Reducing high Reynolds-number hydroacoustic noise using superhydrophobic coating

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Abstract. The objective of this study is to assess and quantify the effect of a superhydrophobic surface coating on turbulence-generated flow noise. The study utilizes results obtained from high Reynolds-number full-scale flow noise measurements taken on a commercial seismic streamer and results from low Reynolds-number direct numerical simulations. It is shown that it is possible to significantly reduce both the frictional drag and the levels of the turbulence generated flow noise even at very high Reynolds-numbers. For instance, frequencies below 10 Hz a reduction in the flow noise level of nearly 50% was measured. These results can be attributed to a reduced level of shear stress and change in the kinematic structure of the turbulence, both of which occur in the immediate vicinity of the superhydrophobic surface.

1. Introduction

The work in this study relates primarily to towed hydrophone arrays (seismic streamers) used for subsurface hydrocarbon exploration, but the results also apply to other hydroacoustic sensors. Marine seismic exploration is normally conducted by towing very long flexible streamer cables in the ocean. These are equipped with a very large number of pressure sensors (hydrophones) on which recordings are made from subsurface reflections of acoustic energy originating from a pressure source (air guns towed behind the seismic vessel). Figure 1 shows a schematic drawing of a seismic operation where streamer cables with a typical diameter of 5 cm and length of up to 12 km are used.

Seismic subsurface reflection data appears normally in the frequency range 0 - 250 Hz, and it is noise within this frequency range that most detrimental to the quality of the recorded signals. Examples of sources that tend to create noise within this relatively narrow frequency range include surface wave motion, wake behind vessels, and external currents that cause structural vibrations of the steamer cables. Various types of ambient noises that propagates over large distances include seismic interference (Greene and Richardson, 1988), oceanic traffic, and noise from marine creatures.

Early work to characterize and identifying noise sources was conducted by Schoenberger and Mifsud (1974) and Fulton (1985), whereas more recent efforts include e.g. Dowling (1998). Since then, the seismic industry has focused on systematically improving streamer system technology to reduce the effects of many of the identified sources of noise. With few exceptions Nishi (1970),
Knight (1996), and Cipolla and Keith (2008), work toward these improvements has not focused on noise originating from the turbulent boundary layer.

The relative motion between a streamer cable and the ocean creates a turbulent boundary layer (TBL) that surrounds the cable. The noise generated by the fluctuating velocity and pressure fields within this TBL significantly degrades the quality of data collected (Elboth et al 2010). The acoustic field in this case is quadrupole in nature, i.e. its intensity reduce as 1/d^4 with distance d from the source. However, on a seismic streamer, where hydrophones are placed close to the outer streamer surface, the effect of the quadrupole turbulent flow noise can still be significant, and many cases the dominant source of noise in modern streamer technology.

A recent promising approach for passive turbulence control involves superhydrophobic (SH) coatings. On a microscopic scale, superhydrophobic surfaces are rough, with micrometer-sized surface features. In combination with chemical hydrophobicity, the material prevents water from moving into space between the peaks of the rough surface, cf. Martell et al. (2010). On a macroscopic scale, a superhydrophobic surface will have, on average, a non-zero (slip) velocity, and have recently been shown to reduce surface frictional drag both for laminar and turbulent flows, cf. e.g. Daniello et al (2009) and Woolford et al (2009). The present study combines low-Reynolds-number direct numerical simulations and full-scale open-sea experiments of towed seismic arrays in order to provide insight of both the drag and potentially also noise reducing properties of superhydrophobic coatings.

![Figure 1](image_url). Illustration of a vessel that tows an air gun (energy source) and an array of hydrophones (seismic streamers). The air-gun releases an energy pulse that propagates down into the subsurface where it is reflected at the interfaces between the different layers. The reflected energy is recorded by a large number of hydrophones mounted inside the streamer cables and used to reconstruct an image of the subsurface geology.

