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Review

Acoustic methods for biofouling control: A review

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ABSTRACT

Biological fouling is a significant problem to the shipping industry causing significant increases in fuel, maintenance, and downtime costs. Environmental concerns associated with toxic antifouling coatings have led to studies on alternative methods of biofouling control. This paper provides a literature review on laboratory and sea trial studies, which have used acoustic techniques for biofouling control. To the best of the authors' knowledge, this is the first in depth literature review on this topic. Applications of the reviewed studies have included the inhibition of biofouling on vessel hulls and pipes and also treatment of ballast water. The studies have used transducers operating in the audio and ultrasonic frequency range and sparkers. Variations were found in these acoustic parameters, which were reported to provide inhibition. Some have reported that low ultrasonic frequencies (about 20 kHz) may be optimal. The potential effect of marine life is considered. The use of ultrasonic frequencies for biofouling control appear to be more desirable than audio frequencies since they are outside the hearing range of most marine life. More studies are needed on this topic, which are well documented in terms of the parameters used and efficiency of the trials.

Contents

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1. Introduction

Biological fouling, also called biofouling, is the undesirable formation of organisms on a surface immersed in water. Biofouling build-up increases the drag force caused by water flowing past the surface. It can cause blockage of intake pipes and heat exchangers, and can result in biocorrosion (Yebra et al., 2004). Biological fouling is a significant problem for all marine structures such as ships, offshore rigs and oceanographic sensors (Guo, 2012).

Biofouling has a significant economic cost for the shipping industry. Biofouling can substantially increase ship hull friction. Heavy calcareous fouling is calculated to increase required shaft power by 86% as compared to a hydraulically smooth hull at cruising speed (Schultz, 2007). Higher fuel consumption is required to compensate for this effect, which results in increased cost and pollution. Biocorrosion may also be caused by the biofouling, which may affect the structural integrity of structures in contact with water. There are maintenance costs, loss in operation time, and production of toxic waste associated with addressing these biofouling problems (Guo, 2012). There are different kinds of measures taken to combat the effects of biofouling, which include antifouling coatings, see Fig. 1. Environmental concerns associated with toxic antifouling coatings have led to studies into alternative methods for biofouling control, which include acoustic techniques (Yebra et al., 2004; Gittens et al., 2013).

This paper was conducted as part of the Cleanship project. This project will perform trials on plates in a port environment with the aim of investigating the use of ultrasonic waves for prevention and detection of biofouling on ship hulls. Key information required for the project were the operating parameters, such as frequency and power, which would provide the optimal biofouling control, while minimising the potential undesired effect on marine life. A literature review on this topic was made to address these questions. To the best of the authors' knowledge, this is the first in depth literature review performed on studies using acoustic techniques for biofouling control.

In the following sections, biofouling and some non-acoustic methods for its control are briefly described. A literature review of acoustic methods for biofouling control is then presented. The applications include inhibiting biofouling on vessel hulls and pipes and also treatment of water including ballast water. These studies have used transducers operating in the ultrasonic and audio frequency range and also acoustic sparkers. An analysis of the potential effect of acoustic biofouling techniques on marine life is provided. A discussion then emphasises the need for developing a methodology, which documents the operating parameters used and the performance of the trials so that a design of an effective system can be more easily obtained.

Fig. 1. Photo of a ship with antifouling coating on the hull. Photo provided by Lloyds Register.

2. Biofouling

Fouling, in general, can be defined as the accumulation of organic or inorganic matter on a surface. Biofouling is the formation of microorganisms, plants, and other marine life on a surface in contact with water (Yebra et al., 2004). Upon immersion of a surface into water, a film composed mainly of dissolved organic material begins to form almost immediately (Guo, 2012). Next microorganisms begin to colonise the surface in a layer referred to as microfouling. These microorganisms include fungi, algae, bacteria, and diatoms. This layer starts forming within hours of immersion. Larvae of larger marine invertebrates such as bryozoans, mussels, barnacles, and polychaetes also begin to attach to the microfouled surface in a layer referred to as macrofouling (Callow and Callow, 2002; Guo, 2012). The development of these biofouling layers is dependent on a combination of different environmental conditions such as salinity, temperature, conductivity, pH, dissolved oxygen content, organic material content, hydrodynamic conditions, currents, light, depth, and distance from the shore (Delauney et al., 2009). Refer to Fig. 2 for two example photos of biofouling on ship hulls.

3. Non-acoustic methods for biofouling control

A broad spectrum, high-toxicity antifouling coating system containing Tributyltin (TBT) compounds was developed in the mid-1950s (Yebra et al., 2004). This became a very successful antifouling system, covering an estimated 70% of the world fleet at one time (Thomas and Brooks, 2010). Unfortunately, TBT systems adversely affect the environment. Copper, with the addition of

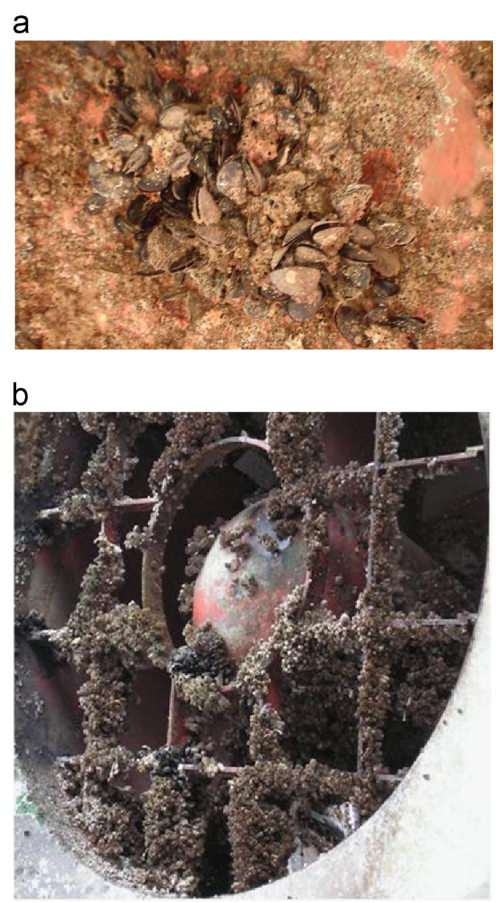

Fig. 2. Example photos of fouling on vessel hulls. Photos provided by WRS Marine and Lloyd's Register.

