Reducing the drag of underwater vehicle in the shape of a small boat by using piezoelectric transducers

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Abstract. Reducing the flow resistance of moving underwater vehicles can improve their performance and reduce the energy consumption. This paper presents a method to interfere the turbulent boundary layer for achieving the drag reduction by using piezoelectric transducers. The transducer produces ultrasonic traveling waves vibration near the hull surface. The working frequency and the maximum vibration amplitude of the transducers placed in different locations were obtained through the structural dynamic analysis. The fluid-solid coupling simulations were performed to explore the reduction drag performance. The simulation results show that better drag reduction performance can be obtained when the angle between the vibration direction of the piezoelectric transducer and the flow direction is 67.62°. The method of using piezoelectric transducer vibration for drag reduction is proved to be feasible. The present work provides a valuable reference for the study of drag reduction of underwater vehicles.

1. Introduction
Underwater vehicles consume a lot of energy to improve their speed during navigation, the energy consumption are mainly caused by the resistance of the boundary layer. Therefore, it is extremely important to find ways to reduce the resistance of the flow field. Streamlined objects are mainly subject to frictional resistance, while blunt bodies are mainly subject to differential pressure resistance due to the severe boundary layer separation around them. Approaches to achieve drag reduction in the flow fluid have varied widely, including active and passive methods. The drag reduction by wall vibration is a new active drag reduction method in recent years. Compared with other drag reduction technologies [1-3], the wall vibration drag reduction technology does not need to change the structure and surface properties of the object, does not need to change the fluid properties, and does not need to make the object move at high speed in order to produce super cavitation and other advantages.

The researches on drag reduction by wall vibration in fluids are mainly focused on the periodic oscillation of a flat plate in plane. Jung et al. [4] found that the turbulent burst activity of channel flow was suppressed by the influence of spanwise oscillating wall, leading to sustained reduction of 10% to 40% in the turbulent drag. Laadhari et al. [5] found that the mean velocity and turbulence intensities of the turbulent boundary layer near the wall are reduced, meaning that the drag of the boundary layer may be reduced by the spanwise oscillation of a flat plate. Braon et al. [6] demonstrated that the drag reduction of turbulent boundary layer and channel flow can be achieved by applying appropriate frequency and amplitude to the spanwise oscillation wall. Choi et al. [7; 8] observed that turbulence intensities decrease when the spanwise oscillation of the plate works on, which can cause as much as 45% reduction in frictional drag. Therefore, the wall oscillation can reduce the drag by interfering with the boundary layer near the wall. Piezoelectric transducers can be employed in the fields of ultrasonic...
motor [9-11], ultrasonic processing [12], energy harvesting [13; 14], droplet ejecting [15], ultrasonic welding [16] and so on. However, to the best of our knowledge, the research on wall vibration driven by piezoelectric transducers for achieving drag reduction has hardly been reported.

In this paper, a method to interfere the turbulent boundary layer for achieving the drag reduction by using piezoelectric transducers is presented. These transducers produce ultrasonic traveling waves near the hull surface. The excitation frequency and the maximum vibration amplitude of the transducers placed in different locations were provided by the structural dynamic analysis. The fluid-solid coupling simulation was carried out to explore the reduction drag performance.

2. Structure and working principle
The electrical signals applied on the piezoelectric ceramics are converted into mechanical movements by taking advantages of the inverse piezoelectric effect of piezoelectric ceramics of the ultrasonic transducer. The longitudinal high-frequency vibrations of the piezoelectric transducer will cause periodic vibration of the underwater vehicle wall. The vibration could disturb the boundary layer characteristics near the wall and delay the separation process of the boundary layer, so as to achieve the drag reduction.

Figure 1 illustrates a model of an underwater vehicle in the shape of a small boat by using piezoelectric transducers. Two sandwich piezoelectric transducers are mounted on the model through their respective fixed locking device and the vibration direction of sandwich piezoelectric transducers can be changed.

The sandwich piezoelectric transducer is mainly composed of a rear cover, four piezoelectric ceramic rings, and an ultrasonic horn. The stepped ultrasonic horn and the pre-tightening bolt are arranged as a whole. The components are connected tightly by using the pre-tightening bolt which is connected with the piezoelectric ceramic inner rings. The explosion diagram is shown in Figure 2. The material parameters of the piezoelectric transducer components are listed in Table 1. The material with higher impedance is selected as the material of the rear cover to promote the wave propagation forward. Compared with other piezoelectric materials, PZT-82 has high mechanical quality factor, high electromechanical coupling coefficient and high power weight ratio, so it is used in this work.