2. Direct numerical simulations

The computational part of this study is based on the direct numerical simulations conducted by (Martell et al 2009) who considered fully developed plane channel flow at \( Re_T = u_*l/\nu = 395 \). Here, \( u_* \) is the friction velocity, \( l \) is half the channel height, and \( \nu \) denotes kinematic viscosity. The imposition of a SH coating were modelled by assigning slip wall boundary conditions is a regular pattern on one of the walls. The other wall was modelled with no-slip conditions. The imposition of these mixed wall boundary conditions constitutes a viable method to numerically model a superhydrophobic surface, although at significantly lower Reynolds numbers than experienced in full scale. It should be noted that the effect of transversal curvature of axial boundary layers developing along a towed antenna has been neglected in this study since planar
walls are considered. Neves and Moin (1994) demonstrated on the other hand that as long as the ratio between the boundary layer thickness and the cylinder radius is less than unity, this assumption is fairly accurate. For further details on the direct numerical simulation, cf. Martell et al (2009).

The acoustic simulations preformed in this study is based on Lighthill’s acoustic analogy (Lighthill 1954):

$$\frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} - \frac{\partial^2 p}{\partial x_i \partial x_i} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j},$$  

(1)

where $T_{ij} = \rho u_i u_j - \sigma_{ij} + (p - c_0^2 \rho) \delta_{ij}$, $c_0$ denotes local speed of sound which is considered to be constant in the model domain. The term $p(x,t)$ is the instantaneous pressure and $\rho(x,t)$ is the density of the fluid. The viscous stresses, $\sigma_{ij}$, are usually neglected. Furthermore, it can be assumed that the acoustic energy is much smaller than the turbulent kinetic energy of the flow. The feedback from the acoustic field to the flow field is therefore negligible. By assuming isotropic acoustic conditions, $p - c_0^2 \rho = 0$, the momentum flux density tensor $\rho_0 u_i u_j$ for $i,j \in \{1,2,3\}$ is the dominating source in Equation 1. A simplified Lighthill equation can therefore be written as

$$\frac{1}{c_0^2} \frac{\partial^2 p}{\partial t^2} - \frac{\partial^2 p}{\partial x_i \partial x_i} = \rho_0 \frac{\partial^2 (u_i u_j)}{\partial x_i \partial x_j}.$$  

(2)

Three-dimensional time series of the fluctuating velocity field from the incopressible DNS simulations were subsequently used to computationally solve for propagating acoustic pressure. Any two-way coupling between the acoustic field and the hydrodynamic field can to a good approximation be neglected due to the high speed of sound in water. Despite the Reynolds number difference, the combination of DNS and full-scale measurements aids in forming a physical understanding of the relationship between SHS and flow noise generation.

It was necessary to pay special attention to the acoustic boundary conditions in order to avoid reflections from waves that leave the computational domain; energy from reflecting waves would quickly render the simulation data useless. In order to achieve this, perfectly matched layers (PML) first introduced by Berenger (1994) has been used in this study. PML is a computationally efficient method to construct a non-reflecting boundary. here we use the formulation given by Hu (2005).

Numerical tests have shown that the absorbing PML-region needs to be at least 15 grid cells deep to avoid reflections. The acoustic computations were conducted on a uniform grid with resolution 256x512x256 in the streamwise, wall-normal, and spanwise directions, respectively. We used a high order finite difference approximation computing the spatial derivatives, while a second order approximation was used in time.

Figure 2 displays a snapshot from our acoustic computation of the $Re_\tau = 395$ channel flow simulation with one wall modelled as a SH coating. The channel, with its acoustic sources, is shown as a semitransparent (gray) region within the larger computational domain. Figure 3 shows the instantaneous pressure distributions in a plane parallel to the no-slip and slip boundaries, respectively, located approximately 50 wall units outside each of the boundaries. Note how the amplitudes (the variations in surface height) are much larger outside the normal no-slip surface (left), compared to outside the SHS-surface (right). In order to compare the simulation results with real seismic noise records it becomes necessary to model the effects of the pressure fluctuations on a hydrophone membrane. A hydrophone membrane was modeled by averaging the pressure over a 200x100 (plus units) area in a time series, 50 wall-units outside both the SHS-slip and the normal no-slip boundary. The temporal rms was almost 60% lower close to the Sh coated surface. This illustrates the potential effect of SH coating to reduce turbulence induced noise. It should also be noted that Martell et al (2009) reported an averaged shear stress reduction of 15%. However, that DNS data are only valid for low Reynolds-number
flows in a perfectly controlled environment. The question as to whether a similar reduction of frictional forces and the associated hydroacoustical noise can be observed in a realistic open-sea therefore naturally arise. In an attempt to provide indicative answers to these questions, a series of full-scale experiments were conducted.

