

Optimization Design of Oil Film Thickness of Hydrostatic Pressure Table

Cheng-Han AI, Han-Bing TANG, Guo-Dong SUN*, and Ma-Chao JING

School of Mechanical Engineering, Hubei University of Technology, Wuhan, Hubei, China

*E-mail: sgdeagle@163.com

www.hbut.edu.cn

Keywords: Carrying capacity, Stiffness, Loss, Oil film thickness.

Abstract. Taking the static pressure of the oil film, carrying capacity and stiffness of the table as the main study subjects, in order to achieve the optimum design of oil film thickness, optimization method of the objective function with the linear weighting has been proposed, and the optimum oil film thickness is calculated by using the tool box of MATLAB to program GUI and internal code. The result provides theoretical support for the design of oil film thickness in engineering practice.

Introduction

Thickness of the hydrostatic oil film has great effects on the performance of hydrostatic guideway. Choosing the appropriate oil film thickness can ensure optimal oil film carrying capacity, stiffness, improve machining precision and reduce machining error. Thicker oil film is bound to have less stiffness, and vibration and partial load are more likely to happen in the process of machining, oil film with small thickness is bound to have weak carrying capacity, which can't meet the needs of heavy carrying in actual production. Only in the best range of thickness, can it ensure high oil film stiffness, and high load, low loss, thus ensuring the high precision and qualification of workpieces.

In this research direction, Wen[1] optimized the oil cavity structure size parameters, with the goal of maximizing the comprehensive carrying capacity and stiffness of oil film, but the method is tedious and the calculation is complex. Xie[2] studied the influence of axial force and workpiece quality on the oil film stiffness. Qiao[3] studied the influence of pressure ratio, injection pressure, guide clearance and choke on oil film stiffness, and worked out the maximum oil film stiffness based on the analysis and calculation; Sun[4] carried out the qualitative and quantitative calculation and analysis on the carrying capacity and stiffness of hydrostatic guideway. But these studies about oil film thickness parameters optimization of static workbench haven't been carried out yet.

Summing up the previous studies, combining the characteristics of large and heavy load rotary table, and taking oil cavity size, number of oil cavities, oil cavity pressure, oil film thickness, rotation speed and other process parameters and the main constraint conditions into consideration, a multi-objective optimization system for large platform is designed in this paper. The GUI parameters are used to maximize the carrying capacity and the oil film stiffness as well as to minimize the power consumption and obtain the optimum process parameters[5].

Establish Optimization Model

Design of Evaluation Function

The best oil film thickness not only guarantee to have a better stiffness and bearing capacity, but also be able to reduce costs to improve economic efficiency under the condition of low power consumption. The oil film thickness h_0 was taken as the variable, with high stiffness, high load, low power consumption to be the design purpose, an evaluation function was established, including the targets of stiffness, carrying capacity and power loss.

Static Pressure Stiffness and Carrying Capacity of Oil Film

Under the action of external load W , the displacement of the working table is changed by x . The oil film thickness of the main and the auxiliary oil cushion are respectively $h_0 - x$ and $h_0 + x$. Stress analysis of hydrostatic guideway is shown in Eq. (1).

$$W + mg = P_1 \cdot A_1 - P_2 \cdot A_2 \quad (1)$$

P_1 and P_2 are the pressure of the main and auxiliary oil cushion of the static pressure working table, respectively. A_1 and A_2 are the effective carrying area of main and auxiliary oil cushion.

According to the flow formula of the static pressure guideway[6-7]:

$$Q = \frac{P \cdot h^3 \cdot c}{\mu} \quad (2)$$

c relates to supporting coefficient and μ is kinetic viscosity.

Because this working table supply oil in constant current mode, the oil flow rate of the main and auxiliary static pressure oil cushion is constant. Then

$$h_0^3 \cdot P_{01} = h_1^3 \cdot P_1 \quad (3)$$

Where P_{01} is the initial pressure of the main oil cavity.

