Simulation Analysis of the Performance of an Environmentally Friendly Double-suction Cutter Suction Dredger Based on SolidWorks and ANSYS

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Abstract: As China transforms from a big dredging country to a dredging power, dredging vessels have unprecedented development opportunity and expansion space. Cutter suction dredgers are rapidly becoming more effective, greener, and more energy-efficient. In order that cutter suction dredgers are adaptive to the landform and soil texture in complex water areas and secondary pollution is contained, this thesis develops a new type of environmentally friendly double-cutter suction dredger with SolidWorks and conducts simulation analysis based on ANSYS. Compared with the single-cutter structure, the concentration distribution at the suction outlet in the double-cutter structure has increased and the diffusivity has decreased, effectively reducing secondary pollution. When the total dredging outputs stand at the same, the double-cutter suction dredger is more energy-efficient and environmental friendly than the existing dredger, which reflects its reliability and advancement.

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1. Introduction
As China is transforming from a big dredging country to a dredging power, there is an unprecedented opportunity and huge room for development regarding dredging vessels. The industrial restructuring is gaining speed and demand for high-performance dredging equipment on the market is on the rise. Documents No.1 titled Decisions on Accelerating Reform on Water Resources Management and No.2 titled Guidelines on Accelerating the Development of Inland Water Transportation with the Yangtze River as an Example issued by the state council at the beginning of 2011 have shown that cutter suction dredger will develop towards efficient, green and energy-conserving dredging equipment. Yet, currently in China, most dredgers used for inland river dredging are obsolete and not accurate or environmentally friendly enough, so they cannot meet the requirement of projects, which brings new opportunity for dredger manufacturers. The design of double-cutter and double-suction on the dredger is featured with operational flexibility, efficiency and adaptability to multiple water environments. It has good prospects of development.

2. Structural Design of Double-cutter and Double-suction
Given that existing single-cutter dredgers over-or under-dredge and are too energy-consuming under special working conditions, the design of double-cutter has been proposed. Structural design and simulating calculation have been conducted as well. The use of shogging mechanism and luffing mechanism in adjusting the distance between and angle of the two cutters can make the dredger more...
flexible in the cutting work. Moreover, this structure can add to the cutter’s adaptability to soil layer in complicated terrains so that under-dredging can be reduced, diffusion-caused secondary pollution can be limited and dredging efficiency improved.

2.1 Design of Double-cutter Suction Dredger Model
In order to achieve the self-adaptation of cutter suction dredgers in complicated water areas, this thesis has designed a model of double-cutter suction dredger. There are mainly two parts in this model: the ladder and the hull. The two cutters are installed in the ladder that is mostly used for sludge-dredging while the dredger is operating. Each one of the two cutters is equipped with a suction outlet which is used to carry sludge. The function of the hull is to hold up and put down the ladder. Inside of the hull carries self-priming pump and electrical machinery. The design and production of the double-cutter structure is the critical and key technology of this project. There is some special requirement. Domestic market does not have self-adapting double-cutter product, so the design of this device needs to be completed independently by team members (as is shown in Graph 1).

Graph 1 Graph of Double-cutter and Double-suction Design

There are two parts in the design of the double-cutter structure: the luffing mechanism and the shogging mechanism. The luffing mechanism is installed with the turbine and worm and is equipped with DC motor to drive. When the DC motor rotates, it drives turbine and worm to rotate through the 90° commutator. The turbine is joined to the support through the axis of rotation. The platform rotates as is driven by the turbine and worm. In this way, changing the rotating direction of the cutters at certain time is possible. Each one of the two cutters is equipped with a suction outlet. When there is a need to adjust the angle, the system will sends out an instruction and then the DC motor will drive the turbine and worm to rotate so as to adjust the angle between the two cutters. The shogging mechanism adopts the design of slide rail system with two sliders on the rail. The stepper motor drives the reverse-flighted screws to rotate, which leads the two sliders to move towards or away from each other, thus changing the center-to-center distance between the two cutters. When the distance needs to be adjusted, the system will sends out an order, and then the stepper motor drive the rotation of the screws to do it. By adjusting the luffing mechanism and the shogging mechanism can the dredger get self-adaptable to the environment and work more efficiently.