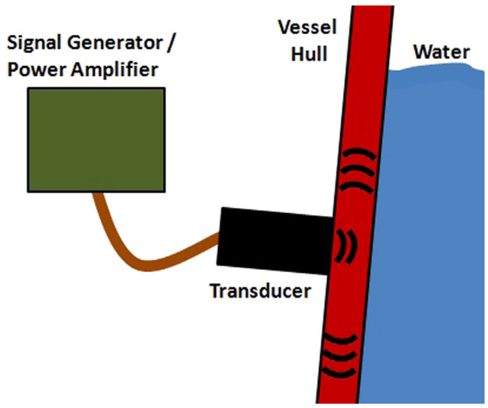

Fig. 3. Diagram showing a basic acoustic antifouling system for a vessel. A signal generator/power amplifier is used to drive a transducer attached to a vessel's hull causing it to vibrate.

booster biocides, has replaced TBTs as the main biocide ingredient in antifouling coatings (Brooks and Waldock, 2009; Guo, 2012). There are still environmental concerns associated with copper based antifoulings (Thomas and Brooks, 2010). There is, therefore, an interest in developing environmentally friendly alternatives.

Naturally occurring antifouling substances may be extracted from a variety of natural sources and incorporated into a paint matrix. These compounds would need to be harvested or synthesised in large quantities at a commercially viable price (Yebra et al., 2004). Fouling release coatings reduce the attachment strength of the fouling, allowing them to be more easily removed by water flow or mechanical cleaning. It has been reported that these coatings are relatively expensive, exhibit poor adhesion to the substrate, and are easily damaged (Brady, 2001; Swain, 1999; Yebra et al., 2004). Other non-toxic antifouling techniques have included textured surface coatings, mechanical techniques, and electrical methods (Chou et al., 1999; Yebra et al., 2004; Salta et al., 2013). For pipes, other methods used include the use of chemicals, acids, hot water, and UV techniques (Yebra et al., 2004; Omae, 2003; Guo, 2012).

4. Acoustics methods for biofouling control

Acoustic antifouling methods may provide a non-toxic alternative for biofouling prevention. The applications that have been studied include biofouling inhibition of vessel hulls and pipes and treatment of ballast water. The methods used may be divided into two groups: ultrasonic and audio range wave emission systems and acoustic sparkers (also called pulsers).

4.1. Marine vessel acoustic antifouling studies

4.1.1. Ultrasonic and audio biofouling hardware

Studies relating to the application of preventing biofouling on vessel hulls have used devices emitting mechanical waves in the ultrasonic (>20 kHz) and audible (20 Hz–20 kHz) frequency range. These devices are generally composed of a signal generator or self-oscillating circuit, power amplifier, and a transducer, see Fig. 3. Transducers used have included piezoelectric transducers (Branscomb and Rittschof, 1984; Choi et al., 2013; Gavand et al., 2007; Kitamura et al., 1995; Seth et al., 2010 Guo et al., 2011a,b, 2012; Mazue et al., 2011) and strips/films (Latour and Murphy, 1981; Murphy and Latour, 1979; Wooden and Edelman, 1981), magnetostrictive transducers (Sheherbakov et al., 1974), and audio speakers (Piper, 1977).

Multiple transducers may be used together as an array to optimise the overall gain. Placement geometry and spacing of the transducers need to be considered, due to the effects of constructive and destructive interference. Destructive interference may produce areas, referred to as anti-nodes, where the acoustic energy will be a minimum, potentially reducing the biofouling effect at these areas. The position of the anti-nodes may change with frequency (Piper, 1977; Mazue et al., 2011). The antifouling effectiveness may be expected to decrease with increasing distance from the transducer locations (Sheherbakov et al., 1974).

4.1.2. Ultrasonic frequency range studies

Acoustic antifouling studies have been performed in the ultrasonic frequency range (Arnold and Clark, 1952; Berkowitz, 1957; Waldvogel and Pieczynski, 1959; Aksel'band, 1960; Mori et al., 1969; Kohler and Sahm, 1976; Ciesluk and Dufilo, 1977; Sheherbakov et al., 1974; Latour and Murphy, 1981; Jenner et al., 1983; Fischer et al., 1984; Donskoy et al., 1996; Suzuki and Konno, 1970; Kitamura et al., 1995; Seth et al., 2010; Aquatic Science Inc, 1995; Mazue et al., 2011 Guo et al., 2011a,b, 2012, 2013, 2014; Panchal et al., 1995)[2]. A number of sea trials have been reported to have successfully used lower ultrasonic frequencies (tens of kHz) for preventing biofouling growth. Latour and Murphy stated that Waldvogel (Waldvogel and Pieczynski, 1959) had reported that 16 ft aluminium boats vibrated at 25–55 kHz with 25 W input (several W/m^2) were "relatively free" of fouling. Similarly, Latour and Murphy stated that Aksel'band (1960) had reported that merchant ship hulls vibrated for periods of several years had "reduced fouling levels". These two references were not able to be found by the authors so it is unclear what the baseline for these reported reduced fouling levels were. Sheherbakov et al. (1974) stated that by 1972 about 20 vessels in the Soviet fleet had been equipped with ultrasonic antifouling protection systems. The hulls were vibrated using oscillators fixed to the inner hull operating between 17 and 30 kHz at 200 W. They observed that fouling prevention was evident, but that a stripped fouling pattern occurred due to reduced vibration amplitude at the bulkheads and framing. At considerable distances from the oscillator, where the oscillation acceleration level was below 70 dB, they reported dense fouling.

A number of lab studies have investigated the effect of ultrasound on barnacles using power levels high enough to cause cavitation. In a lab study on barnacles, Kitamura et al. (1995) investigated three different frequencies (19.5, 28, and 50 kHz) and reported 19.5 kHz to be the most effective. For 19.5 kHz, they stated that 4300 kPa s (sound pressure level multiplied by treatment duration) resulted in 50% mortality in barnacle larvae, while 140 kPa s treatment resulted in 50% inhibition of larvae settlement. Guo et al. (2011b) used selected resonant ultrasound frequencies of 23, 63, and 102 kHz at 20 kPa to investigate its effect on barnacle settlement inhibition. Similar to Kitamura et al., they reported 23 kHz to be the most effective frequency. By varying the cavitation threshold, while keeping the same sound pressure level, they demonstrated that cavitation had a significant barnacle settlement inhibition effect. It was suggested that part of the observed frequency dependence might be due to the cavitation threshold being lower and implosions more powerful at lower ultrasonic frequencies. Sub-cavitation level trials *were* then performed where first the same sound pressure level of 5 kPa and then the same transducer head displacement of 10.05 nm was

[2] Arnold and Clark (1952), Berkowitz (1957), Waldvogel and Pieczynski (1959), Aksel'band (1960), Mori et al. (1969), Kohler and Sahm (1976), Ciesluk and Dufilo (1977), Sheherbakov et al. (1974), Fischer et al. (1984), and Donskoy and Ludyanskiy (1995) have not been viewed by the authors of this paper but have been mentioned by others in the reviewed literature.