If the change of oil film thickness was x , then

$$P_1 = \frac{h_0^3 \cdot P_{01}}{(h_0 - x)^3} \quad (4)$$

Similarly

$$P_2 = \frac{h_0^3 \cdot P_{02}}{(h_0 + x)^3} \quad (5)$$

Combine (1), (4) and (5), then

$$W = \frac{\mu \cdot Q_1}{(h_0 - x)^3 \cdot c} \cdot A_1 - \frac{\mu \cdot Q_2}{(h_0 + x)^3 \cdot c} \cdot A_2 - mg \quad (6)$$

When $x \rightarrow h_0$, oil film thickness is close to 0. At that time, the main rail pressure is the output pressure of the oil pump P_s , and load W achieves maximum value W_{\max} . Record W_{\max} as the oil film bearing capacity F . Then

$$F = P_s \cdot A_1 - \frac{\mu \cdot Q_2}{8 \cdot c \cdot h_0^3} - mg = P_s \cdot A_1 - \frac{P_{02}}{8} \cdot A_2 - mg \quad (7)$$

The oil film stiffness refers to the ability of the oil film to resist load changes. When the load changes, if thickness of oil film changes slightly, the stiffness must be high. So the stiffness of the oil film can be expressed as the partial derivative of x when $x \rightarrow 0$. It can be learned from Eq. (6).

$$J = \frac{\partial W}{\partial x} \Big|_{x \rightarrow 0} = \frac{3}{h_0} \cdot (mg + 2 \cdot p_{02} \cdot A_2) \quad (8)$$

Power Loss

Under certain working conditions, the power consumed by the hydrostatic bearing parts consists of two parts. One part is the friction power consumed by the motion of shearing oil film when there is

relative motion between the supports. Another part is the power consumed by driving the oil through the valve in a certain pressure, that is, the output power of the pump.

The viscous resistance of a oil pad film must be overcome when the support is moving. It can be learned from Newton liquid friction theorem[9].

$$I\left((P-k_i)^2, m_i^2, M\right) = \frac{1}{(2\pi)^5} \int \frac{d^3 k_i}{2\omega_i} \delta^4(P-k_i). \quad (9)$$

At a certain rotating speed, the friction power is the power consumed by the viscous resistance of each oil pad. Using initial oil film thickness to calculate, then

$$f_s = \sum F_t \cdot \omega \cdot R = \sum \mu \cdot A_t \cdot \frac{(\omega \cdot R)^2}{h_0} = N \cdot \mu \cdot A_t \cdot \frac{(\omega \cdot R)^2}{h_0} \quad (10)$$

It can be learned from Eq. (2), when oil supply pressure is p_s and total flow rate is Q , output power of the oil pump is shown in Eq. (11).

$$N_p = P_s \cdot Q = P_s \cdot \left[\frac{(mg + P_{02} \cdot A_2) \cdot \beta}{\mu \cdot A_1} \cdot h_0^3 + \frac{P_{02} \cdot \beta}{\mu} \cdot h_0^3 \right] \quad (11)$$

Multi-objective model

When designing oil film thickness, not only the film should have the maximum load capacity and stiffness, but also the quality of lowest power loss, cost savings or other economic and technical indicators should be taken into consideration. Ignoring some factors with small influence, the multi-objective optimization model is established, which is based on the actual parameters and working conditions, the oil film bearing capacity, the oil film stiffness and power loss, in order to achieve the technical objectives of heavy load carrying, high stiffness, low loss and so on. In this paper, By using MATLAB, a '.m' file is established to build a multi-objective optimization function. And by using the linear weighted sum method, the multi-objective is transformed into a single objective, which is convenient to solve. As Eq. (12)

$$MaxF(x) = Max[a \cdot F_1(x) + b \cdot F_2(x) + c \cdot F_3(x) \cdot (-1)] \quad (12)$$

$F_1(x)$ relates to the maximum load, reflecting the value of the oil film carrying capacity. $F_2(x)$ relates to the stiffness of the oil film, reflecting the value of the stiffness. $F_3(x)$ is the friction power and the output power of the oil pump, reflecting the total power loss. 'a', 'b', 'c' are the weight coefficients, and meet the equation of $a+b+c=1$. 'a' is the weight factor of carrying capacity. If only to consider the best carrying capacity, it can make as $a=1$, $b=c=0$. 'b' relates to the weight factor of oil film stiffness, if only to consider the optimum oil film stiffness, it can be make as $b=1$, $a=c=0$. 'c' represents the factor of weight power, if only to consider the minimum power consumption, it can be made as $c=1$, $a=b=0$.

