The finite element analysis of concrete pipe pile vacuum sucker

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Abstract: The adhesion degree between the vacuum sucker and the surface of the adsorbed object seriously affects its adsorption performance. In order to solve the problem that the curved surface of cylindrical concrete pipe pile is not easy to be adsorbed, an elliptical vacuum sucker is designed. In order to study the influence of different unadsorbed areas on the adsorption force, the flow field inside the vacuum sucker is simulated and analysed by using computational fluid dynamics software (fluent). The corresponding curve between the unadsorbed area of the sucker and its adsorption force is obtained. According to the relationship, through the analysis of the size of the unconnected area of the vacuum sucker, it can be known whether the adsorption capacity of vacuum sucker meet the working requirements of the vacuum sucker adsorption cylindrical concrete pipe pile.

1. Introduction
At present, for the hoisting of concrete pipe pile, the hook is used to fix the pipe pile manually with truss crane. This method is not only inefficient, but also has some mechanical damage to the surface of the pipe pile. In the process of fixing, many people are generally required to cooperate, and there are some safety risks in the whole process. In order to realize the automatic and safe storage and transportation of concrete pipe piles, vacuum sucker is used to lift concrete pipe piles[1]. For the adsorption between the vacuum sucker and the pipe pile, it is impossible to have a complete closed fit, and there will always be a certain unfixed area between the vacuum sucker and the end face. In order to make the simulation closer to the real adsorption situation, the unfixed area of the same area is added around the vacuum sucker[3]. Finite element software was used to analyze the fluid in the vacuum sucker, and the influence of different sizes of unadsorbed area on the vacuum sucker adsorption force was observed, so that the vacuum sucker can achieve the best adsorption effect in the lifting process[4].

2. Simulation modeling of flow field in vacuum sucker

2.1 Research objects
In order to produce more efficient and practical vacuum sucker, researchers at home and abroad have done a lot of research on the vacuum sucker. The existing research mainly focuses on the material, structural modeling and inner surface morphology of the vacuum sucker[2]. Because the concrete component is a slender cylindrical component, its surface is relatively rough compared with metal and glass products, but there is no obvious concave convex defect. In order to increase the bonding area between vacuum sucker and pipe pile, elliptical vacuum sucker is used in this paper[9].
2.2 physical model of sucker

In order to increase the adsorption area, oval vacuum sucker (1600mm long, 280mm wide, 50mm high) is needed. As shown in Figure 1.

Because the vacuum sucker is a symmetrical figure, the surface condition of the pipe pile is relatively uniform, and the contact surface between the vacuum sucker and the pipe pile does not have a completely closed fit. Without considering the cracks of the pipe pile, there is always an unadsorbed area around the end mold of the vacuum sucker. In order to simulate the flow field with uncoated surface product, we make a hypothesis: the uncoated situation between the vacuum sucker and the working surface is consistent. In order to reflect that the vacuum sucker does not fit, we add four equal area leakage ports around the vacuum sucker. Considering that the physical quantities of flow, velocity and pressure at the gas inlet are unknown when the vacuum sucker is adsorbed, the expansion zone is added to the vacuum sucker model. As shown in Figure 2. In addition, there is a distance between the expansion zone and the inlet of the vacuum sucker, so it can be assumed that the far end is not affected, and the static pressure on the boundary of the expansion zone is regarded as 0, which is more consistent with the actual flow field of the vacuum sucker. Assuming that the data of the model are 10, 30 and 50 in length and 2, 4, 6, 8 and 10 in width (all in mm), the length and width are combined respectively.

2.3 mathematical model of sucker flow field

Due to the negative pressure generated inside the vacuum sucker during the adsorption process, it is impossible to form a completely closed area between the vacuum sucker and the pipe pile. The external gas is sucked into the vacuum sucker through the gap, which has an impact on the vacuum degree inside the vacuum sucker. In order to maintain the adsorption stability of the vacuum sucker, the gas leaked from the outside will be sucked away by the upper gas pipe of the vacuum sucker. This is a mathematical model of the process the results showed that:

1) Continuity equation:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0
\]  
\[(1)\]

Where: \(\rho\) is the fluid density, kg / m\(^3\); \(V\) is the fluid velocity vector, m/ s.

2) Momentum conservation equation:
\[
\rho \frac{\partial V}{\partial t} + \rho (V \cdot \nabla) V = -\nabla p' + \nabla \cdot (\mu_{ee} \nabla V) + \nabla \cdot (\mu_{ee} (\nabla V)^T)
\]  
\[(2)\]

Here correction pressure: \(p' = p + (\frac{2}{3} \mu - \zeta) \nabla V\)
Where: $P$ is the static pressure, $\text{PA}$; $\zeta$ is the volume viscosity coefficient, $\text{PA} / \text{s}$.