Table 1
Example information from the literature on ultrasonic frequency range acoustic treatment of biofouling. In this table, the citations have been sorted by transmission frequency. Where more than one frequency was used, reported optimal frequency has been used for sorting.

Treatment types	Frequency	Organism type	Power	Treatment duration	Application	Comments
Magnetostrictive transducer	17–30 kHz	Biofouling	200 W	–	Ship (fixed to inner hull)	Prevention achieved. Settlement inhibition only (Sheherbakov et al., 1974)
Transducer	20 kHz	Biofouling	1000 W	–	Boat	Biofoulers and other foulers removed. Cleaning rate 4–6 cm/s (Mazue et al., 2011)
PZT transducer	23, 63, 102 kHz	Barnacle	9, 12, 22 kPa pressure	30–300 s	Laboratory	23 kHz optimal frequency at 22 kPa for 30 s. Settlement inhibition. Mortality observed only in long duration. Cavitation (Guo et al., 2011a,b)
Transducer	20–25, 63 and 102 kHz	Barnacle	10.5 nm substratum vibration and 5 kPa pressure.	Continuous and "5 min on 20 min off" treatment.	Laboratory	23 kHz optimal frequency. Settlement inhibition. Intermittent signal achieved same efficacy with continuous signal treatment. Not cavitation (Guo et al., 2012)
PVF_2 piezo-film strips	24 kHz	Barnacles worms, mussels	2 A–12 V. Acceleration 0.004–1g	6–7 months	Fiberglass yacht hull. No antifouling on 3 m^2 section.	No fouling observed (Latour and Murphy, 1981)

Table 2
Example information from the literature on audible frequency range acoustic treatment of biofouling.

Treatment types	Frequency	Organism type	Power	Treatment duration	Application	Comments
Transducer	30 Hz	Barnacle	–	20 h	Laboratory dishes	Settlement inhibition only (Branscomb and Rittschof, 1984)
PZT Transducer	70–445 Hz	Barnacle	Velocities 3 mm/s, 1.5 mm/s, and 0.75 mm/s	3 months	Sea trials (vibrated panels)	Barnacles only affected by treatment. Settlement inhibition only. Increasing frequency and velocity amplitude increases inhibition level. No effect below 200 Hz (Choi et al., 2013)
PVF_2 film and a vibrator	50 Hz and 5 kHz	Barnacles worms, mussels	0.05*g* (5 kHz) and 0.005*g* (50 Hz)	5.5 months	Panels and 2 m fiberglass skiff	Skiff and 5 kHz panel unfouled after 5.5 month, 50 Hz and control panel completely fouled after 5 month and 2 months respectively (Latour and Murphy, 1981)
Vessel generator noise and speaker in bath (lab)	Wide bandwidth (30–100 Hz) dominate	Wide range of fouling. Lab study *Ciona intestinalis* larvae	127.5–140.6 dB re 1 μPa. Reduces with increased frequency	24 h (lab)	Four 25 m vessels and lab trial	Biofouling higher on the fishing vessel in the sites closest to the generator. In lab trial, the rates of settlement, metamorphosis and survival are significantly increased in *C. intestinalis* larvae when exposed to vessel noise (McDonald et al., 2014)
Speaker playing vessel generator noise	30 Hz–2 kHz dominant	Wide range.	128 dB re 1 μPa RMS. Reduces with increased frequency	27 days	Fiber-cement panels (200 × 200 mm) in the sea	More than twice as many bryozoans, oysters, calcareous tube worms and barnacles settled and established on surfaces with vessel noise compared to those without (Stanley et al., 2014)

used for all three frequencies. In both cases, they again reported 23 kHz to be the most optimal. They concluded that this frequency dependence was not simply related to cavitation effect but must also be related to some additional factors, such as vibration of the surface or acoustic waves in the water. They also demonstrated that turning the equipment on and off in cyclical operation mode achieved similar settlement inhibitory effects compared to continuous mode. They suggested that 5 min on and 20 min off might be suitable in terms of energy antifouling efficiency and lifespan of the equipment. Table 1 provides a brief summary of some ultrasonic biofouling control studies (Guo, 2012).

4.1.3. Audio frequency range studies

Acoustic antifouling studies have been performed in the audible frequency range (Branscomb and Rittschof, 1984; Fischer et al., 1984; Choi et al., 2013; Latour and Murphy, 1981; Gavand et al., 2007; Donskoy and Ludyanskiy, 1995). Branscomb and Rittschof (1984) investigated the effects of low frequency (15–45 Hz) sound waves on barnacle settlement rates in laboratory studies. They reported that settlement inhibition was achieved, with 30 Hz being the most efficient. The effectiveness was observed to reduce after five days. In subsequent trials, however, other researchers have not observed this antifouling efficiency at these low frequencies (Fischer et al., 1984; Choi et al., 2013). In sea trials, Choi et al. (2013) investigated the effect of low frequency (70–445 Hz) vibration on biofouling. In contrast to Branscomb and Rittschof, no effect was observed, compared to a control, for frequencies below 200 Hz. Above this, they reported an increased deterrence in barnacle settlement rates with increased vibrational frequency. This effectiveness for barnacles lasted the period of the sea trial, which was over 98 days. Other forms of biofouling, including tubeworms, bryozoans, ascidians, and algae, seemed to be unaffected by the applied excitation. In sea trials, Latour and Murphy (1981) reported that a panel vibrated at 5 kHz was unfouled after 5 months, while a panel lightly vibrated at 50 Hz and a control panel was completely fouled by algae, barnacles,

Table 3
Example information from the literature on ultrasonic antifouling treatment of pipes.

