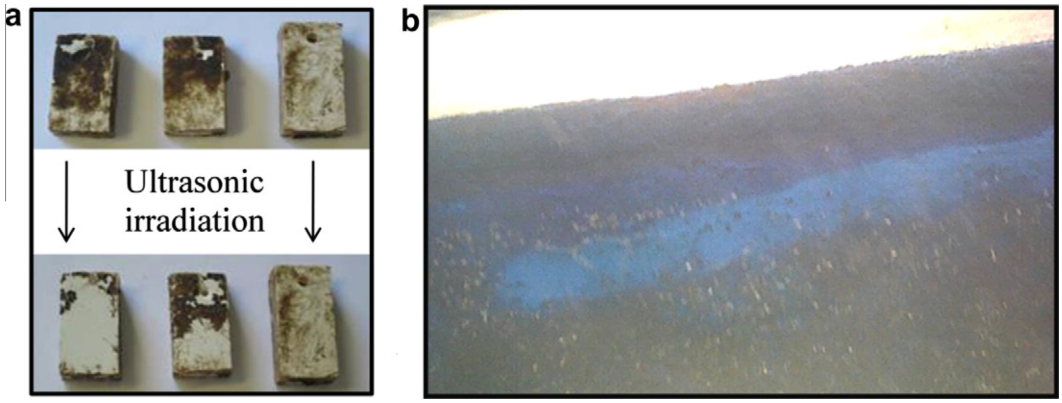

Fig. 1. Results from first cleaning tests: a. Cleaning test on dirty polymer samples; b. cleaning test on a real boat hull.

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.