Dynamic reliability analysis of a heat-roller based on finite element method

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Abstract. Taking a heat-roller of a laser printer as the research object, the dynamic characteristics and reliability were analyzed by using the finite element software ANSYS. Through modal analysis, it can be concluded that the first eighth natural frequencies of the heat-roller are 1343, 1365, 3612, 3677, 6885, 7001, 7168, 10634 Hz. The corresponding modal modes are as follows: except that the fifth mode is the torsional mode of the structure, the other modes are the bend mode. Through the harmonic response analysis, it can be concluded that the first mode has the greatest influence on the dynamic characteristics of the structure. The sensitivity analysis results show that the material characteristics and size parameters which have great influence on the dynamic characteristics of the structure are $l_2$, $den$, $ex$, $d_1$, $d_3$ and $x$.

1. Introduction

Laser printer is a commonly used office supply. As one of the key parts of fuser mechanism, the heat-roller is mainly used to press and heat the ink image adsorbed on paper, melt the ink and immerse it in the printing paper to form a fixed image. When the printer works, the heat-roller will rotate periodically at a certain speed, and at the same time, it will always contact with the pressure roller and paper. From the point of view of structure and function, the heat-roller belongs to the spindle parts. In the work, it mainly bears the periodic bending moment load from the pressure roller and paper contacted with it. Due to the inevitable errors in manufacturing and installation process, random vibration along all directions often occurs in the actual working process of the heat-roller. These random vibration will affect its working accuracy on the one hand, on the other hand, it will aggravate its fatigue damage and affect its working life. Structural random vibration response under external excitation is closely related to its dynamic characteristics. When designing mechanical devices or components, including large construction machinery, automobiles, manufacturing equipment, etc., designers usually consider the dynamic characteristics. In the field of crane design, Wei Xiaoling et al. [1] took bridge crane as the research object, carried out modal analysis and harmonic response analysis of the structure, and obtained the natural frequency, mode shape and displacement-frequency response curve of the structure. Wang Lingjuan et al. [2] carried out modal analysis and harmonic response analysis of a tower crane boom, investigated the influence of different constraints on the natural frequencies of structural modes, and studied the structural displacement response characteristics under different excitation frequencies. Ma Shihui et al. [3] also carried out modal analysis for a truss gantry crane, and obtained the natural frequencies and vibration modes of the structure. In the field of automobile design, Wang Ke [4] took the front axle of a light truck as the research object, and used modal analysis method to extract the natural frequencies and modes of the structure. Duan Nengquan
et al. [5] carried out the finite element analysis by extracting the peak force of an explosion-proof rubber-tyred vehicle when walking on the road, and the stress of the frame under dynamic conditions was obtained. Zhou Chi et al. [6] took a heavy dump truck frame as the research object, and modal analysis of its structure before and after optimization was carried out. In the field of large-scale processing equipment design, Ding Tengfei et al. [7] and Liu Panzhong [8] carried out structural modal analysis in the design of vertical processing center and powder finishing equipment machine respectively. Therefore, it is necessary to study its dynamic characteristics when designing the heat-roller. However, up to now, there are few reports on the dynamic characteristics of the heat-roller of laser printers. In addition, when carrying out structural design, the design parameters are often complex. If sensitivity analysis [9-10] can be carried out before the design, and the parameters that have great influence on the structural natural vibration characteristics can be selected as the design variables, the design efficiency can be further improved. Therefore, the dynamic sensitivity analysis of heat-roller is also of certain research significance. In this paper, modal analysis and harmonic response analysis were carried out for the heat-roller of a laser printer by using finite element software. The natural frequencies and vibration modes of the structure were obtained, and then the dynamic sensitivity analysis was carried out. The analysis results provide a basis for the dynamic optimization of the heat-roller of the printer, and also provide a reference for the design of other similar structures.

2. Finite element model of laser printer heat-roller

As shown in Figure 1, the whole structure of the heat-roller is hollow shaft, which is made of seamless aluminium alloy tube. The thickness of the tube wall is between 1mm and 3mm. The surface of the heat-roller is coated with PTFE to prevent the melting toner from sticking to the roller during fixing. In Fig. 1, the shaft section 1 is the spring support part, the bus of the rotary body is a straight line, the shaft section 2 is the paper contact part, and the bus of the rotary body is a spline curve. The material used for manufacturing is aluminium alloy. The material properties are as follows: density is 2700 kg/m³, Poisson's ratio is 0.3, modulus of elasticity is $0.7e^5$ MPa and yield limit is 70 MPa.