Treatment types	Frequency	Organism type	Power	Treatment duration	Application	Comments
Piezoelectric transducer	20 kHz	Fungi, bacteria, algae	600 W. Amplitude varied: included 40% and 20%	3 × 30 s treatments per day.	Heat exchanger tubes: 18 mm I. D × 1 m long.	Biofilm thickness reduction dependent on maximum amplitude. 92% reduction at 40% amplitude (Bott, 2000)
PZT Transducer	250–2000 kHz	Colonial hydroid, *Garveia franciscana*	6.2 W/cm^2 sound intensity	Pulse of 0.2 s, with 100 s inter-pulse duration.	Intake pipes	250 kHz most energy efficient. High frequency requires higher sound intensity (power) for same results (Taylor et al., 1983)

mussels, and worms after a period respectively of five and two months. They reported similar results for their trial on a fibreglass skiff vibrated at 5 kHz over a 6 month period. They reported different mortality rates for different life cycles with maximum mortality rate for larvae. Refer to Table 2 for a brief summary of some audio frequency acoustic antifouling studies.

4.1.4. Vessel noise may increase biofouling

The audio frequency studies described above, reported reduction of biofouling with the use of audio frequencies. However, some recent studies have reported that generator sound, mainly composed of frequency components from 30 Hz to 2 kHz, emitted by ships at port can actually promote biofouling accumulation rather than prevent it (Stanley et al., 2014; McDonald et al., 2014; Wilkens et al., 2012). It was reported that it may even result in faster growth and metamorphosis of some taxa. Stanley et al. (2014) performed marine trials using panels in the sea, which were vibrated by playing recordings of generator noise emitted through a vessel's hull in port. They reported that more than twice as many bryozoans, oysters, calcareous tube worms, and barnacles settled and established on surfaces with vessel noise compared to those without. It was suggested that the noise from vessel hulls, having predominately components in the low to mid audio frequency range (0.1–2 kHz), has characteristics similar to the preferred natural settlement habitats of these fouling species, such as reefs. In marine trials on vessels, McDonald et al. (2014) showed that there appeared to be spatial correlation in biofouling with the intensity and frequency of the noise emitted by the vessels generator. They also performed laboratory experiments where they reported that *ascidian Ciona intestinalis* larvae showed significantly faster settlement, metamorphosis, and larval survival rates when exposed to underwater sound from a vessel generator.

4.2. Biofouling prevention in pipes

Pipes or heat exchanges, that take water from the sea, lakes, or rivers, can experience problems with biofouling formation on their interior surface. There have been studies relating to the inhibition of fouling in pipes using acoustic techniques. A few studies have been found, which used ultrasound (Taylor et al., 1983; Bott, 2000), see Table 3. However, the majority have used sparkers for biofouling inhibition.

4.2.1. Acoustic sparkers

Acoustic sparkers, also referred to as pulsers, generate impulsive, wide frequency bandwidth acoustic waves. A sparker circuit generates a large voltage, which is stored on a capacitor. This voltage is rapidly discharged between two electrodes in water. By

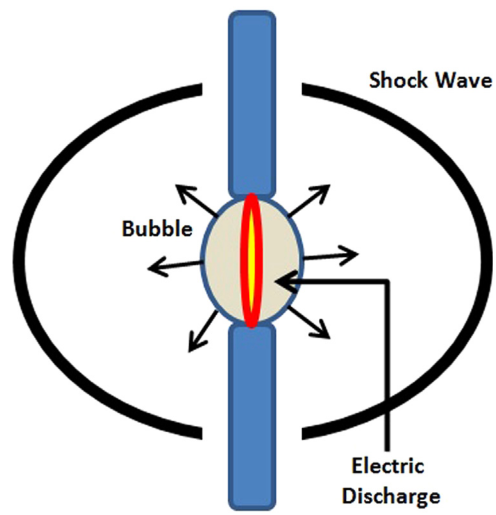

Fig. 4. Diagram reproduced from Schaefer et al. (2010) showing a basic sparker system with an electrical discharge between electrodes in water, which produces a vapour cavity bubble and a shock wave.

applying a voltage to the electrodes, which is high enough to exceed water breakdown level, the surrounding water may be vaporised causing an acoustic shock wave, see Fig. 4. Parabolic dishes have been used as acoustic mirrors to direct the energy of the pulse. A generic way of designing sparkers and how they work is explained in detail in Bryden (1995) and Grothaus et al. (1997).

The use of sparkers for biofouling control has been documented in various patents and papers over the last few decades. Virtually all the studies reviewed on sparkers were related to the application of biofouling inhibition of intake pipes of industrial facilities (Schaefer, 2002; Schaefer et al., 2010; Mackie et al., 2000). In an investigation using a sparker to prevent fouling of Zebra mussels on a 0.76 m diameter intake pipe from a freshwater lake, Schaefer et al. (2010) report that the effective range of mortality and settlement inhibition from a sparker were respectively 1.5 and 26 m, see Fig. 5.

According to Walch et al., the effect of sparkers on biofouling control has been attributed to cavitation and the resulting acoustic shock wave. Sub-cavitation threshold sparker treatments may manage to prevent fouling, but generally fail to remove adhered organisms (Walch et al., 2000). The effect of sparker induced cavitation on juvenile barnacles was studied by Guo et al. (2013) using a high speed camera. They reported that ultrasonic cavitation damaged the barnacle shell. Newly attached barnacles were able to be removed completely. Older barnacles were less easily removed and left the base plate cement on the surface. The shock wave induced by sparkers also provides inhibition. Schaefer et al. (2010) suggested inhibition of mussels in a pipe could be due to the shock wave causing the mussels to close their shells and drift to the bottom of the pipe. Refer to Table 4 for a summary of some acoustic sparker treatment studies.

The fouling prevention efficacy may depend on the applied acoustic frequency; and the optimum antifouling frequency may be species specific. A spark by nature produces a broad spectrum, typically ranging from about 10 Hz to 100 kHz, but may extend up to tens of MHz (Brizzolara et al., 1999). This broadband nature of sparkers could be beneficial in terms of covering a wide range of organisms. However, total energy is spread across the produced spectrum, potentially meaning that the energy intensity in a desired frequency range may not be large. Also, the intensity of energy that arrives at a specific location is affected by losses such as attenuation in the medium during propagation. Sound absorption in water generally increases with increasing frequency. In contrast, for pipes, geometric effects may cause higher frequencies components of the signal to propagate further (Brizzolara et al., 1999; Schaefer et al., 2010). It has been suggested that a sparker could be designed to maximise the energy in the desired frequency range (Brizzolara et al., 2003, 1999). It appears that control over the peak acoustic frequency generated by a sparker may be able to be achieved by controlling parameters such as capacitance, which affects the pulse length (Brizzolara et al., 1999; Heigl et al., 2012; Paillet, 1984).