![Figure 1. Assembly diagram of drag reduction device.](image-url)
A high strength stepped horn is designed to increase the amplification factor in order to satisfy the large amplitude requirement. The theoretical amplification factor of the stepped horn is the area ratio of the large end to the small end of the horn, as follows

$$M = \frac{S_1}{S_2} = \left(\frac{D}{d}\right)^2 \tag{1}$$

Where $M$ is the amplification factor, $S_1$ and $S_2$ represent the area of the large end and the small end, respectively, $D$ and $d$ represent the diameters of the large end and the small end, respectively. The amplification factor in this work, which can be calculated by the above equation (1), is equal to 11.1.

The inner wall of the hull is composed by several planes to ensure that the output end of the piezoelectric transducer can closely fit the inner wall of the hull. In order to avoid changing the external structure of the hull, a cavity is reserved at the bottom of the hull to install the fixed locking device. The double-layer structure of the hull is shown in Figure 3.

![Double-layer hull structure](image_url)

**Figure 3.** Double-layer hull structure.

### 3. Simulation analysis

Simulation analyses are performed to verify the possibility of wall vibration drag reduction. The axisymmetric model can be divided into four parts according to the quadrant, for the convenience of
calculation. Figure 4 shows the different positions of the transducer placed in the first quadrant to verify the effect of transducers at different locations, where \( \alpha \) represents the angle between the vibration direction of the transducer and the z-axis of the hull (flow direction). In this work, the angles of 0°, 26.03°, 50.75°, 67.62° and 78.68° are selected.

The modal analyses and transient analyses are carried out by using the finite element analysis software, and the working frequencies and vibration results are obtained. By establishing UDF (User Defined Function), the vibration results are adopted as boundary conditions for the fluid dynamics analysis in software FLUENT.

![Figure 4](image1.png)

**Figure 4.** Schematic diagram of the position and angle for the transducer: \( \alpha \) represents the angle between the vibration direction of the transducer and the z-axis.

3.1. Vibration simulation of the sandwich piezoelectric transducer

Figure 5 shows that the longitudinal vibration state occurs at the fifteenth mode with the corresponding frequency of 21.555 kHz. When applying excitation voltage of 100 V and frequency of 21.555 kHz on the four piezoelectric ceramic rings, the transient analysis was carried out. Figure 6 shows the result of transient analysis. It can be seen that the steady state vibration amplitude of the transducer is 3.75 μm.

![Figure 5](image2.png)

**Figure 5.** Modal analysis of piezoelectric transducer.

![Figure 6](image3.png)

**Figure 6.** Transient response of piezoelectric transducer.

3.2. Vibration simulation of the underwater vehicle
When the angle between the vibration direction of the transducer and the z-axis of the hull is 0°, the longitudinal resonant frequency of the working mode obtained in modal simulation analysis is 1529.11 Hz, as shown in Figure 7. Figure 8 displays that the maximum deformation occurred on the wall is 0.135 μm, which is obtained by transient simulation analysis.

\[ f(x) = a_0 + a_1 \cos(\omega x) + b_1 \sin(\omega x) + a_2 \cos(2\omega x) + b_2 \sin(2\omega x) + a_3 \cos(3\omega x) + b_3 \sin(3\omega x) \]  

where \(a_0, a_1, a_2, a_3, b_1, b_2, b_3\) are the coefficients of Fourier. It is found that the fitting confidence for \(z(\Delta x)\) (when \(z\) is independent variable and \(\Delta x\) is dependent variable) is 0.9858 and for \(x(\Delta z)\) is 0.8714 by using the third-order Fourier series. Therefore, \(z(\Delta x)\) is chosen to be fit by Fourier series to obtain the vibration equations in different quadrants.

Figures 9 shows the vibration fitting curves in different quadrants, and the corresponding Fourier coefficients in the vibration equation are shown in Table 2.

![Figure 7. Modal analysis at the angle of 0°.](image)

![Figure 8. Transient analysis at the angle of 0°.](image)

![Figure 9. Vibration fitting curve of the wall: (a) In the first quadrant, (b) In the second quadrant, (c) In the third quadrant, (d) In the fourth quadrant.](image)
The Fourier coefficients of the vibration equation when the angle is 0° are given in Table 2.

