Design and research of underwater hydraulic driven diamond chain saw cutting machine

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Abstract. The hydraulic driven chain saw is a cutting tool for underwater operation. The hydraulic driven chain saw was designed, the hydraulic adjusting device was designed, the hydraulic chain saw experimental platform was designed, the sawing efficiency and power consumption experiments were carried out, and the diamond saw chain wear experiment was carried out. The experimental results show that: When cutting C25 standard reinforced concrete floor plate, the tension of tight edge of diamond saw chain is large; the dynamic load of diamond saw chain has the greatest influence on the tension of diamond saw chain, and the dynamic load is proportional to the rotation speed of chain wheel, the pitch of diamond saw chain, the weight per meter of diamond saw chain and the length of tight edge, among which the rotation speed of chain wheel has an effect on it. The noise is the largest; the power consumption of cutting concrete is 2.85kw, the efficiency of sawing concrete is 0.93m²/h, and the sawing area of diamond saw chain per meter is 16.7m²/m.

1. Introduction
Concrete is a kind of composite material mainly composed of cement, steel bar, stone, etc. There are 19 grades in total[1-2], it is a very important and popular building material. With the wide application of concrete, its cutting demand is increasing. Hydraulic driven chain saw is a cutting tool for underwater operation. In this experiment, the idling experiment and concrete cutting experiment of the hydraulic driven chain saw are carried out on the hydraulic chain saw experimental platform, so as to further understand and analyze the performance characteristics of the hydraulic driven chain saw.

2. Design of hydraulic driven chain saw
The hydraulic driven chain saw is generally used for underwater concrete cutting. It is mainly composed of hydraulic motor, sprocket, guide plate, guide plate adjusting device and diamond saw chain (Figure 1). A diamond bit (diamond segment) is welded every other link of diamond saw chain. Driven by the hydraulic motor, the diamond saw chain rotates at high speed on the guide plate by the rotation of the driving sprocket to realize the cutting of concrete.
3. Design of hydraulic regulating device

3.1. Design of hydraulic regulating device

The hydraulic regulating device includes input end, box body, output end, cylindrical sealing sleeve, left bearing, rotating shaft, right bearing, plane bearing, speed regulating motor, input end cover and output end cover. The structure diagram is shown in Figure 2 and the explosion diagram is shown in Figure 3. When in use, the speed regulating motor rotates and the fluid flows in from the input hole. When the speed regulating motor rotates until the input hole is aligned with the through-hole of the rotating shaft, the fluid flows through the through-hole of the rotating shaft and flows out from the output port. Thus, the flow rate of the fluid flowing out is determined by the speed of the speed regulating motor.

Figure 1. Hydraulically driven chain saw
1. Hydraulic motor, 2. Guide plate, 3. Diamond saw chain, 4. Diamond cutter head

Figure 2. The structure diagram of hydraulic regulating device

Figure 3. The explosion diagram of hydraulic regulating device
1. Input end, 2. Box, 3. Output end, 4. Cylindrical sealing sleeve, 5. Left bearing, 6. Rotating shaft,
7. Right bearing, 8. Plane bearing, 9. Adjustable speed motor, 10. Input end cover, 11. Output end cover

3.2. Design of spherical hydraulic regulating device
The spherical hydraulic regulating device includes left box, bearing I, rotating shaft, right box, sealing ring, bearing II and speed regulating motor. When in use, the speed regulating motor rotates, and the fluid flows into the inner hole at the input end. When the speed regulating motor rotates to make the flow through hole align with the inner hole at the input end, the fluid passes through the flow through hole and flows out from the inner hole at the output end. Thus, the flow rate of the fluid flowing out is determined by the speed of the speed regulating motor. The structure diagram is shown in Figure 4. and the explosion diagram is shown in Figure 5.