Sparkers require maintenance in the form of replacing the electrodes, which erode over time (Brizzolara et al., 1999, 2003). This erosion is likely to be due largely to cavitation effects. If cavitation occurs on the surface of the structure being protected from biofouling, there is the potential that erosion of the surface may occur. However, this may not be an issue especially if, as was the case in many references, the sparker was not inside the pipe but in a separate enclosure onto which the pipe was attached.

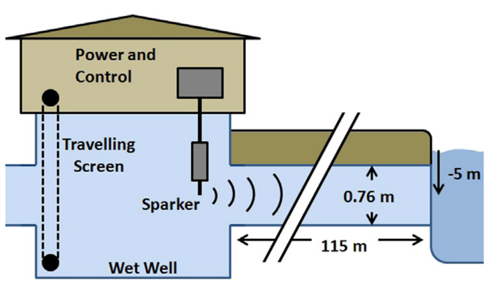

Fig. 5. Diagram reproduced from Schaefer et al. (2010) showing the experimental setup used to investigate biofouling control of an intake pipe from a lake using a sparker.

The references relating to biofouling control using sparkers were almost entirely for the application of fouling prevention of intake pipes (Schaefer, 2002; Schaefer et al., 2010; Mackie et al., 2000). No references were found where sparkers were applied to the application of biofouling protection of vessel hulls. In a pipe, the shock wave induced by a sparker would be guided by the structure causing it to propagate along the pipe. However, for the application of a vessel hull, the shock wave would be unconstrained causing much of the energy to propagate away from the vessel. Therefore, sparkers might be expected to be less efficient for vessel antifouling applications, than an ultrasonic system where the hull is vibrated and the energy is likely to be more efficiently guided through the vessel structure. Sparkers also require high power levels to function, although this is also true for an ultrasonic device that functions using cavitation.

4.3. *Treatment of organisms suspended in water*

Undesirable *marine* organisms are often spread to different regions through the emptying of vessel ballast water tanks (Holm et al., 2008). Several acoustic studies have investigated the mortality rates of organisms suspended in water. In a study relating to control of organisms in ballast water, Gavand et al. (2007) showed that mortality of brine shrimp larvae, cysts, and adults could be induced when exposed to sonication at 1.4 kHz for 20 min. A number of laboratory studies have investigated the effect of high power ultrasound on barnacle survival rates (Gavand et al., 2007; Suzuki and Konno, 1970; Seth et al., 2010). Suzuki and Konno (1970) used high power, pulsed ultrasonics between 28 kHz and 200 kHz and reported the higher frequency to be more lethal to barnacle larvae. Seth et al. (2010) attempted to quantify the energy needed for barnacle larvae destruction, using high power levels where cavitation might be expected to occur. They reported that 20 kHz at 0.0975 W/cm^3 can effectively pulverise barnacle larvae within 45 s (Seth et al., 2010).

Holm et al. (2008) investigated the power levels and application times required for 19 kHz ultrasound to produce mortality of bacteria, phytoplankton (dinoflagellate, diatom, cyanobacterium) and zooplankton (brine shrimp, cladocerans, rotifers) for the application of ballast water treatment. They found that the ultrasonic treatment efficiency varied with the size of the test organism. Zooplankton required only 39 s of 619 J/mL energy to cause 90% reduction in survival. In contrast, the smaller bacteria and phytoplankton required from 1 to 22 min at 31 to 1240 J/mL to

Table 4
Example information from the literature on acoustic sparker treatment of biofouling.

Treatment types	Frequency	Organism type	Power	Treatment duration	Application	Comments
Sparker	100 Hz–150 kHz	Zebra mussels	5.5 kV, 968 J/pulse, 0.16–5.8 J/m^2, 0.75 Hz pulses rate	2 months	Steel pipeline 115 m length. 0.76 m I.D.	0.04 MPa and 0.16 J/m^2 inhibit settlement. 0.23 MPa and 5.8 J/m^2 adult mussel mortality. 1.5 m from source: mortality, 23 m from source: inhibition (Schaefer et al., 2010)
Sparker	–	Zebra mussels	5 kV	3 months	PVC pipes 4 m, 30 cm I.D., 4.5 mm wall thickness	53.7% of adult mortality after 5 weeks. Estimated 9.3 weeks for 100% mortality (Mackie et al., 2000)
Sparker	10 Hz–100 kHz	Micro-fouling	17 kV discharge	4 weeks	Outside 5/8 in titanium pipe of 20 ft. Sea water	95% inhibition of Microfoulers. 15 ft from source affected. Removal and prevention achieved. Flow rate: 1.8 ft/s (Brizzolara et al., 2003)
Sparker	10 kHz–1 MHz	Slime	5–10 kV discharge	4 weeks	5/8 ft titanium pipe	On pipe: Slime inhibition achieved. Close to pipe: no inhibition achieved. Flow Rate: 2 ft/s (Brizzolara et al., 1999)
Sparker	–	Algae, bacteria	12–15 kV, 4 W/ft^2	10 h/day for 10 days	Centre of a 2 in PVC pipe	6–8 in close to source fully cleared. 10 ft affected by the source. Flow rate: 0.5 ft/s. Prevention achieved. Removal not achieved. Fouling occurs, but slowly (Walch et al., 2000)

Table 5
Example information from the literature on acoustic treatment of organisms suspended in water. In this table, the citations have been sorted by transmission frequency. Where more than one frequency was used, reported optimal frequency has been used for sorting.