| Coefficient | The first quadrant | The second quadrant | The third quadrant | The fourth quadrant |
|-------------|--------------------|---------------------|-------------------|--------------------|
| $a_0$       | 6.347e-08          | -6.347e-08          | -6.347e-08        | 6.347e-08          |
| $a_1$       | -9.182e-09         | 9.182e-09           | 9.182e-09         | -9.182e-09         |
| $b_1$       | -2.133e-08         | 2.133e-08           | -2.133e-08        | 2.133e-08          |
| $a_2$       | 3.486e-08          | -3.486e-08          | -3.486e-08        | 3.486e-08          |
| $b_2$       | -3.257e-08         | 3.257e-08           | -3.257e-08        | 3.257e-08          |
| $a_3$       | -1.313e-08         | 1.313e-08           | 1.313e-08         | -1.313e-08         |
| $b_3$       | -3.14e-09          | 3.14e-09            | -3.14e-09         | 3.14e-09           |
| $\omega$   | 44.18              | 44.18               | 44.18             | 44.18              |

When the angle between the vibration direction of the transducer and the z-axis of the hull is 26.03°, the longitudinal resonant frequency of the required mode is 1375 Hz. The maximum deformation of the wall is 0.150 µm. The corresponding Fourier coefficients in the vibration equation are shown in Table 3.

| Coefficient | The first quadrant | The second quadrant | The third quadrant | The fourth quadrant |
|-------------|--------------------|---------------------|-------------------|--------------------|
| $a_0$       | 4.996e-08          | -1.021e-06          | -7.713e-08        | 1.602e-07          |
| $a_1$       | -1.484e-08         | -2.48e-07           | 1.57e-08          | 1.427e-07          |
| $b_1$       | 7.984e-09          | 1.63e-06            | -5.597e-09        | 1.102e-07          |
| $a_2$       | -6.758e-10         | 8.827e-07           | -6.209e-06        | -1.8e-08           |
| $b_2$       | -1.101e-08         | 2.444e-07           | 1.604e-08         | 1.483e-07          |
| $a_3$       | 3.369e-08          | 1.001e-07           | 1.249e-08         | -3.523e-08         |
| $b_3$       | -1.266e-08         | -2.345e-07          | -1.349e-08        | 7.405e-08          |
| $\omega$   | 29.51              | 14.95               | 46.49             | 22.05              |

When the angle between the vibration direction of the transducer and the z-axis of the hull is 50.75°, the longitudinal resonant frequency of the required mode is 769 Hz. The maximum deformation of the wall is 0.116 µm. The Fourier coefficients in the vibration equation are shown in Table 4.

| Coefficient | The first quadrant | The second quadrant | The third quadrant | The fourth quadrant |
|-------------|--------------------|---------------------|-------------------|--------------------|
| $a_0$       | 7.449e-07          | -6.083e-07          | 3.727e-07         | 4.293e-07          |
| $a_1$       | -9.208e-08         | -2.655e-08          | -8.227e-08        | -4.501e-08         |
| $b_1$       | -1.101e-06         | 8.919e-07           | 6.106e-07         | 6.547e-07          |
| $a_2$       | -5.477e-07         | 4.654e-07           | -2.809e-07        | -3.318e-07         |
| $b_2$       | 8.827e-08          | 2.674e-08           | -8.528e-08        | -4.006e-08         |
| $a_3$       | 1.733e-08          | 2.39e-08            | 3.584e-08         | 6.066e-09          |
| $b_3$       | 8.693e-08          | -7.49e-08           | -6.695e-08        | -7.261e-08         |
| $\omega$   | 14.7               | 14.95               | 14.95             | 14.7               |

When the angle between the vibration direction of the transducer and the z-axis of the hull is 67.62°, the longitudinal resonant frequency of the required mode is 1761 Hz. The maximum deformation of the wall is 0.214 µm, and the Fourier coefficients in the vibration equation are shown in Table 5.

| Coefficient | The first quadrant | The second quadrant | The third quadrant | The fourth quadrant |
|-------------|--------------------|---------------------|-------------------|--------------------|
| $a_0$       | -1.177e-07         | -5.123e-08          | -5.459e-08        | -3.282e-06         |
| $a_1$       | 2.559e-07          | 1.384e-08           | 1.652e-08         | 6.624e-07          |
| $b_1$       | 1.655e-07          | 2.063e-08           | -1.408e-08        | -5.346e-06         |
| $a_2$       | -1.434e-08         | -1.996e-08          | -2.104e-08        | 2.498e-06          |
| $b_2$       | -2.431e-07         | 6.634e-09           | -2.11e-08         | 6.424e-07          |
| $a_3$       | -8.552e-08         | 3.316e-09           | 1.933e-08         | -2.776e-07         |
| $b_3$       | 3.57e-08           | -1.208e-09          | 2.474e-09         | 6.311e-07          |
| $\omega$   | 14.7               | 44.86               | 44.86             | 14.7               |
When the angle between the vibration direction of the transducer and the z-axis of the hull is 78.68°, the longitudinal resonant frequency of the required mode and the maximum deformation of the wall are 2698 Hz and 0.471 μm, respectively. The corresponding Fourier coefficients in the vibration equation are shown in Table 6.