![Fig. 1 Sketch of heat-roller](image)

Before the natural vibration characteristics analysis, the finite element model was established in the finite element software ANSYS. In order to improve the calculation efficiency, the structure of the heat-roller was simplified to a certain extent on the premise of ensuring the calculation accuracy. The specific simplification principles were as follows: the chamfer structure in the actual structure was not considered. In the process of modeling, firstly, the axial section was established in ANSYS, and then the solid structure of the heat-roller was established by rotation. The whole axis was simulated by solid element solid187. After the solid model was established, the mesh was divided. Because the structure is irregular, the free mesh method was adopted. The finite element mode of the heat-roller is shown in Fig. 2. The whole model was discretized into 4071 elements and 7937 nodes.
3. Self-vibration characteristics analysis of the heat-roller of laser printer

The finite element software can be used to carry out various structural dynamics research, such as modal analysis, harmonic response analysis, transient dynamic analysis and so on. In this paper, the heat-roller of laser printer was taken as the research object, and the modal and harmonic response analysis were mainly carried out. The modal analysis was mainly used to investigate the self-vibration characteristics of the roller, obtain its natural frequency and vibration mode. It is the basis for the follow-up dynamic analysis [11]. Harmonic response analysis was mainly used to analyze the steady-state response of the roller under periodic simple harmonic loads, and to determine the modal which has the greatest impact on the natural vibration characteristics of the structure.

According to the relevant theory, the dynamic equation of the heat-roller can be described by the following formula [12]:

\[ [M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[F(t)] \]

(1)

Without considering the load on the roller, i.e. neglecting the contact pressure between the heat-roller and the paper or pressure roller, the dynamic equation of the roller can be transformed into the following equation:

\[ [M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=[0] \]

(2)

After neglecting the structural damping of the heat-roller, the undamped free vibration differential equation of the roller can be obtained by formula (2):

\[ [M]\{\ddot{u}\}+[K]\{u\}=[0] \]

(3)

In the above formula: \([M]\) - mass matrix; \([C]\) - damping matrix; \([K]\) - stiffness matrix; \([u]\) - node displacement vector; \([\ddot{u}]\) - node acceleration vector; \([\dot{u}]\) - node velocity vector; \([F(t)]\) - node load vector.

In this paper, assuming that the heat-roller is an elastic body with free vibration, the vibration of the roller can be decomposed into the superposition of a series of simple harmonic oscillations, and the solution of equation (3) can be set as follows:

\[ \{u\}=[A]\sin(\omega t + \varphi) \]

(4)

In the above formula: \(\omega\) - angular frequency; \(\varphi\) - initial phase angle; \([A]\) - nonzero amplitude array. Formula (4) is substituted for Formula (3) and the following equation can be obtained.
The natural frequencies and vibration modes of the heat-roller can be obtained by solving formula (5).

3.1 Modal Analysis

In this paper, the self-vibration characteristics of heat-roller under non-working conditions were mainly analyzed. The natural frequencies and mode shapes were extracted by modal analysis. Landssos method [13] was used in the analysis. According to the modal analysis theory, the low-order modes of the heat-roller have a greater contribution to its dynamic response, while the high-order modes have less influence. Therefore, this paper mainly analyzed the first eight modes. The natural frequencies and modes extracted after analysis are shown in Table 1, and the first eight modes of the structure are shown in Figure 3.

| Order | Frequencies /Hz | Vibration mode                                      |
|-------|-----------------|-----------------------------------------------------|
| 1     | 2023.6          | First-order bending of the central part of the heat-roller in the vertical plane (xoy plane) |
| 2     | 2152.9          | First-order bending of the middle part of the heat-roller in the horizontal plane (xoz plane)  |
| 3     | 5162.5          | Second-order bending of the central part of the heat-roller in the vertical plane (xoy plane)  |
| 4     | 5418.9          | Second-order bending of the central part of the heat-roller in the horizontal plane (xoz plane) |
| 5     | 7133.0          | Torsion around the x-axis of the central part of the heat-roller                             |
| 6     | 9404.2          | Third-order bending of the central part of the heat-roller in the vertical plane (xoy plane)  |
| 7     | 9639.9          | Third-order bending of the middle part of the heat-roller in the horizontal plane (xoz plane) |
| 8     | 11096           | Fourth-order bending of the central part of the heat-roller in the vertical plane (xoy plane) |

(a) the first order  
(b) the second order
From Table 1 and Figure 3, it can be seen that the first eight modes of the heat-roller are all bending modes except that the fifth one is torsional mode. Among them, the first and second modes are the first bending mode of the roller, the third and fourth modes are the second bending mode of the roller, the sixth and seventh modes are the third bending mode of the roller, the eighth mode is the fourth bending mode of the roller.

