Design and hydrodynamic simulation analysis on debris cleaning robot underwater

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Abstract. In order to clean up the debris in the underwater pipeline or culvert, the structural design and simulation analysis of the underwater dredging robot were carried out. First, the overall structure of the robot was modelled in three dimensions. This robot features a multi-degree-of-freedom moving robotic arm that cleans up any debris in any corner of the culvert under the coordinated operation of the vehicle body. After that, the static analysis of the key parts was carried out, and the dredging robot was hydrodynamically simulated by FULENT software. The drag characteristics of the dredging robot in the culvert environment were calculated by simulation analysis. The results show that the underwater dredging robot meets the requirements for underwater operations in culverts.

1. Introduction

The culvert openings generate a large amount of silt due to the natural deposition of sediment and leaves and the accumulation of biological excreta, and it is currently necessary to clean these silt [1]. The current domestic and international underwater dredging devices include hull type, wheeled walking type, crawler walking type and hydraulic propulsion type [2]. These dredging robots have problems in the removal of culvert silt, such as poor adaptability to complex silted ground, incomplete corner cleaning, and lack of positioning methods. Therefore, this paper designs an underwater dredging robot that adapts to the narrow hole and deep hole of the culvert.

Studying the resistance performance of dredging robots under water driving is of great significance for verifying its feasibility and further optimizing the body structure [3]. With the development of computer simulation technology, computational fluid dynamics (CFD) has been widely used in hydrodynamic simulation calculation [4]. Taiyou Wang et al [5] used CFD technology to analyse the flow field of the propeller with ROV added volume force. Hang Bai et al [6] discussed the effects of different support structures on the resistance of underwater robots. Jianguo Wu et al [7] analysed the resistance of the robot in three states: direct flight, dive and traverse.

In this paper, the overall structure and working principle of the underwater dredging robot are first described. Then the standard $k$-$ε$ model in the turbulence mode is selected by the boundary laminar flow [8], and the dredging robot is used in the underwater operation by using the CFD method. The resistance characteristics of the time were studied and the surface pressure of the dredging robot and the surrounding flow field were analysed.
2. Overall design of dredging robot

2.1. The whole frame
The underwater dredging robot consists of two parts: the onshore control cabinet and the underwater dredging machine. The main unit of the underwater dredging machine is mainly composed of a chassis running mechanism, a front clamping mechanism, the 3 degree of freedom adjustment mechanism, a main frame, a fuel tank, a hydraulic valve box, etc. Its overall structure is shown in Figure 1. The onshore control cabinet communicates with the underwater dredger through several multi-core watertight cables. The sludge is transported by the dredger to the shore via a hose.

![Overall structure of the dredging robot](image1)

1-cutter mechanism 2-3 degrees of freedom adjustment mechanism 3-valve box 4-tank 5-underwater camera 6-main frame 7-submersible sewage pump 8-track 9-hydraulic pump

Figure 1. Overall structure

2.2. Mechanical body structure design

1) Walking mechanism
The collecting mechanism of the sludge in the culvert, the hydraulic transmission system and other accessory accessories are placed on the crawler chassis. The track structure is shown in Figure 2. The working principle is that the hydraulic motor rotates to transmit the power to the driving wheel, the driving wheel drives the crawler belt, the supporting wheel shares the gravity of the dredging robot, and the driven wheel is controlled by the tensioner to ensure that the track is in tension and prevent slipping. The track selects a rubber track with high friction. This track is suitable for underwater walking and has excellent anti-skid ability. Its climbing obstacle and handling performance are superior to similar steel chassis.

2) 3-Degrees-of-freedom adjustment mechanism
The 3-degree-of-freedom adjustment mechanism can realize the swinging of the 3 degrees of freedom of the cutter mechanism, and clean any corners of the culvert. The structure is shown in Figure 3. The hydraulic cylinder A is placed on the main frame to control the steering of the adjustment mechanism, and the hydraulic cylinder B is connected with the cutter mechanism to control the steering of the cutter mechanism. The hydraulic cylinder C can control the lifting and lowering of the cutter mechanism. Before the dredging machine is lowered, the hydraulic cylinder A rod cavity feed the oil, and the auger part is lifted to a certain angle. After the dredger is placed in the water bottom, the hydraulic cylinder A rod less cavity feed the oil, the cutter mechanism is lowered until the wheel touches the ground, after which the auger gravity is supported by the wheel. The wheel mounting position is adjustable to ensure that the height of the cutter mechanism is adjustable from the ground.