Constraints

After the evaluate function has been established, it is necessary that constraints be added to the evaluation function, so that to get the optimal variable^[5]. When talk to the normal operation of the working platform, the constraints are generally related to the initial output pressure of the pump, the speed of the working table and the initial pressure of the oil chamber, etc. In order to be more realistic and accurate to the normal working conditions of the working table, the establishment of a constraint model is as follows:

(1) A too thin oil film will lead to the contacting of upper and lower working table, greatly damage the performance of the work table or even injures it, greatly impaired the performance of the table. And a too thick oil film will reduce the accuracy and precision of the working table. So the thickness of oil film should be constrained. Boundary is set as:

$$0 < h_0 \quad (13)$$

(2)The output pressure of the oil pump has a great influence on the output power of the pump. High output pressure will lead to the consumption of the power and the oil leakage. Low output pressure will fail to form stable oil film. Set boundary conditions for the output pressure of the oil pump as:

$$p_{\min} \leq p_s \leq p_{\max} \quad (14)$$

(3)Too fast rotating speed of the working table will not only affect the thickness of oil film, but affect the friction loss as well. Too slow speed will reduce production efficiency. Rotating speed of the working table is constrained as:

$$0 \leq \omega \leq \omega_{\max} \quad (15)$$

(4)In order to keep the balance of no-load working condition, the initial oil pressure of the oil cavity must be satisfied with:

$$p_{01} \cdot A_1 - p_{02} \cdot A_2 = mg \quad (16)$$

Among them:

$$p_{02} < p_{01} < p_s \quad (17)$$

Optimum Calculation of Optimum Oil Film Thickness

Design of The Optimum interface

This design is based on MATLAB GUI (graphical user interface) to achieve multi-objective optimization of oil film thickness. The software interface is concise and convenient, users only need to input corresponding parameters and constraints, and select the objective to be optimized. Then, the software will perform the optimum calculation and solve the optimum problems. The interface delivers the corresponding parameters to the objective function. If a single-objective optimization is needed, the user only needs to select the target to be optimized in the optimization target selection module. If the multi-objective optimization is needed, the user only needs to fill in the weight factor column with the specific value. No-need for multiple input parameters, re-write code, determine the constraints and other links in different types of target optimization. The system interface we designed is shown in Figure 1.

Figure 1. Interface of the optimum oil film thickness calculation system

Optimization of Objective Function

This optimization is based on the genetic algorithm optimization toolbox of MATLAB and its calculation and processing function of data to optimize the calculation. After the interface design is completed, the internal code of the system interface is written, and the objective function and constraint function are added so that the user can deliver the parameters to the objective function and the constraint function by inputting the parameters in the system interface. By setting the algorithm parameters of the genetic algorithm toolbox, if it is a single-objective optimization, it is directly calculated through the optimization of each objective function. If it is multi-objective optimization, users can also use linear weighting method to set the weight factor and transform multi-objective calculation into a single target calculation, and then optimize the solution. Specific optimization process of the calculation is shown in Figure 2.