### 3.2 Harmonic Analysis

In order to analyze the mode which has the greatest influence on the dynamic characteristics of the heat-roller, the harmonic response of the roller was analyzed. Since the first eighth natural frequencies of the structure are all within 12,000 Hz, the frequency range of external excitation load was set to 0-12,000 Hz, which was divided into 600 equal parts. The load is 142.288 N in the middle of the roller, and the load is step uniformly distributed, and the direction is vertical downward. The constraints at
both ends of the heat-roller are consistent with the modal analysis. The gravity of the structure itself was simulated by applying gravity acceleration. The full method was used to analyze and extract the displacement response of the middle node of the roll-er in the vertical direction (as shown in Figure 4).

![Displacement response in vertical direction-excitation frequency curve of middle node of heat-roller](image)

As can be seen from Fig. 4, when the excitation frequency is 2020 Hz, the displacement response of the node in the vertical direction is the largest, and the excitation frequency is close to the first natural frequency of the roller. Therefore, it can be considered that the first mode has the greatest influence on the dynamic characteristics of the roller. In the subsequent optimization design, the influence of the first mode should be taken into account.

4. Dynamic Sensitivity Analysis of the Heat-roller of Laser Printer

Taking the first modal natural frequency as the objective parameter, which has the greatest influence on the dynamic characteristics of the heat-roller, as a random variable, assuming that the size of the roller and the material characteristic parameters obey the Gauss or truncated Gauss distribution, the probabilistic reliability analysis of the roller was carried out. The parameters of the roller are as follows: length $l_1$, diameter $d_1$, length $l_2$ of the middle part, slope $1/x$ at both ends of the spline curve, inner diameter $d_3$, material density $den$, Poisson’s ratio $prxy$, elastic modulus $ex$, and contact load $F$. Assuming the mean value of the variable $X_i$ is $X_i$, its variance is $0.1X_i$. In the above variables, considering the relative relationship between the diameter $d_1$ at both ends of the roller, the minimum diameter $d_2$ in the middle and the inner diameter $d_3$, the constraints were defined: $d_1$ is greater than or equal to $d_2+0.1$, and $d_3$ is less than or equal to $d_2-3$. The analysis process was carried out in the PDS module of the finite element ANSYS software. The superlatin sampling method in Monte Carlo method was used to simulate the sampling. The target parameter obtained after 1000 sampling times has converged. From the analysis results, it can be concluded that the influence of various sizes and material characteristics parameters on the dynamic characteristics of the roller, that is, the dynamic sensitivity of the roller (shown in Fig. 5).
From Fig. 5, it can be seen that the design parameters which have great influence on the dynamic characteristics of the heat-roller are $l_2$, $den$, $ex$, $d_1$, $d_3$ and $x$. Among them, the parameters $ex$, $d_1$ and $d_3$ are positively correlated with the target parameters, i.e. the first natural frequency of the roller, while $l_2$, $den$ and $x$ are negatively correlated with it.

5. Conclusion
In this paper, modal analysis, harmonic response analysis and probability analysis were used to study the self-vibration characteristics and dynamic sensitivity of a laser printer's heat-roller by using finite element software ANSYS. The main conclusions are as follows:

1. The first eighth natural frequencies of the heat-roller under the restrained state are 2023.6, 2152.9, 5162.5, 5418.9, 7133.0, 9404.2, 9639.9 and 11096 Hz respectively. Except the fifth mode is the torsional mode of the roller, the other mode is the bending mode of the roller.

2. The first mode has the greatest influence on the dynamic characteristics of the heat-roller.

3. Among all the design parameters, the dimension parameters $l_2$, $d_1$, $d_3$, material density $den$, material elastic modulus $ex$ and slope parameter $x$ at both ends of the spline curve have great influence on its dynamic characteristics.

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