**Figure 4.** The structure diagram of spherical hydraulic regulating device

**Figure 5.** The explosion diagram of spherical hydraulic regulating device

1. left box, 2. bearing I, 3. shaft, 4. right box, 5. seal ring, 6. bearing II, 7. Adjustable speed motor

4. **Design of hydraulic chain saw experimental platform**

**Figure 6.** Hydraulic chain saw test bench

The hydraulic chain saw test bench is shown in Figure 6. The hydraulic motor is connected to the pump station through the high-pressure oil pipe CB-FE20E-F1L1-R1 Hydraulic gear
pump, The rated pressure is 20MPa, Rated flow is 26.1L/min; Select 7.5kW explosion-proof motor).

5. Experiment on sawing efficiency and power consumption

5.1. Purpose of the experiment
The sawing efficiency and power consumption of hydraulic driven chain saw were tested, and the bending degree of diamond saw chain was measured to calculate the tension of diamond saw chain.

5.2. Experimental methods
The specific experimental conditions and methods are as follows:\[3\]:
(1) Cutting with water, the water flow is adjusted according to the actual situation of sawing in the experiment;
(2) The ball screw + NC motor + CNC system is used to adjust the feed speed and make the feed uniform;
(3) The cutting object is reinforced concrete (C25 standard reinforced concrete floor plate, with thickness of 100 mm and width of 400 mm, and the rebar with diameter of Φ10 mm is evenly placed at about 100 mm intervals inside);
(4) Clamp one of the output wires of the three-phase asynchronous motor with a clamp type ammeter, and place it in the center of the clamp as far as possible to accurately measure the output current of the motor;
(5) In the experiment, the electric current of motor, hydraulic pump, hydraulic motor and diamond saw chain rotation was recorded\[1\], then start sawing concrete, start timing when the chain saw just touches the concrete, record the time to the end of sawing, and record the stable current value during the sawing process\[2\];
(6) Calculation formula of chain saw cutting efficiency
\[ V_q = \frac{\text{feed distance of cutting concrete} \times \text{cutting concrete thickness}}{\text{cutting time}} (m^2/h) \]
(7) Calculation formula of power consumption in cutting concrete
\[ P = (I_1 - I_0) \times 380 \]
\[ I_1 \] is the working current, in A; \[ I_0 \] is the idle current, in A; \[ P \] is the motor power, in W.

5.3. Experimental results and analysis
Before cutting, the starting position of diamond saw chain should be adjusted first; the NC system is used for feeding, and the NC program is written and input into the NC system, and the feed speed is generally controlled between 2-10 cm/min; tap water is used as the cooling and flushing fluid, the water outlet is aligned with the diamond saw chain inlet, the water flow is about 1L/min, and the chain sag is measured to be 18.5 mm after cutting. The experimental data and results of sawing concrete are shown in Table 1.

| No load current | Working current | Cutting feed distance | Cutting thickness | Linear speed of diamond saw chain | Cutting time |
|-----------------|-----------------|----------------------|------------------|----------------------------------|--------------|
| 11.3A           | 18.8A           | 400mm                | 100mm            | 11.5m/s                          | 155s         |

The experimental results are analyzed as follows:
(1) Analysis of sawing efficacy
The cutting efficiency of hydraulic driven chain saw is as follows:
\[ V_q = \frac{\text{feed distance of cutting concrete} \times \text{cutting concrete thickness}}{\text{cutting time}} (m^2/h) \]
= 0.4×0.1/155×3600m²/h=0.93m²/h
The power consumption of chain saw cutting concrete is:
\[ P = (I_1 - I_0) \times 380 (W) = (18.8 - 11.3) \times 380 W = 2.85 kW \]
(2) The force analysis of diamond saw chain was carried out

(I) Tension of diamond saw chain caused by screw driving \( F_0 \)

\[
F_0 = g \sqrt{\frac{ql^2}{8f}} + \frac{ql}{2}
\]  

(1)

Where,

\( g \) —— Acceleration of gravity, \( g = 9.8 \text{ m/s}^2 \).

\( q \) —— Mass of diamond saw chain per meter, kg/m. In this project, through the actual weighing, the quality of diamond saw chain per meter (including diamond cutter head) is calculated \( q = 0.451 \text{ kg/m} \).

\( l \) —— Loose edge span, m. In this project, \( l = a = 458 \text{ mm} = 0.458 \text{ m} \).