Figure 2. Instantaneous three-dimensional acoustic field at $Re_T = 396$.

3. Experimental measurements

Two different experiments were conducted in order to elucidate the effect of a SH coating on a towed antenna operated in a realistic environment. Both experiments were conducted in open sea. The objective of the first test were to investigate the drag reducing properties whereas the objective of the second were to measure the hydroacoustical field generated by the turbulent boundary layer. The SH coating used in these experiments is commercially available and it consists of a silane blend mixed with isopropanol and ethanol.

Figure 3. Instantaneous fluctuating pressure field in a plane parallel to the walls (located approximately at $y^+ = 50$.)
3.1. Skin friction drag
Our results can be compared with the laboratory controlled experiments by ? which indicated up to 50% drag reduction on a carefully manufactured regular patterned SHS at relatively low Reynolds numbers.

The first set of experiments were set up to conduct an assessment of what drag reduction that can be expected under full-scale conditions in open sea using a seismic streamer cable with an outer skin made of polyurethane. Two identical 25m long seismic streamer cables were towed side by side, each with a diameter of 5 cm, and the drag was separately monitored on each cable. Each cable were equipped with a metal weight (drag body) attached at the end of the cable in order to keep it submerged. The drag induced by the drag body was the same in all cases and it should be noted that this probably dominated the total drag on each cable. Despite this, an overall drag reduction of approximately 4% could be observed, cf. Figure 4.

![Figure 4](image-url)

Figure 4. Measured drag on a SH coated and an uncoated 25m long seismic streamer cable towed in open sea. The Reynolds number based on the boundary layer thickness was $O(10^6)$.

3.2. Hydroacoustical noise
The same SH coating as was used in the first set of experiments was subsequently applied on parts of an ION Digistreamer® seismic cable used for full-scale commercial exploration on the Fugro Geotem AS operated seismic vessel _Geo Arctic_. These gel-filled streamers have an outer diameter of 5.3 cm and the individual hydrophones are placed close to the center of the streamer. The Digistreamer is made up of a large number of hydrophone groups, each consisting of eight individual hydrophones spanning an axial distance of 12.5 m. The output from all hydrophones within each group are summed up and recorded on the vessel. Typically, there are 480 groups in a seismic streamer, giving it a total length of 6 km. The vessel was operating in the Barents Sea when the data was acquired. On average, four 30s noise recordings were acquired every day during a 30 day period in July and August 2009. The data was recorded with a 2 ms sampling rate, limiting the maximum frequency to 250 Hz. Before any analysis was done a low-cut filter was applied to remove hydrostatic fluctuation noise and swell noise below 4 Hz. During this survey the streamers were towed 7 m below the sea surface at a velocity of approximately five knots. Sea state 0 - 2 were experienced throughout the experiments. Spectral estimates and root-mean-squared noise level was computed from the measurements and compared the noise levels between coated and uncoated parts of one streamer section.
Figure 5 shows the measured power spectrum estimates from the first twenty samples. The SHS coating mostly seems to have an effect on frequencies below 10-15 Hz where most of the flow noise is present. In this range the noise level is reduced by up to 6 dB, which roughly corresponds to halving the noise level. Few significant differences are observable above 15 Hz.

![Graph showing measured drag on a SH coated and an uncoated 25m long seismic streamer cable towed in open sea. The Reynolds number based on the boundary layer thickness was $O(10^6)$.

Figure 5. Measured drag on a SH coated and an uncoated 25m long seismic streamer cable towed in open sea. The Reynolds number based on the boundary layer thickness was $O(10^6)$.

4. Concluding remarks

The present study has combined low-Reynolds-number direct numerical simulations with full-scale flow noise measurements using industrial scale seismic arrays. The theoretical findings obtained by applying Lighthills acoustic analogy to compute the turbulence generated flow noise are supported by high-Reynolds-number measurements. However, Lighthills analogy inherently neglects possibly very important noise generating mechanisms. These include boundary effects such as wall-pressure fluctuations and the movement of the structure itself caused by the propagating sound waves. Ongoing efforts therefore includes the more general methodology developed by Ffowcs Williams and Hawkings (1969).

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