The research of hourglass worm dynamic balancing simulation based on SolidWorks motion

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Abstract. Hourglass worm is extensively used in industry due to its characteristic of heavy-load and a large reduction ratio. Varying sizes of unbalanced mass distribution appeared in the design of a single head worm. With machines developing towards higher speed and precision, the vibration and shock caused by the unbalanced mass distribution of rotating parts must be considered. Therefore, the balance grade of these parts must meet higher requirements. A method based on theoretical analysis and SolidWorks motion software simulation is presented in this paper; the virtual dynamic balance simulation test of the hourglass worm was carried out during the design of the product, so as to ensure that the hourglass worm meet the requirements of dynamic balance in the design process. This can effectively support the structural design of the hourglass worm and provide a way of thinking and designing the same type of products.

1. Introduction
There are two main methods for correcting the dynamic unbalances of rotate parts: One way is to measure the dynamic force of the support to correct the amount of unbalances. Another way is to measure the vibration of the support to correct the amount of unbalance [1]. The above two methods, both using a certain test system to detect the existence dynamic unbalance of rotate parts after the completion of manufacture, are unable to provide guidance for the design of the dynamic balance of the parts during the design phase. In addition, for single-headed worms, single-headed screws, single-head conveyor screws and other non-axisymmetric complex surface rotary parts, the size and phase of the unbalanced mass calculation is extremely complex. What has been the focus of designers’ attention is how to effectively solve the dynamic unbalance of such parts.
Therefore, in order to effectively solve the problem of dynamic unbalance of non-axisymmetric complex surface rotating parts in the design stage, a virtual dynamic balance test platform is designed and a dynamic balance design method based on SolidWorks motion is proposed in this paper. A single-head hourglass worm is used as the experimental object as one of the non-axisymmetric complex surface rotating parts, and a simulation experiment is carried out to verify and analyze the method.

2. Design and test method of virtual test platform

2.1. Composition and structure of virtual test platform
In three-dimensional software, the frame, spring, swing-rod, column and the motor are constructed, as shown in Figure 1.
Figure 1. The structure of the test platform [2]
1—frame  2—spring  3—swing-rod  4—column  
5—motor  6—rotary parts

The midpoint of the swing-rod is fixedly connected to the middle of the column. The lower end of the column is connected to the frame and the column axis is perpendicular to the horizontal plane of the frame. The upper end of the column is set with a revolute joint and the axis of revolute joint is perpendicular to the swing-rod. Two identical sets of springs are both fixed to the frame on the one end and the other end is mounted vertically at both ends of the swing-rod. The length of the swing-rod is $s$ and the stiffness of the spring is $k$. The two springs are parallel and the distance is $s$. The motor is located on the revolute joint of the column. The motor drives the unbalance of hourglass worm to rotate around the axis of revolute joint and the speed is $\omega$. Establish a fixed coordinate system $\sigma(C; X, Y, Z)$ on the frame, with column axis being the Z-axis and intersect to the horizontal plane of the frame at point C. The XCY plane is on the horizontal plane of the frame. The Y-axis is collinear with the initial installation of the axis of revolute joint; the X-axis direction is the vertical direction of the C-point and Y-axis on the horizontal plane of the frame [2].

2.2. Experiment method

Figure 2. The model of hourglass worm

The three-dimensional model of the hourglass worm is established in the SolidWorks as the test part, as shown in Figure 2. Two planes are selected in the axial direction of the rotating parts suitable for increasing and reducing the weights. The left balance plane P is on the left side of middle of the throat and the distance is $L_1$, and the right balance plane Q is on the right side of middle of the throat and the distance is $L_2$. Plane P and plane Q are perpendicular to the axis of the rotating part and intersects the axis at point A and B respectively. Optionally select a shoulder and set a mark line along its radial direction as I.

The first step in the hourglass worm simulation test is to balance the right balance plane Q. The following three conditions are required to ensure the hourglass worm to be balanced during the simulation test. First of all, the axis of the unbalanced hourglass worm is aligned with the axis of revolute joint. Secondly, the left balance plane P is overlap with the axis of column. Finally, line I has to be made parallel to the plane of the frame at the beginning of installation.

The motor drives the hourglass worm with a rotation speed of $\omega$, $X_1$ is the maximum amplitude of the point B in the X-axis direction, $\phi_1$ is the phase angle corresponding to the maximum amplitude. The mass-radius product $G_1$ can be calculated by equation (1).

$$G_1 = \frac{ks^2X_1}{2(L_1 + L_2)^2\omega^2}$$ (1)
According to the calculation results, there are two ways to balance the right balance plane Q. The first way is to add a counterweight to the phase angle of $\phi_1 + 180^\circ$ on the right balance plane Q and the mass-radius product is $G_1$. Another way is to reduce a counterweight to the phase angle of $\phi_1$ on the right balance plane Q and the mass-radius product is -$G_1$ [2].

The next step after balancing the right balance plane P is to balance the left balance plane Q. Just like balancing the right balance plane Q, the three conditions are also required to install the hourglass worm to be balanced during the simulation test. First of all, the axis of the unbalanced hourglass worm is aligned with the axis of revolute joint. Secondly, the right balance plane Q is overlap with the axis of column. Finally, line I has to be make parallel to the plane of the frame at the beginning of installation.

The motor drives the hourglass worm with a rotation speed of $\omega$; $X_2$ is the maximum amplitude of the point A in the X-axis direction; $\phi_2$ is the phase angle corresponding to the maximum amplitude. Use the same way as to balance the right balance plane Q to measure the phase angle $\phi_2$ and the maximum amplitude of the point A in the X-axis direction. Then, calculate the value of mass-radius product $G_2$. Reduce or add a counterweight to the left balance plane P based on the calculation.