\( f \) —— Chain sag, m. In this project, from the above, \( f = 18.5 \text{ mm} = 0.0185 \text{ m} \).

After calculation, \( F_0 = 6.3 \text{ N} \)

(II) Tension of diamond saw chain caused by centrifugal force \( F_1 \)

\[
F_1 = qv^2
\]  

(2)

Where,

\( q \) —— Mass of diamond saw chain per meter, kg/m. In this project, through the actual weighing, the quality of diamond saw chain per meter (including diamond cutter head) is calculated \( q = 0.451 \text{ kg/m} \).

\( v \) —— The linear velocity of diamond saw chain, m/s. In this project, the linear speed of diamond saw chain is \( v = 11.5 \text{ m/s} \).

After calculation, \( F_1 = 59.6 \text{ N} \)

(III) Cutting resistance of diamond saw chain \( F_c \)

\[
F_c = 1000\frac{P}{v}
\]  

(3)

Where,

\( P \) —— Chain drive input power, kW. In this project, through the actual measurement, the input power of the chain drive is 2.25 kW.

\( v \) —— Linear velocity of diamond saw chain, m/s. In this project, through the actual measurement, the linear speed of diamond saw chain is \( v = 11.5 \text{ m/s} \).

After calculation, \( F_c = 195.7 \text{ N} \)

(IV) Dynamic load on diamond saw chain \( F_d \)

The dynamic load of diamond saw chain caused by uneven rotation of diamond saw chain is [4-5]:

\[
F_d = 9.8\pi^2(\lambda J/R_2 + mp/2)\psi/90
\]  

(4)

Where,

\( F_d \) —— Dynamic load of diamond saw chain.

\( n \) —— Sprocket speed. In this project, the linear velocity of diamond saw chain is \( v = 11.5 \text{ m/s} \), after calculation, \( n = 6033 \text{ r/min} \).

\( \lambda \) —— Coefficient, which comprehensively considers the influence of the number of teeth of sprocket, speed ratio and tight edge length of diamond saw chain. In this project, the speed ratio \( i = 1 \), so \( \lambda = 0 \).

\( J \) —— Inertia moment of driven sprocket and all rotating masses connected to it.

\( R_2 \) —— Radius of driven sprocket.

\( M \) —— Right edge mass of diamond saw chain, kg. In this project, \( M = 0.451 \text{ kg/m} \times 0.458 \text{ m} = 0.21 \text{ kg} \).

\( P \) —— Diamond saw chain pitch, m. In this project, \( P = 9.53 \text{ mm} = 0.00953 \text{ m} \).

\( \psi \) —— Coefficient taking into account the influence of the elongation and sag of diamond saw chain. In this project, the value of \( \psi \) depends on the wheelbase of diamond saw chain, the larger the wheelbase, the smaller the value of \( \psi \). In this project, \( \psi = 0.6 \).

After calculation, \( F_d = 4759 \text{ N} \)

Based on the above calculation, it can be concluded that
When cutting concrete, the force on the tight edge of diamond saw chain is as follows:
\[ F_1 = F_0 + F_L + F_C + F_D = 6.3 + 59.6 + 195.7 + 4759 = 5020 \text{N} \]

When cutting concrete, the stress on loose edge of diamond saw chain is as follows:
\[ F_2 = F_0 + F_L + F_D = 6.3 + 59.6 + 4759 = 4825 \text{N} \]

The stress of diamond saw chain under no load is as follows:
\[ F_3 = F_0 + F_L = 6.3 + 59.6 = 66 \text{N} \]

Compared with \( F_0, F_L, F_C \) and \( F_D \), it can be seen that the dynamic load of diamond saw chain has the greatest influence on the tension of diamond saw chain. According to the above calculation formula, the dynamic load is directly proportional to the square of sprocket speed, the pitch of diamond saw chain, the mass per meter of diamond chain and the length of tight edge, and the speed of sprocket has the greatest influence on it.

6. Wear experiment of diamond saw chain

The life test of diamond saw chain has nothing to do with the square number of sawing concrete, only related to its running time, which includes sawing time and idling time.