Treatment types	Frequency	Organism type	Power	Treatment duration	Application	Comments
H_2O_2 and ozone. Ultrasonic bath	1.4 kHz	Algae and shrimp (larvae, cysts, adults)	–	2–20 min	Water treatment	Combined treatments at 2 min yielded mortality: Algae: 100%, Shrimp (larvae, adult) (100%, 95%) Sonication alone at 20 min yielded mortality at: Algae: 35%, Shrimp (cysts nauplii, adults) (55%, 100%, 85%) (Gavand et al., 2007)
Transducer	19–20 kHz	Bacteria, phytoplankton and zooplankton	6–1240 J/mL	3 s–22 min	Laboratory	Zooplankton (brine shrimp, Cladocerans, rotifers) required 39 s of 619 J/mL for 90% reduction in survival. Bacteria and phytoplankton (dinoflagellate, diatom, cyanobacterium) ranged from 1 to 22 min of 31–1240 J/mL. Concluded 19–20 kHz effective for planktonic organisms > 100 μm (Holm et al., 2008)
Transducer	19.5, 28.0, 50 kHz	Barnacle	240 W, 1.3 W/cm^2. 0–8000 kPa s	5–90 s	Laboratory	19.5 kHz optimal frequency. 4300 kPa s gave 50% larvae mortality; 140 kPa s gave 50% larvae settlement inhibition. Cyprids had greater mortality rates (Kitamura et al., 1995)
Transducer	20 kHz	Barnacle	0.0975 W/cm^3. 30, 50, 80. 110 W	45 s	Laboratory	Pulverisation. Higher power reduced required exposure duration for pulverisation (Seth et al., 2010)
Ultrasonic bath	26 kHz	Bacteria, fungi, virus	1.1–3 W/cm^2	30 min	Water treatment	*Pseudomonas Aeruginosa* up to 80% killed. *Bacillus Subtilis* up to 75% killed. *Staphylococcus Aureus* up to 45% killed. Ultrasound can kill fungi (Scherba et al., 1991)
Ultrasonic reactor	28 , 21.5, 39.5, 84.4 kHz	Cyano-bacteria, algae	40, 120, 1200 W	30 min	Water treatment	28 kHz optimal frequency, 120 W, 3 s, 80% algae settlement (Lee et al., 2001)
Probe	20, 150, 410, 1007 kHz	Algae	30, 60, 90 W	20 min	Water treatment	Optimal frequency 150 kHz at 30 W, 70% removal rate (Ma et al., 2005)
Ultrasonic bath	20, 40, 580, 864, 1146 kHz	Algae	0.0015–0.0714 W/cm^3	Up to 30 min	Water treatment	Most algae reduction 21.05% at 864 kHz at 0.0049 W/cm^3 over 30 min. Most efficient algae reduction at 580 kHz (Joyce et al., 2010)
Homemade multi-frequency cell system	20, 80, 1320 kHz	Algae	32 and 80 W	5 min	Water treatment	1320 kHz was optimal. Algae effectively removed by sonication. Gas vesicle collapse (Zhang et al., 2006)
Piezoelectric transducer	1 MHz	Algae	3 W/cm^2	15 min	Water treatment	30% cell destruction. Related with the cavitation generation (Giordano et al., 1976)
PZT transducer	20 kHz and 1.7 MHz	Cyano-bacteria algae	14 and 70 W	5 min	Water treatment	1.7 MHz was optimal. Algae reduced by 63% after 5 min ultrasonic irradiation (Hao et al., 2004)

achieve similar results. They suggested that this efficiency correlation with organism size might be related to the fact that the occurrence of cavitation microjet formation is dependent on the frequency of sonication and the size of the particle. Particles smaller than the size of the collapsing bubble cannot cause microjet formation. They concluded that a stand-alone ultrasonic treatment system for ballast water, operating at 19–20 kHz, may be effective for planktonic organisms larger than 100 μm in size, but smaller planktonic organisms such as phytoplankton and bacteria would require treatment by an additional or alternative system. Refer to Table 5 for more details on these studies.

These ultrasonic studies used high power levels and it is likely that cavitation may have been a main cause of mortality of the biofouling. However, this mechanism appears to be unsuitable for the application of preventing biofouling forming on ships hulls where the sub-cavitation power levels would be expected to be used, due to power limitations and potential impact on marine life. Caution should, therefore, be taken when comparing parameters used in these studies. The same applies to the study performed by Mazue et al. (2011) who developed a device for cleaning the exterior of boat hulls in dock using high power ultrasonic cavitation operating at 20 kHz.

A number of laboratory studies have investigated the use of ultrasound for purifying water. Some of the organisms investigated in water treatment studies, such as algae and fungi, are also biofouling organisms, and hence some of these studies have been included in this review. However, as in the previous section, high power ultrasound is used in these studies, and it is likely that the mechanism causing the organism mortality is related to cavitation. Hence any comparison with vessel hull antifouling applications should be treated with caution.

Lee et al. (2001) reported that 28 kHz was more effective in decreasing algae photosynthetic activity than 100 kHz. In contrast, Joyce et al. (2010) investigated declumping and inactivation of algae in water at ultrasonic frequencies of 20 and 40, 580, 864 and 1146 kHz. They found 580 kHz to be the most efficient frequency for algae reduction. Low ultrasonic frequencies initially inactivated algae cells, but also broke apart clumps of algae resulting in an increase in individual algae cell count. Ma et al. (2005) reported that algae removal rate increased with power. Zhang et al. (2006) hypothesised that the main cause of algae cell removal was the loss of buoyancy resulting from ultrasound causing the collapse of the gas vesicles in the algae. Hao et al. (2004) stated that 1.7 MHz was more efficient than 20 kHz for causing algae settlement in water. They also associated this with collapsing of gas vesicles in the algae and suggested the higher frequency might be more efficient since it was closer to the resonance frequency of a free bubble in water, which they calculated to be in the order of 6.5 MHz. Purcell et al. (2013) investigated the use of ultrasound on different types of algae and described the optimal frequency to be species specific. Refer to Broekman et al. (2010) for a brief review listing several studies investigating the effect of using low and high ultrasonic frequencies, including a combination of both, for water treatment. Table 5 provide a brief summary of some literature using ultrasonic for algae and fungi control.

5. Potential environmental consideration of acoustic antifouling systems

Biofouling is a significant economic and environmental problem to the shipping industry. Acoustic antifouling systems appear to have environmental advantages in terms of not producing, for example, toxic leachates. However, if these systems are inefficient and do not control biofouling as efficiently as a toxic paint, for example, the environmental costs associated with increased fuel use or transportation of non-indigenous species might be greater than those associated with the biocides. Another environmental consideration is the potential impact of introducing acoustic energy into the marine environment. This acoustic energy represents anthropogenic (man-made) noise, which has the potential to have a negative impact on marine life.