Table 6. Fourier coefficients of the vibration equation when the angle is 78.68°.

| Coefficient | The first quadrant | The second quadrant | The third quadrant | The fourth quadrant |
|-------------|--------------------|---------------------|-------------------|---------------------|
| $a_0$       | -7.417e-07         | 8.695e-07           | -5.196e-08        | 3.135e-08           |
| $a_1$       | -8.221e-07         | 1.035e-06           | 6.944e-08         | -1.096e-08          |
| $b_1$       | 1.238e-06          | -1.351e-06          | -5.532e-10        | 7.885e-09           |
| $a_2$       | 2.991e-07          | -2.355e-07          | -7.251e-08        | 1.142e-08           |
| $b_2$       | 7.123e-07          | -8.701e-07          | -1.111e-08        | 5.521e-09           |
| $a_3$       | 3.039e-07          | -3.367e-07          | 6.359e-08         | -4.344e-12          |
| $b_3$       | 1.698e-08          | -9.949e-08          | 2.298e-08         | -6.96e-09           |
| $\omega$    | 22.05              | 22.43               | 44.86             | 44.17               |

3.3. Fluid dynamic simulation of the underwater vehicle

The two-dimensional model is used to simplify the fluid dynamics analysis. By using UDF, the obtained vibration equations of transducers at different locations are introduced into the two-dimensional flow field as the boundary condition for the fluid simulations. The flow direction is along the negative direction of the z-axis, and the velocity of the flow field is 0.4 m/s. The velocity contours of different positions are shown in Figure 10, where the fields surrounded by dotted lines represent low velocity region of the wall of the underwater vehicle. Figure 10 (a) shows the velocity contour of the underwater vehicle without vibration. Figure 10 (b), (c), (d), (e) and (f) show the velocity contours of the underwater vehicle when the angles between the vibration direction of the transducer and the z-axis is $0^\circ$, $26.03^\circ$, $50.75^\circ$, $67.62^\circ$ and $78.68^\circ$, respectively.

As it can be seen from Figure 10, the width of the low velocity region of the tail of the underwater vehicle becomes narrower when the vibration is applied, compared with that of without vibration. This indicates that the pressure differential resistance decreases when vibration is applied, which proves the possibility of reducing the drag by creating the wall vibration with piezoelectric transducer.

At the same time, it can be seen that the width of the low velocity region near the wall of the underwater vehicle varies with the angle of the transducer arrangement, which proves that the different locations of the transducer have an effect on the wall vibration drag reduction. When the angle between the vibration direction of the sandwich piezoelectric transducer and the z-axis is $67.62^\circ$, the width of the low velocity region near the wall is the narrowest and the drag reduction effect is the best.

When the fluid flows through an object, a certain high-pressure zone is formed at the head of the object, thus generating a low velocity region. Due to the viscous nature of the fluid, when the flow velocity at the tail of the object falls to the point where the wall resistance cannot be overcome, the high pressure outside the boundary layer produces reverse flow to squeeze out the liquid micro-clusters that come from the direction of inflow. It results in the formation of vortex and the separation of the boundary layer at the tail of the object, then, negative pressure is generated.

The aim of wall vibration drag reduction by using piezoelectric transducer is to disturb the boundary layer. Periodic vibration of the wall can squeeze out the hysteretic fluid in the boundary layer to let the fluids get larger kinetic energy enter, which result in the delaying of the boundary layer separation and increasing the pressure at the tail of the hull. The reduction of the pressure differential resistance of the model indicates the method of using piezoelectric transducer vibration for drag reduction is feasible.
Figure 10. The velocity contours: (a) Without vibration, (b) When the angle is 0°, (c) When the angle is 26.03°, (d) When the angle is 50.75°, (e) When the angle is 67.62°, (f) When the angle is 78.68°.

4. Conclusion
A method to interfere the turbulent boundary layer of the hull wall for achieving the drag reduction by using piezoelectric transducers is proposed. The wall vibration equations, which is used as boundary condition for fluid dynamic simulation analysis, are acquired based on the results obtained by finite element simulation and Fourier transformation. Velocity contours of the underwater vehicle under different conditions show that better drag reduction performance can be obtained when the angle between the vibration direction of the piezoelectric transducer and the flow direction is 67.62°. The simulation results demonstrate that the method of using piezoelectric transducer vibration for drag reduction is feasible. The present work provides valuable references for the research of underwater vehicle drag reduction.
Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (No. 51575130 and 51677043).

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