3. Analysis on the Advantage of Environmental Protection of the Double-cutter Double-suction Design

3.1 Suction Efficiency and Diffusion Control Analysis
Conventional dredging devices are installed with a suction to suck up bottom sludge, but usually dredgers only have one suction. In the dredging process, as the horizontal movement of the cutter ladder changes its direction, the sludge diffusion zone also changes. Therefore, this thesis has decided to adopt the double-suction design to reduce sludge diffusion in the dredging process. By
doing so, the diffusion caused by the cutting of cutters is no longer as intensive so that the secondary pollution of water can be curbed and the dredging efficiency can be raised.

The device in this thesis can solve the problem of sludge diffusion by adding a pair of symmetrical suctions to the back of the cap of the two cutters and connecting the pipe that links the two suctions with the the pump through a triple valve.

The working environment of cutters are relatively special since the cutter, the surrounding water area and the cutting of sludge altogether can lead to the formation of a complicated flow field. In the dredging process, what is being cut may diffuse to surrounding water area, causing secondary pollution there. In an effort to figure out respective effect of single-cutter and double-cutter on the suction volume and diffusion volume of sludge, we set up a two-phase flow model of the water and the sludge in the flow field of the cutter and adopt the numerical simulation method to calculate the suction volume of different types of cutter suction to make a comparison between the results of the suction volume and diffusion volume of the two types of suction.

The single-cutter fluent field and double-cutter fluent field are modeled in the same volume with the same boundary conditions of for flow field[3-4] to ensure an objective comparison analysis on the suction characteristics of the single-suction and double-suction[5-6]. The initial conditions are set as follows:

The intake area of the fluent field was 7.712m². The flow velocity of sediment was 2m/s. The discharge volume of sediment was 1.5424m³/s. The concentration distribution at the suction outlet of the single-suction and the double-suction in the fluent field were analyzed as is shown in Graph 2.

Graph 2 Comparison Graphs of Concentration Distribution at Suction Outlet

Calculations show that the in the single-suction structure, the concentration distribution of is 0.11m²/s, the flow velocity is 8.1m/s and the discharge volume at the outlet is 0.26m³/s. Finally, the diffusivity is calculated at 58%. As for the double-suction structure, the concentration distribution of is 0.13m²/s, the flow velocity is 8.1m/s and the discharge volume at the outlet is 0.87m³/s. It diffusion effect is shown in Graph 3. The diffusivity is calculated at 43%. Compared with the single-suction structure, the concentration distribution is higher while the diffusivity is lower for the double-suction structure.

3.2 Calculation of Energy Consumption of Double-suction Structure

The calculation of the ratio of output to energy consumption involves following steps: Firstly, the total output is confirmed at 300m³/h. This device is equipped with two cutters and each one of them has the
same dredging depth, so the output of each is 150 m$^3$/h. Based on the empirical formula of the cutter diameter:

$$D = 0.18Q^0.35 \text{ (for soft soil)}$$  \hspace{1cm} (1)$$

the cutter diameter is calculated at 1.03 m. Inputting soil texture and output into the above mentioned PLC control system leads to such parameters as the rotation speed, dredging depth and horizontal moving speed of the cutters. In this calculation, the output is 300 m$^3$/h and the soil texture parameters are $c_1=0.302$, $c_2=0.114$, $k_m=3\times10^3$ and $\varepsilon=0.15$. Calculation results are: the rotation speed of the cutter: $n=26.14$ rpm; dredging depth: $h=0.623$ m; and the horizontal moving speed: $U_{SW}=0.3$ m/s.

Geometric parameters and operating parameters of the cutter are as follows:

(1) Geometric parameters of the cutter

Shape: Cylinder
Diameter $D$: 1030 mm
Number of teeth $Z$: 6
Tool arm width $b$: 320 mm
Cutting angle $\alpha$: $40^\circ$

(2) Operating parameters of the cutter

Rotating velocity $n$: 26.14 rpm
Dredging depth $h$: 0.623 m
Horizontal moving velocity $U_{SW}$: 0.3 m/s
Angular velocity $\omega$: 2.736 rad/s
Tangential velocity $V_t$: 1.409 m/s

Analysis and calculation of the force on the cutter in the cutting process can be conducted with data above. Hereby set 15° condition as an example. When $\omega t=15^\circ$, the force on the cutter is shown in Graph 4 in which the cutter revolves 15° around the axis O, tool arms A and B are for the cutting. Tool arm A revolves 15° and B 75° around the axis. Calculations for tool arm A are as follows:

Layer thickness: $h_{i1} = \frac{60V^2}{n\pi} \sin \omega t = 0.0297$ m  \hspace{1cm} (2)$$

Cutting velocity: $V_{cl} = \sqrt{U_{sw}^2 + V_t^2 - 2U_{sw}V_t \cos (\pi - \omega t)} = 1.071$ m/s  \hspace{1cm} (3)$$

Component force in the direction of cutting velocity: $F_{h1} = \frac{c_1 \cdot \rho_w \cdot g \cdot V_{cl} \cdot e \cdot h_{i1}^2 \cdot b}{k_m} = 10849.69$ N  \hspace{1cm} (4)$$

Torque: $M_t = M_{h1} + M_{v1} = F_{h1} \cdot L_{h1} + F_{v1} \cdot L_{v1} = 5587.58$ N·m  \hspace{1cm} (5)$$
Power: \[ P_1 = M_1 \cdot \omega = 15341.06W \]  
Similarly, the cutting power of tool arm B can be calculated:

\[ h_2 = 0.111m \quad V_c = \sqrt{U_w^2 + V_1^2 - 2U_w V_1 \cos (\pi - \frac{2\pi}{Z})} = 1.514m/s \]  
Component force \( F_{h2} \) in the direction of cutting velocity:

\[ F_{h2} = \frac{c \cdot \rho_w \cdot g \cdot V_c \cdot e \cdot h_1^2 \cdot b}{k_m} = 138982.86N \]  
\[ M_{h2} = M_i = M_{h1} + M_{v1} = F_{h1} \cdot L_{h1} + F_{v1} \cdot L_{v1} = 71576.17N \cdot m \]  
\[ P_2 = M_2 \cdot \omega = 190411.65W \]  
So the total cutting power of cutters is: \[ P = P_1 + P_2 = 211.12kW \]

The six tool arms are evenly distributed around the cutter, which means that the cutting condition will be the same at the interval of \( T/6 \) cutter, so only what within the \( T/6 \) is studied. That is 0-60 degrees. Analysis on the entire \( T/6 \) part shows that within 0-34 degrees, tool arm A and B are cutting. Tool arm B just leaves the cutting soil layer at 34 degrees. Then only tool arm A is cutting in 34-60 degrees. When A arrives at 60 degrees, tool arm F happens to arrive at 0 degree, just entering the cutting layer, exactly the same as the situation at 0 degree. When the cutting soil layer thickness is 0.623m, the scope of each tool arm will be 0-94 degrees. Take 1 degree as the computing interval, the cutting power at all moments and the average power of one period can be calculated. The average power of one cutter in one period is calculated at 160.34kW. **Therefore, the cutting power of the cutters in the double-cutter suction dredger is 160.34x2=320.68kW.**

There are two parts included in the motor power of the cutters in the working process, namely, power consumed while cutting and power consumed while the axes rotate. For the sake of scientificity and effectiveness, this thesis adopts the empirical formula to calculate the power consumed while the cutter axes rotate. The power consumed by the cutter motor is acquired by adding the cutting power and rotary power together. The specific calculation of the axes’ rotary power is as follow:

The power of the motor axes of the cutters:

\[ P = 0.35 \frac{F_c \cdot r \cdot n}{716 \times 0.736} \]  
In the formula: \( F_c \)—cutting resistance of the cutters  
\( n \)—rotation speed of the cutters  
\( r \)—radius of cutters

Cutting resistance:

\[ F_c = \frac{\tau \cdot t \cdot b}{\cos (\theta - \alpha + \rho_0) \sin \theta} \]  
In the formula:

\( t \)—cutting thickness;  
\( b \)—effective width of the cutting blade;  
\( \tau \)—shear stress;  
\( \theta \)—shear angle;  
\( \phi \)—internal friction angle of the soil cut, among them, 25°—30° for silty soil, 35° for fine sand and 40° for coarse sand;  
\( \alpha \)—cutting edge angle, usually 45° is picked;  
\( \rho_0 \)—friction angle between clay and steel, usually 20° is picked;
After calculation, \( F_c = 111.79 \text{kg/cm} \), \( P = 199.91 \text{kW} \).

Therefore the power consumed while the axes rotate (PB) is \( 199.1 \times 2 = 398.2 \text{kW} \) and the power consumed by the motor is \( P_{\text{Total}} = P_A + P_B = 718.88 \text{kW} \). \( P_A \) represents the power consumed while cutters cut and \( P_A \) the power consumed while the cutter axes rotate.