5.1. Effects of noise on marine life

Sound in the oceans can be divided into ambient or anthropogenic noise. Breaking waves, precipitation, and marine life sounds are examples of ambient noise in the marine environment. Shipping, sonar, seismic surveying, pile driving, and dredging are examples of anthropogenic generated noise in the marine environment (Wenz, 1962; Wartzok and Ketten, 1999; Yan et al., 2010; Götz et al., 2009). Refer to Table 6 for the frequency ranges and sound pressure levels for several examples of underwater sound.

Sound appears to be a means for marine life to communicate, navigate, and detect other life (Opper, 2008; Radford et al., 2011; Wilkens et al., 2012). Recent studies have shown that low frequency noise from vessel generators may be a settlement queue for biofouling species, see Section 4.1.4 for more details. Over the last few decades there has been increasing concern about the effect of anthropogenic noise on marine life. If the noise is within the hearing range of a life form, masking may occur. The life form may be unable to detect, interpret, or respond to biologically relevant sounds in the same frequency range as the introduced sound (Wartzok and Ketten, 1999). Behavioural effects may occur, such as the life form moving from its current site; a possible feeding or breeding ground. If the sound level is intense enough, there may be physical damage to auditory or non-auditory tissue. Depending on the extent of auditory damage, temporary or even permanent hearing loss may occur. Death may occur in extreme cases of body tissue damage (Opper, 2008; Southall et al., 2008; Wartzok and Ketten, 1999).

Table 6
Examples of ambient and anthropogenic sound frequency and sound pressure levels (SPL) in the marine environment. Data is taken from Wartzok and Ketten (1999), Yan et al. (2010), http://www.dosits.org/science/soundsinthesea/commonsounds/, and Götz et al. (2009).

Sound source	**Frequency** (kHz)	**SPL** (dB re. 1 μPa)
Shrimp snapping	0.7–30	183–189
Humpback whale song	0.03–8	144–186
Sperm whale click	0.1–30	160–180
Bottlenosed dolphin whistles	0.8–24	125–173
Precipitation	0.1–20	35
Seismic survey air gun	0.01–0.120	260–262
Military mid-frequency sonar	1–10	223–256 peak
Echosounder	1.5–36	235 peak
Large ship	0.05–0.5	180–190 rms
Dredging	0.1–0.5	168–186 rms

Hearing thresholds have been measured for perhaps only 100 of the many thousands of living fish species. The majority of the fish species studied cannot hear sounds above about 3–4 kHz and most of these can only hear up to 1 kHz (Opper, 2008). In contrast, cetaceans (whales, dolphins) can detect sounds up to 22, 160, or 180 kHz depending on the species. Pinnipeds (seals, etc.) can hear sounds in water up to about 75 kHz (Southall et al., 2008). Refer to Opper (2008) and Ketten (2004) for example graphs of fish, cetacean, and pinniped hearing threshold levels in water. There have been studies investigating the physical effect of sound on fish, refer to Table 7. For marine mammals, it has been suggested that hearing losses may occur when noise is 80 dB above the animal's hearing threshold (Ketten, 1998), and permanent tissue damage for cetaceans and pinnipeds may respectively occur at sound pressure levels of 230 and 218 dB re. 1 μPa over a 24 h period (Southall et al., 2008). However, it seems that there is currently insufficient data to provide accurate hazardous exposure levels for marine mammals (Wartzok and Ketten, 1999).

5.2. Acoustic antifouling marine life considerations

Antifouling systems that use audio frequencies may have the potential to have negative impact to marine life since they are in the frequency range of most marine species. Acoustic biofouling methods that use sparkers may generate audio frequency signals. These signals are impulsive and have a broad bandwidth. Impulsive, broad bandwidth noise may be more likely to cause auditory tissue damage than continuous narrow bandwidth noise (Wartzok and Ketten, 1999). However, since these sparkers are usually used inside pipes, this may have minimal undesirable effects, especially if the section of the pipe being treated for biofouling is above water. Ultrasound frequencies should be well above the hearing range of almost all fish and above that of low frequency cetacean species (Opper, 2008; Southall et al., 2008). These frequencies also have much higher attenuation rates compared to audio frequencies and will, therefore, have significantly reduced range of propagation through the water. At moderate power levels, ultrasonic biofouling systems appear have less potential to effect marine life. More study might be required to determine the safe operating parameters for the use on exposed surfaces in the marine environment, particularly in locations where mid to high frequency cetaceans and pinnipeds frequent.

6. Discussion

Many of the reviewed trials were based on small-scale lab studies looking at single species (predominantly barnacles). Of the sea trials, most were not vessel-scale studies, but small vessels (yachts and skiffs) or small panels placed in the sea. Most of the reviewed laboratory and sea trial studies have reported successful biofouling inhibition using acoustic techniques, mainly using low ultrasonic frequencies. A few recent studies have reported increased levels of biofouling due to ship's generator noise, which is mainly composed of low audio frequency components.

For high power ultrasound studies, cavitation appears to be the main mechanism causing biofouling mortality and inhibition. However, these high power levels do not appear to be suitable for the application of biofouling inhibition on vessel hulls. For sub-cavitation power levels, it is unclear what the mechanism is that can cause biofouling inhibition. The biofouling inhibition could be related to the vibration itself or perhaps could be masking other ambient or antropogenic noise that might attract biofouling organisms. More studies are needed to identity what the

Table 7
Results from studies on physical effect of sound sources on fish. LFA refers to low-frequency active, MFA refers to mid-frequency active, and TTS refers to temporary threshold shift. The SPL dB values are relative to 1 μPa.

Sound type	**SPL** (dB)	**Max freq.** (kHz)	**Effect**
Impulsive	203.6 rms	0.02–0.1	Snapper – permanent hearing damage (Air gun noise) (McCauley et al., 2003)
Non-impulsive	193 rms	0.17–0.31	TTS for one set of rainbow trout in one of the two groups of fish. No mortality. (LFA sonar) (Popper et al., 2007)
Non-impulsive	210	2.8–3.8	Rainbow trout – no effect (outside their hearing range). Catfish – TTS (24 h) duration. No fish mortality. (MFA sonar) (Halvorsen et al., 2012)
Non-impulsive	115, 130, 150	2–20	Rainbow trout – hearing sensitivity, growth, survival, stress, and disease susceptibility were not negatively impacted. (Aquaculture production noise) (Wysocki et al., 2007)

mechanism is which causes acoustic techniques to inhibit or attract biofouling.