Effective viscosity coefficient $\mu_{\text{eff}}$ is defined as

$$
\mu_{\text{eff}} = \mu + \mu_T
$$

(3)

Where: $\mu$ is the laminar viscosity coefficient; $\mu_T$ is the turbulent viscosity coefficient.

$$
\mu_T = C_k \rho \frac{k^2}{\varepsilon}
$$

(4)

Where $k$ is turbulent kinetic energy and $\varepsilon$ is kinetic energy dissipation coefficient. They satisfy the K - $\varepsilon$ double equation.

The K - $\varepsilon$ double equation of equation (2) is as follows:

$$
\frac{\partial p}{\partial t} = \nabla \cdot (\rho V k) - \nabla \cdot \left( \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla \kappa \right) = p - \rho \varepsilon
$$

(5)

$$
\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho V \varepsilon) - \nabla \cdot \left( \left( \mu + \frac{\mu_T}{\sigma_k} \right) \nabla \varepsilon \right) = C_k \frac{\varepsilon}{k} p - C_2 \rho \frac{\varepsilon^2}{k}
$$

(6)

among $P = \mu_{\text{eff}} \nabla \cdot \left( \nabla V + (\nabla V)^T \right) - \frac{2}{3} \nabla \cdot \left( \mu_{\text{eff}} \nabla V + pk \right)$

2.4. CFD preprocessing and boundary strip settings

After modeling the vacuum sucker according to the size of the target adsorbed object, in order to shorten the calculation time, the structure of the vacuum sucker was simplified [8]. The sealing strip and the vacuum sucker body were simplified into one part and imported into ICEM CFD, in order to reduce the amount of calculation, the hexahedral mesh is used to divide it. Initially, an automatic mesh generation is carried out for the whole, and then some parameters of the mesh are adjusted. In order to improve the calculation accuracy, the local mesh needs to be encrypted.

The meshed model is imported into fluent for calculation, and the boundary condition at the entrance of expansion zone is set as a standard atmospheric pressure. According to the commonly used vacuum generator, the pressure at the exhaust port is set at $-60$ kPa. The simple algorithm is used to solve the problem. The results show that the convergence of each parameter is good.

3. Analysis of vacuum sucker flow field

Among these parameters, there are three identical combinations: $2 \times 30$ and $6 \times 10$, $2 \times 50$ and $10 \times 10$, $6 \times 50$ and $10 \times 30$. According to the calculation of FLUENT software, the average adsorption force of $2 \times 30$ unadsorbed area is about $-3421.75$ Pa, and the average adsorption force of $6 \times 10$ unadsorbed area is about $-3226.52$ Pa. The average value of adsorption force is $-3226.52$ Pa when the unabsorbed area is $2 \times 50$, and $-2017.44$ Pa when the unabsorbed area is $10 \times 10$. When the unabsorbed area is $6 \times 50$, the average adsorption force is about $-1159.99$ Pa, and when the unadsorbed area is $10 \times 30$, the average adsorption force is about $-1094.54$ Pa.

Through the analysis of the above data, it can be seen that the adsorption force of the sucker is only related to the bonding area, and has nothing to do with the length and width of the gap of the sucker. Therefore, we obtained the corresponding adsorption forces (taking the average value) according to the above unadsorbed areas through fluent simulation, as shown in Table 1.

| Unabsorbed area/(mm$^2$) | Cohesive force/(Pa) |
|------------------------|---------------------|
| 20                     | 10174.58            |
| 40                     | 3356.63             |
| 60                     | 3324.14             |
| 80                     | 2352.26             |
| 100                    | 2356.49             |
| 120                    | 2201.63             |
| 180                    | 1523.95             |
| 240                    | 1273.30             |
According to the data in Table 1, the two-dimensional relationship between the unadsorbed area and the vacuum sucker adsorption force is established, as shown in Figure 3. It can be seen from the reaction relationship in Fig.3 that the adsorption capacity of the sucker decreases with the increase of the unadsorbed area. In the range of 0-170 mm², the leakage area and the adsorption capacity are basically linear, and the decline rate is the fastest. After the unadsorbed area reaches 170 mm², with the increase of unadsorbed area, although the unadsorbed area is still declining, the decline rate gradually decreases, and finally tends to a stable value.

| Unadsorbed area/mm² | Adsorption capacity/Pa |
|---------------------|------------------------|
| 300                 | 1127.27                |
| 400                 | 1026.10                |
| 500                 | 1024.35                |

Figure 3 Relationship between vacuum sucker adsorption force and unadsorbed area

4. Conclusion
In this paper, through the hydrodynamics simulation, the relationship between the unadsorbed area and the adsorption force of the vacuum sucker of the adsorption concrete pipe pile is obtained. By giving the unadsorbed area, the adsorption force can be obtained, so as to judge whether the vacuum sucker can work safely. The analysis directly links the unadsorbed area of the vacuum sucker with the adsorption force, simplifies the process of judging whether the vacuum sucker can be reliably adsorbed, and provides a theoretical basis for the design of vacuum sucker of concrete pipe pile.

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