### 3. Dynamic balance simulation analysis

Set the parameters for the simulation: the motor speed $\omega$ as 60r/min, spring stiffness $k$ as 1N /mm, the frames per second as 200, simulation time as 5s (five cycles), $L_1$=48mm, $L_2$=50mm, $s$=270mm.

First of all, ensure that the axis of the unbalanced hourglass worm is aligned with the axis of revolute joint. The left balance plane P must overlap with the axis of column. Line I was parallel to the plane of the frame at the beginning of installation. Measure the maximum amplitude $X_1$ of the point B in the X-axis direction. The result of $X_1$ is illustrated in the Figure 5.

Select the last stable period to calculate the maximum amplitude $X_1$. With the assistance of SolidWorks, it is easy to know that the maximum value of displacement is 0.006019mm at 4.965S, and the minimum value of displacement is -0.006011mm at 4.46S. The maximum amplitude is $X_1$=0.01203mm, the phase angle $\phi_1$=360°×0.965=347.4°, and the mass-radius product is $G_1$ = -1157.69g·mm.

Remove the counterweight in the right balance plane Q based on the calculated value to balance the right balance plane Q and keep the installation position unchanged. Measure the displacement of the point B in the X-axis direction again. The results are illustrated in Figure 6.
The maximum amplitude is 0.00024mm. It can be easily found that the maximum amplitude was down by 98% compared to the maximum amplitude before the right balance plane Q was balanced. Therefore, it was concluded that the effect of balancing the right balance plane Q is very significant.

Secondly, it becomes the right balance plane Q overlap with the axis of column while other installation requirements are unchanged. Measure the maximum amplitude $X_2$ of the point A in the X-axis direction. The results of $X_2$ were illustrated in the Figure 7.

Select the last stable period to calculate the maximum amplitude $X_2$ as well. It is easy to know that the maximum value of displacement is 0.005994mm at 4.305s, and the minimum value of displacement is -0.005993mm at 4.805s. The result of maximum amplitude is $X_2=0.01187$mm, the phase angle $\phi_1=360^{\circ}\cdot0.3055=109.8^{\circ}$, and the mass-radius product is $G_1 = -1153.5$g·mm.

Remove the counterweight in the left balance plane P based on the calculated value and keep the installation position unchanged. Measure the displacement of the point A in the X-axis direction again. The results were illustrated in the Figure 8.

The maximum amplitude is 0.000198mm. It can be easily found that the maximum amplitude was down by 98.3% compared with the maximum amplitude before the left balance plane P was balanced. Thus, it was concluded that the effect of balancing the left balance plane P is very significant as well.

4. Balance check calculation for the balanced worm

$m = 5353$g is the mass of the balanced hourglass worm and the coordinates of the centroid is (-0.0011, 0.0063, 16.4102). The distance between the centroid and the left balance plane P is $a=L_1=16.4102=31.5898$mm. $b=L_2+16.4102mm=66.4102mm$ is the distance between the centroid and the right balance plane Q. Some other parameter information is as follows: the motor speed $\omega$ is 6.28rad/s; the dynamic balance grade of hourglass worm G is 6.3; the dynamic balance precision of hourglass worm G is $A=6.3$mm/s [3].

The total permissible residual unbalance was calculated by equation (2).
\[ U = \frac{Am}{\omega} = \frac{6.3 \times 5353}{6.28} = 3570 \text{g \cdot mm} \tag{2} \]

The permissible residual unbalance of left balance plane P was calculated by equation (3).

\[ U_1 = \frac{b}{(a+b)} \times \frac{66.4102}{98} \times 5370 = 3639 \text{g \cdot mm} \tag{3} \]

The permissible residual unbalance of right balance plane Q was calculated by equation (4).

\[ U_2 = \frac{a}{(a+b)} \times \frac{31.5898}{98} \times 5370 = 1730.99 \text{g \cdot mm} \tag{4} \]

The amount of unbalance of the left balance plane P is \( U_1' \) after the hourglass worm is balanced. Equation (5) shows the relationship between \( U_1' \) and \( U_1 \).

\[ U_1' = \frac{3639}{6.28^2} = 92 \text{g \cdot mm} < U_1 \tag{5} \]

The amount of unbalance of the right balance plane Q is \( U_2' \) after the hourglass worm is balanced. Equation (6) indicates the relationship between \( U_2' \) and \( U_2 \).

\[ U_2' = \frac{1730}{6.28^2} = 43.8 \text{g \cdot mm} < U_2 \tag{6} \]

According to the calculation of the above check, the balanced hourglass worm satisfied the permissible unbalance requirements.

5. Conclusion

(1) A virtual dynamic balance simulation test method is proposed. It can effectively solve the problem of single-headed worm, single-headed screw, single-head extrusion screw, single-head conveyor spiral and other non-axisymmetric complex surface rotary parts dynamic balance at design stage.

(2) A virtual dynamic balance test platform was established. A platform consisting of a frame, spring, swing rod, column and a motor was built in three-dimensional software. This platform can measure and calculate the mass-radius product and corresponding phase of the simulation experiment.

(3) The hourglass worm is used to simulate experiment in the virtual dynamic balance test platform. The results show that the maximum amplitude of point B and point A decrease by 98% and 98.3% respectively after the virtual dynamic balance simulation test method is used to balance the worm. Therefore, this method meets the design requirements and can provide guidance for the design of similar products.

6. References

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Acknowledgments

The work in this paper was fully supported by National Natural Science Foundation of China under Grant No. 51475460.