There has been some variation in the acoustic parameters, which have been reported to be optimal for biofouling control, and limited information as to how efficient the trials were at preventing fouling. There is also ambiguity about the frequency dependent gain of the hardware. The gain is the efficiency of the hardware in converting an electrical signal into acoustic vibration. This efficiency may vary with frequency. These factors make comparisons and potential replication of these trials difficult. Variation in the antifouling efficiency was reported with the use of different ultrasonic frequencies. However, since the relative gain of the acoustic antifouling hardware (signal generator, power amplifier, and transducers) at the frequencies used was generally not provided, it is difficult to know if the antifouling efficiency at a given frequency was due to the gain of the hardware or because this frequency was better at inhibiting biofouling formation. Similarly, often the acoustic energy used in a trial was expressed in terms of the voltage or the power applied to the transducer. This is important information in terms of assessing the economic viability of the technique. However, the input electrical power used does not provide information on how efficient the transducers were at converting the electrical energy into vibration amplitude of the substrate being protected from biofouling formation or the sound pressure level of the water that the biofouling was suspended in. It was also difficult to make comparisons with the studies on the effect of underwater noise on marine life, which expressed the acoustic energy in terms of sound pressure levels in dB relative to 1 μPa, either at the source location, at a distance of a meter from the source, or at the location of the marine organism.

The relative effectiveness of the acoustic antifouling trials was also often difficult to evaluate. It was often said that fouling “inhibition” had occurred or that the surfaces were “relatively free” of fouling. However, without a baseline such terms become ambiguous. Often no control was used and generally little quantitative information was provided on the amount of accumulated biofouling that occurred. Very little photographic documentation of the biofouling trials was found.

Future studies would benefit from the development of a methodology that would allow these studies to be conducted in a way such that the fundamental operating parameters and performance characteristics are well defined. This should allow multiple studies to be compared and built upon, so that the design of an effective system could be obtained. Choi et al. (2013) is an example of a study that documented the operating parameters and performance characteristics in a more rigorous manner. They investigated the use of different low audio frequencies on multiple small panels with transducers attached in marine trials. The materials and operational parameters were documented. Laser vibrometry was used to measure the velocity of vibration of the panels in air as a function of frequency. A non-vibrated control panel was used. The different biofouling organisms attached were recorded. Comparisons were made between the control and different excitation frequencies and different panel velocities. The number of barnacles that settled on the plates was documented and the fact that other species were unaffected by the acoustic treatment was stated. Photographic documentation of the results was included.

Future studies would benefit from the use of similar methodology. In addition to the above methodology, it would be beneficial to use a calibrated hydrophone to measure the sound pressure level (dB re. 1 μPa) of the water at a set distance from the source. This would provide an indication of the vibrational amplitude in the water as a function of frequency. Measurements made at different times during the trial would enable the stability of the acoustic excitation hardware to be determined. This may be particularly important if resonant transducers are used where a drift in operating frequency or the resonant frequency of the transducer could cause the resulting vibrational amplitude to change during the trial period. It also would enable comparisons to be made with marine noise studies to determine the safe operating parameters for marine life.

7. Conclusions

Biofouling has a significant economic cost for industry, particularly the shipping industry. Biofouling results in extra fuel and maintenance costs, loss in operation time, and production of toxic waste associated with addressing biofouling problems. Acoustic antifouling methods may provide a non-toxic alternative for biofouling prevention (see above). This paper presented a literature review on acoustic antifouling techniques. The potential impact on marine life of different acoustic biofouling prevention methods was also considered.

There has been a range of studies investigating the use of acoustic techniques for the application of preventing biofouling formation on vessel hulls. Ultrasound has been reported to be effective at inhibiting the formation of biofouling on surfaces suspended in water. However, quantification of how successful this has been limited. The majority of the studies have used frequencies from 17 to 30 kHz. There have been some reports that the lower ultrasonic frequencies such as 19 kHz may be more effective for barnacle inhibition than higher ultrasonic frequencies or audio frequencies. There have also been studies, which have reported audio frequencies to cause some biofouling inhibition. However, other recent studies may indicate that audio frequencies potentially up to 2 kHz should be avoided since these may replicate ambient noise in natural settlement areas, such as reefs, and be a settlement cue for some biofouling species. Also, audio frequencies are in the hearing range of most marine life and, therefore, may have the potential to have negative results.

Although more research needs to be performed, the reviewed literature indicates that lower ultrasonic frequencies may be optimal for biofouling inhibition on vessel hulls.

Studies using acoustic techniques for the control of biofouling in pipes were also reviewed. Several of these studies use ultrasound, but the majority use sparkers. Fouling inhibition has been reported for distances up to 23 m. None of the reviewed sparker studies related to the application of preventing fouling forming on a vessel's hull and no indication was found that it would be suitable for this application. A range of studies were also reviewed involving the use of acoustics to control biofouling organisms suspended in water. In ballast water studies, low frequency (i.e. 19 kHz) ultrasound cavitation was reported to be more efficient at inducing mortality of larger biofouling zooplankton such as brine shrimp compared to smaller organisms such as bacteria and phytoplankton. Several studies on water treatment found higher ultrasonic frequencies (several hundred kHz) to be more efficient than lower ultrasonic frequencies at inducing mortality of algae. It should be noted, however, that the application of killing biofouling suspended in water is different from that of trying to prevent the initial formation of biofouling on a vessel hull where much lower power levels are likely to be used.

Much of the reviewed studies have been small-scale lab studies looking at single species. More photographically documented trials should be performed to determine the optimal and efficient operating parameters and practical circumstances of use of an acoustic biofouling system that would cover a wide range of fouling organisms, and also study its safe use in the marine environment. Future studies would benefit from the development of a methodology that would allow these studies to be conducted in a way such that the fundamental operating parameters and performance characteristics are well defined. This should allow multiple studies to be compared and built upon, so that the design of an effective system could be obtained. Trials should be more scale-appropriate (i.e. vessel scale). They should take into account factors such as variations in hull form and shape, disruptive frequency sources (e.g. vessel machinery) and seasonal effects (e.g. varying levels of propagule pressure and species abundances related to spawning periods).

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