When the team looked through relevant materials, they found following working parameters of the cutters of 300m\(^3\)/h dredgers commonly used on the market: diameter of the cutter (D) = 1.580mm; tool arm width (b) = 405mm; dredging depth = 1.043m; cutting angle (\( \alpha \)) = 40\(^\circ\); rotation speed (n) = 18.14rpm; horizontal moving speed \( U_{SW} \) = 0.4m/s; angular velocity (\( \omega \)) = 1.898rad/s; tangential velocity (\( V_t \)) = 1.51m/s; and cutting scope of each tool arm on the cutter: 0—109\(^\circ\). Calculated based on the above formulae, in normal operation, the cutting power of the dredger cutter is 380.64kW, the rotary power of cutter axes is 380.05kW and the total power consumed by the cutter motor is 760.69kW. The above analysis shows that when the total dredging volumes are the same, the double-cutter suction dredger saves motor power by 5.8\% compared with the existing single-cutter dredger.

In order to ensure the effectiveness of contrastive analysis, this thesis has also taken into account the power consumed by the suction system and the shogging mechanism while considering the power consumed by the cutter motor of the suction dredger in the real work. Since the comparison is done under the condition that the dredging volumes are the same, the power consumed by the suction system is approximately the same as well. Moreover, single-cutter and double-cutter are different in size and the total weights of them are roughly the same, so the tensile force and energy consumption of their shogging system can be seen as the same. After consulting experts and referring to materials, we can reach the following conclusion: The double-cutter suction dredger is more energy efficient than the existing dredger when their total dredging volumes are the same.

The above discussion is mainly about calculations and analysis of the cutter suction dredger under normal working conditions. When the cutter suction dredger works in complex water areas, because the new double-cutter suction dredger is more adaptive to this environment, it can reduce the times moving back and forth in the same water area and energy consumption while it is working compared with the conventional cutter suction dredger. In the same complex water area, the conventional dredger cannot finish dredging work at a time. Instead, it needs three back-and-forth trips and the depth of the cutter laid down needs to be adjusted each time, which consumes too much energy. In contrast, the new double-cutter suction dredger can finish dredging by one or two round trips, cutting the back-and-forth trips in the same water area. To sum up, the new double-cutter suction dredger can reduce the total energy consumption by one or two times compared with the conventional type.

4. Social Benefit
The new dredger designed according to this proposal has improved significantly, as is shown in Table 1.

| Increased dredging depth | The dredger has become more capable of operating in deep waters. |
|--------------------------|---------------------------------------------------------------|
| Improved time efficiency | Dredging time has been considerably cut.                      |
| Higher construction efficiency | Dredging efficiency and working efficiency of the improved dredger have been significantly raised. |
| Environmentally friendly dredging | The redesign of the suction outlet has achieved environmentally friendly dredging. |

According to the survey on the energy consumption of vessels in five shipping companies including Sichuan Changjiang Water Transport Co., Ltd, Nanjing Changjiang Tanker Co., Ltd, Minsheng Co., Ltd, Chongqing Changjian Shipping Co., Ltd and CCNSG Wuhan Automotive Logistics Co., Ltd,
except for a small proportion of dredgers powered by electric motors, most cutter suction dredgers are powered by diesel at the rate of 2.5 tons per hour. If on average, each one works 14 hours each day at the rate of 2.5 tons/h, then each dredger can save 12,000 tons of diesel each year after transformation. Meanwhile, pollutant emissions such as carbon dioxide, sulfur dioxide, hydrocarbon, carbon monoxide, nitrogen oxide and dust particles can be cut by 10%-15% year on year.

5. Conclusion
The device designed by this thesis can effectively solve the problem of silt diffusion by adding a pair of symmetrical suctions to the back of the cap of the two cutters and connecting the pipe that links the two suctions with the the pump through a triple valve. A new double-cutter structure model has been set up with SolidWorks and single-cutter fluent field model and double-cutter fluent field model of the same volume have been established with ANSYS to conduct contrastive analysis on the characteristics of single-suction and double-suction. The diffusivity of the single-suction structure is 58% while that of the double-suction structure is 43%, so the latter is more environmentally friendly. Take a cutter suction dredger that dredges at the rate of 300 m³/h as an example. The double-cutter structure is obviously less energy consuming and more efficient, thus bringing about more economic and social benefit.

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