2.3. Working principle
Use the crane to hoist the dredging robot into the water. When the water has not reached the bottom of the culvert, open the submersible motor to control the hydraulic cylinder to extend and lift the cutter
mechanism. Then, turn on the mud pump to start working, then turn on the auger hydraulic motor. The auger turns to agitate the sludge, which is sucked by the mud pump and transported to the shore. When the crawler hydraulic motor is turned on, the dredging robot starts to work forward, and the steering speed difference between the two sides can be adjusted according to the terrain and the detected sludge position. The 3-degree-of-freedom adjustment mechanism controls the swinging mechanism to swing, realizes the sweeping function at any position, and at the same time cooperates with the positioning function of the sensing system to achieve very good corner cleaning. Real-time monitoring of various data during the work process to prevent collisions, overloads, etc. After the dredging is completed, the dredging robot is returned to the initial position, and each device is turned off to be in a stopped state, and the culvert is lifted by the crane.

![Figure 2. Track Figure](image)

1-driven wheel  2-tensioner  3-rollers  4-support  5-track  6-travel hydraulic motor and drive wheel

Figure 2. Track Figure

1-Support rod  2-frame  3-Hydraulic cylinder A  4-Hydraulic cylinder C  5-Hydraulic cylinder B

Figure 3. 3-Degree-of-freedom adjusting

2.4. Technical parameter calculation

2.4.1. Underwater walking resistance calculations.

The operating speed that the underwater robot can achieve is related to the power provided by the propulsion system and the total resistance of the system itself. The total resistance mainly includes the frictional resistance \( R_f \) and the cohesive resistance \( R_p \). This paper cites the flat panel hypothesis proposed by Froude, which simplifies the whole robot into a flat plate, and the flow rate of water flowing through the plate is constant at \( v \). To calculate the frictional resistance of the robot, first determine the motion state of the boundary laminar flow of the plate. The laminar flow state is determined by the Reynolds number \( R_e \). The formula is:

\[
R_e = \frac{\rho v L}{\mu}
\]  

Where: \( \rho \) is the density of water, 1000kg/m\(^3\); \( v \) is the relative flow rate, taking 2m/s; \( L \) is the characteristic length, taking 3m; \( \mu \) is the dynamic viscosity, 1.792×10\(^{-3}\)Pa·s at 0°C.

According to the calculation, the Reino number \( R_e \) range value under different boundary layer flows is observed. The laminar flow: \( R_e < (3.5~5.0)×10^5 \); the transition flow: \( 5.0×10^5 < R_e < (3.5~5.0)×10^5 \); the turbulent flow: \( R_e > 3.0×10^6 \). After calculating the Reynolds number of the robot boundary layer \( R_e = 3.348×10^6 \), it is determined that the boundary flow of the robot boundary is in a turbulent state. In the turbulent state, the formula for calculating the average frictional resistance coefficient \( C_f \) is:

\[
C_f = \frac{0.072}{R_e^{1/3}}
\]  

In the end, you can conclude:

\[
R_f = 0.5C_f \rho v^3 S
\]  

\[
R_p = 0.5C_p \rho v^3 S
\]
Where: $C_f$ is the frictional resistance coefficient, calculated to be 0.0036; $C_p$ is the viscosity and pressure resistance coefficient, taking 0.8; $S$ is the wet area in the moving direction, obtained by the calculation function of Solidworks software, taking 2.25 m$^2$. Finally, the water resistance of the robot body was 4291.2N.

2.4.2. Selection of main components

The weight of the dredging machine is 1032kg, and the walking acceleration is 1.2 m/s$^2$. Table 1, 2 and 3 are the operating parameters of the hydraulic motor, hydraulic cylinder and mud pump.

| Table 1. hydraulic motor Parameters |
|------------------------------------|
| Type | model     | Displacement (ml/r) | preset pressure (Mpa) | Rated torque (N·m) | range of rotation (rpm) |
|------|-----------|----------------------|------------------------|---------------------|-------------------------|
| Track| XHM2-175  | 180                  | 20                     | 526                 | 15~1000                 |
| Auger| XHM1-63   | 64                   | 25                     | 225                 | 15~1000                 |

| Table 2. Hydraulic Cylinder Parameters |
|----------------------------------------|
| Type | Piston rod diameter (mm) | Work pressure (MPa) | stroke (mm) | Effective area of the rod end (cm$^2$) |
|------|--------------------------|---------------------|-------------|----------------------------------------|
| Hydraulic Cylinder A | 35 | 16 | 100 | 9.6 |
| Hydraulic Cylinder B | 35 | 16 | 200 | 9.6 |
| Hydraulic Cylinder C | 35 | 16 | 80  | 9.6 |

| Table 3. Fluid pump parameters |
|--------------------------------|
| Model     | Nominal displacement (ml/r) | Preset pressure (Mpa) | Rated speed (rpm) | Volumetric efficiency (≥%) | Weight (kg) |
|-----------|-----------------------------|-----------------------|-------------------|---------------------------|-------------|
| CBHz-F30  | 30                          | 20                    | 2500              | 92                        | 4.8         |