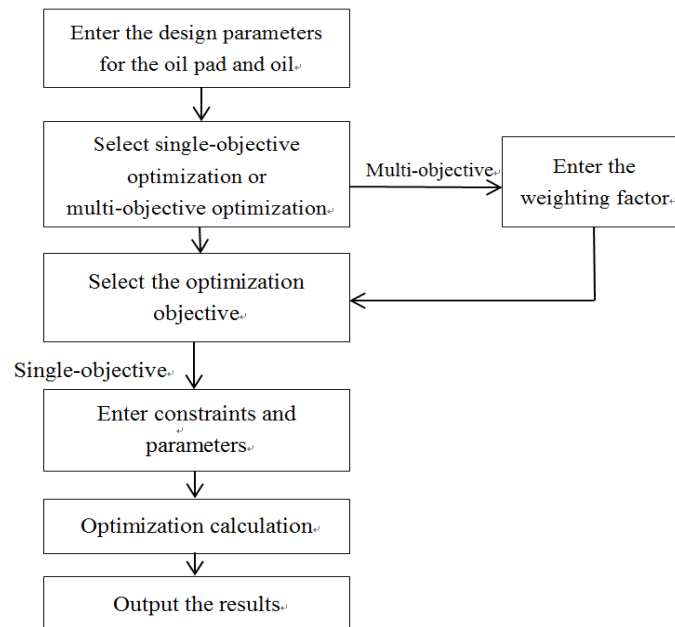


Figure 2 Flow diagram of optimization process of the calculation

Instance Optimization Calculation and Analysis

The system takes a hobbing machine table with a diameter of 2500mm as an example, the relevant data parameters is shown in Table 1.

Table 1. Relevant parameters of hobbing machine table

Parameter name	Symbo	Value	Unit
Table weight	G	98000	N
Number of pads	N	12	-
Diameter of table	D	2500	mm
The maximum load of the table	W_{\max}	50000	Kg
Maximum output pressure of oil pump	P	25	MPa
Pressure range of the oil pump	P	5-20	MPa
Dynamic viscosity of oil	μ	0.04	Kg/m2
Support flow coefficient	c	1.17	
Speed of the table	w	0-4	r/min
Effective bearing area of main guide rail	A_1	0.424	m ²
Effective bearing area of auxiliary guide rail	A_2	0.393	m ²

In the case of single-objective optimization, the carrying capacity of the oil film, the stiffness of the oil film, and the power consumption are selected as the optimization targets. In the case of multi-objective optimization, to ensure the large load carrying capacity, weight factors are set as $a = 0.4$, $b = 0.3$, $c = 0.3$. After several experiments and attempts, enter the parameters, click the button of calculate, the results are shown in Table 2.

Table 2. Contrast optimization results

Calculation results Optimization objective	Initial pressure of primary rail(Mpa)	Initial pressure of auxiliary rail (Mpa)	Initial flow of hydrostatic guideway(L/min)	Multi- head pump output pressure(Mpa)	thickness of oil film (mm)
carrying capacity of oil film	4.1692	3.8782	1.6032	12.1320	0.0612
Stiffness of oil film	3.2975	2.7885	0.8894	9.2052	0.0289
Power consumption	2.7738	2.1340	0.7320	6.3253	0.0265
Multi-objective optimization	3.4779	3.0141	1.0041	10.0120	0.0348

Acknowledgement

This work is partially supported by grant 2014AAA013 of the Major Scientific and Technological Innovation Project in Hubei Province.

Conclusion

From the optimization results, it can be seen that when the oil film carrying capacity is the optimization objective, the power consumption is the largest and the oil film is also thick. When the power consumption is taken as the optimization objective, the load and stiffness are smaller and the oil film thickness is the smallest. By using multi-objective optimization, the oil film thickness is approximately 0.35 millimeter, it is between the maximum and minimum oil film thicknesses. Taking other factors into account, such as temperature and working conditions, it can be determined that when the oil film thickness is between 0.3 to 0.4 mm, the machine can achieve the maximum load, the maximum film stiffness and minimal power consumption. Further, the feasibility of optimizing the oil film thickness through the toolbox of GUI and genetic algorithm is proved, and it also provides some theoretical support and reference for choosing the optimal oil film thickness in engineering practice.

Reference

- 1.W. Chen, Y. HongLing, et al. AMBSTAM (2013)
- 2.X. LiMing, C. Qin, J. Luan, Z. Bin, et al. MD&M **3**,130-133 (2014)
- 3.Q. Ming. TTTM **3**,11-13 (1994)
- 4.S. XueZan, L. SongBao. APMT **1**,14-16 (2005)
- 5.Z. DaXing, Z. Song, D GguoLong, Z. DongXiong, et al. MMT & AMT **2**, 117-120 (2014)
- 6.J. Zhao, Y. Liang, D. Gao, CJME **5**,1008-1017 (2014)
- 7.W. H C, C.L Y. J N & N,**5**:5218-5221 (2016)
- 8.Z. JanHua, G. DianRong, et al. China Mechanical Engineering **11**,1421-1430 (2013)