6.1. Experimental methods

After running for 2 hours, the diamond saw chain will pass through the running in period, and then the diamond saw chain will be removed. Several segments of the chain will be tensioned by the universal material testing machine, and the tension force will be kept at 500N. Then the length \( L_1 \) of 13 chains will be measured, and the average value of the total length will be calculated. The diamond saw chain will be re installed on the hydraulic chain saw test bench, and then the diamond chain will run for 5 hours Using the same method, measure the length \( L_2 \) of 13 diamond saw chains and calculate the average value.

When \( t_0= 5h \), the average elongation of single segment of diamond saw chain was obtained
\[ \Delta t_0 = \frac{(L_2 - L_1)}{13} \text{ (mm)}. \]

The life calculation formula of diamond saw chain is as follows:
\[ T = \frac{T_0 (\Delta t_h - \Delta t_t)}{\Delta t_0} \quad (5) \]

Where,
- \( \Delta t_h \) —— Allowable elongation limit of average link, mm.
- \( \Delta t_t \) —— Maximum elastic elongation of diamond saw chain, mm.

6.2. Experimental results and analysis

The experimental results are shown in Table 2.

| number | 1     | 2     | 3     | average value |
|--------|-------|-------|-------|---------------|
|        | 129.1 | 129.4 | 128.7 | 129.07        |
|        | 129.9 | 130.0 | 129.7 | 129.87        |

It can be seen that the average elongation of diamond saw chain after working for 5h is :
\[ \Delta t_0 = \frac{(L_2 - L_1)}{13} = (129.87-129.07)/13 = 0.062 \text{mm}. \]

Referring to the chain drive written by vorobeyev of the former Soviet Union[6], when the number of teeth of the largest sprocket of chain drive device is less than or equal to 50, the allowable elongation limit of diamond saw chain average pitch \( p \) is calculated as follows:
\[ \Delta t_h = \zeta_p \times p \quad (6) \]

Where,
- \( \Delta t_h \) —— Allowable elongation limit, mm.
- \( \zeta \) —— Test coefficient, for ordinary roller and silent chain, \( \zeta=0.03 \sim 0.04 \).
- \( p \) —— Chain pitch of diamond saw, mm.

Taking \( \zeta=0.035 \), therefore, in this project, \( \Delta t_h = \zeta \times p = 0.035 \times 9.53 = 0.33355 \text{mm} \).

From the tensile test of diamond saw chain \( \Delta t_0 = 0.07 \text{mm} \).

The life of diamond saw chain is obtained from equation (5):
\[ T = \frac{T_0 (\Delta t_h - \Delta t_t)}{\Delta t_0} = (0.33355-0.07) / 0.07 = 0.26355 \text{h} \]

The life of diamond saw chain is :
\[ T = 0.26355 \times 5 = 1.3175 \text{h} \]

The life of diamond saw chain is 21h.
When the safety factor is 85%, the working life of diamond saw chain is $21 \times 85\% = 18h$.
The calculation is based on the sawing concrete efficiency of 0.93 m$^2$/h, The cutting area of diamond saw chain is $0.93 \times 18 = 16.7$ m$^2$/m.

7. Conclusion
The hydraulic driven chain saw was designed, the hydraulic adjusting device was designed, the hydraulic chain saw experimental platform was designed. Through the idling experiment and concrete cutting experiment of hydraulic driven chain saw, the following conclusions are obtained:

1) When hydraulic driven chain saw cuts C25 standard reinforced concrete floor slab, diamond saw chain cutting tight side tension is large. The dynamic load of diamond saw chain has the greatest influence on the tension of diamond saw chain. The dynamic load is directly proportional to the speed of sprocket, the pitch of diamond saw chain, the weight per meter of diamond chain and the length of tight edge;

2) The power consumption of hydraulic driven chain saw cutting concrete is 2.85 kw, the sawing efficiency of concrete is 0.93 m$^2$/h, The cutting area of diamond saw chain is $16.7$ m$^2$/m.

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