3. Hydrodynamic simulation analysis

3.1. Control equations and numerical methods

Based on the fluent module of ANSYS, the numerical calculation and simulation analysis of the hydrodynamic performance of the underwater dredging robot are carried out. The numerical solution of the turbulence problem is to solve the N-S equation. There are two major methods of direct numerical simulation (DNS) and indirect numerical simulation. Indirect numerical simulation mainly includes numerical methods such as large eddy simulation (LES), Reynolds average N-S model (RANS), and separation vortex model. The number of computational grids required by such methods as DNS and LES is very large, which limits the scope of application. Currently, it is limited to the numerical simulation of simple objects, so this paper uses the RANS model method $^{11}$.

The incompressible continuity equation after the Reynolds time homogenization and the N-S equation (RANS) are as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (5)$$

$$\rho \frac{\partial \bar{u}_i}{\partial t} + \rho u_j \frac{\partial \bar{u}_i}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \rho \frac{\partial \bar{u}_i u_j}{\partial x_j} + \rho f_i \quad (6)$$
Where: \( \rho \) is the fluid density; \( \mu \) is the fluid motion viscosity coefficient; \( p \) is the pressure; \( f_i \) is the quality strength; \( \bar{u}_i \) is the average speed of Reynolds; \( u' \) is the pulsation speed; \(-p\partial \bar{u}_i/\partial_j\) is "Reynolds stress".

3.2. Simplified model and meshing

The underwater dredging robot has a complicated structure and many components, and is difficult to perform meshing, and the workload during calculation is also large. Therefore, the robot model is simplified, but its main feature structure is maintained, so that the simulation of the flow field structure can be truly reflected in the simulation calculation. The main dimensions of the CAD model of the dredging robot: length \( \times \) width \( \times \) height \( (L \times B \times H) \) is \( 3m \times 1.6m \times 1m \). The calculation area model of this paper is set to a rectangular parallelepiped, and the length \( \times \) width \( \times \) height is \( 5L \times 3.7B \times 6H \). The ICEM software in the workbench is used to mesh the dredging robot model and the simulation calculation domain. The total number of meshes of the model is 5042013, as shown in Figure 4 and Figure 5.

![Figure 4. Dredging robot meshing](image)

![Figure 5. Computing area model meshing](image)

The entrance boundary uses a speed inlet with a water flow rate of 6 m/s. The entrance is 2.5L from the centre of the car. The exit boundary is chosen to be a free outlet, and the exit is 2.5L from the centre of the car. All surfaces of the robot are set to a static, non-slip wall with a roughness value of zero. The cell wall boundary is set to a no-slip boundary by default.

3.3. Simulation calculation result analysis

3.3.1. Surface pressure analysis.

The Fluent software was used to analyse the surface resistance of the robot at a flow rate of 6 m/s, and the surface pressure distribution of the robot was obtained, as shown in Figure 6. The pressure on the surface of the machine becomes small. It can be seen from the figure that the model receives a maximum positive pressure of \( 1.83 \times 10^4 \) Pa and a maximum negative pressure of \(-4.553 \times 10^4\) Pa. The dredging machine as a whole receives less pressure, so it can work well underwater.

![Figure 6. Dredging robot surface pressure distribution map](image)

3.3.2. Flow field analysis.

The flow velocity distribution of the flow field around the dredging robot under different cross sections is shown in Figure 7. The tail of the robot forms a large low-speed zone, forming a vortex in this area, which causes a loss of eddy current. The vortex is generated at the same time, causing the pressure in the rear region of the robot to suddenly drop, forming a low pressure zone, which generates a large viscosity resistance, thereby increasing the resistance of the dredging robot when driving
underwater. In the trailing area of the tail end, the robot has a phenomenon of dense streamline and chaotic flow field, accompanied by flow separation. This phenomenon will lead to increased resistance of the robot, which is not conducive to underwater dredging operations.

![Figure 7. Flow velocity distribution under different cross sections](image)

(a) Symmetrical middle section (b) Track vertical section (c) Horizontal section

4. Conclusion

The robot uses a three-degree-of-freedom sweeping mechanical arm to move with the car body. The total resistance of the water flow includes frictional resistance and cohesive resistance. Among them, the viscosity resistance is dominant in the water flow resistance, accounting for about 85%, and the other resistance is a small proportion.

The fluid flow in the rear part of the dredging robot is separated, and a vortex motion is formed in this area, and the vortex motion causes the eddy current to be lost. When the vortex is generated, the pressure in the rear region of the robot suddenly drops, forming a low pressure zone and increasing the viscosity resistance. The structural design of the rear part of the robot should be optimized to reduce drag.

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