Design of external vibration absorber for vibration suppression of milling cutter in processing

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Abstract. A new type of external dynamic vibration absorber is designed to control the vibration at a specific frequency of the milling cutter during the milling process. The structural design of the dynamic vibration absorber and the selection of the corresponding parameters are conducted. The finite element model of the cutter is established and connected with the vibration absorber. The results of the harmonic response analysis of milling cutter before and after the installation of the vibration absorber are compared and show that the vibration absorber can reduce the vibration of the cutter at the resonant frequency, which means it has a good vibration damping performance. The vibration absorber has the advantages of simple structure, convenient frequency modulation and easy installation. This context lay the foundation of further application for damping cutter.

1. Introduction

Because of the high efficiency of processing, high-speed milling has accounted for more and more in the machinery manufacturing industry in recent years. Process the aerospace heterogeneous thin-walled structural parts usually requires milling cutter with a long tool bar. Because of the large aspect ratio of the milling cutter, it is very easy to produce vibration during processing, which will reduce the machining precision of the parts and will restrict the processing efficiency seriously.

The dynamic vibration absorber is used by adding the vibration absorber substructure to the main system to change the vibration response of the main system. The development and application of the vibration absorber has a history of over one hundred years. In the aspect of control mode, it is mainly divided into passive, semi-active and active dynamic vibration absorbers [1, 2], in the aspect of freedom, it develops from single degree of freedom to multi degrees of freedom [3, 4]. Dynamic vibration absorber has been applied in the control of vibration, Handong used built-in dynamic vibration absorber to reduce the cutter vibration of the large aspect ratio cutter, and obtain the desired effect through the experiment [5]. Yang et al. Proposed a long-span milling cutter structure with a built-in two-degree-of-freedom damper, experiments show that the surface quality of the parts can be significantly improved [6]; Zhang Hengming et al. studied the vibration reduction effect of various kinds of milling cutters filled with different parameters of damping particles [7]; Madoliat improved the damping performance of the cutter by applying friction damping to long end mill [8]. Wang et al [9] designed a nonlinear single-degree-of-freedom dynamic vibration absorber, modal test and cutting test showed good vibration suppression effect. The silent vibration reduction tool series of Sweden Sandvik Company is dominant in the market, and its aspect ratio can reach more than 12 times [10].
In this paper, based on the dynamic vibration absorption method, the dynamic vibration absorber is used to reduce the vibration of the cutter, and it is placed on the milling cutter bar externally. A new vibration reduction scheme of milling cutter is designed for a certain type of milling cutter bar. The finite element simulation were carried out to verify the effectiveness of the vibration absorber.

2. Damping principle of dynamic vibration absorber for milling cutter
The dynamic vibration absorber is a vibration system composed of mass element, spring element and damping element, usually mounted directly on the target vibration system, its working mechanism is the vibration of the main structure will lead to the vibration of absorber, the reacting force generated by the absorber will transmit to the main vibration system to control the vibration of the main vibration system to a certain extent. The additional absorber is called a subsystem, which forms a two-degree-of-freedom system with the main vibration system. The simplified model is shown in figure 1.

\[
\begin{align*}
\left\{ m_1 \ddot{x}_1 + (c_1 + c_2)x_1 - c_2 \dot{x}_2 + (k_1 + k_2)x_1 - k_2x_2 = F \\
m_2 \ddot{x}_2 - c_2 \dot{x}_1 + c_2 \dot{x}_2 - k_2x_1 + k_2x_2 = 0
\end{align*}
\]

(1)

![Figure 1. Two degrees of freedom system model.](image)

Where F is the external load; m1, k1, c1 are the mass, stiffness and damping of the main system respectively; m2, k2, c2 are the mass, spring stiffness and damping of the dynamic vibration absorber respectively; x1, x2 represent the displacement of main system and subsystem, the kinematics equation is shown as equation (1).

The fixed-point theory was developed in the last century when the optimal design of the dynamic vibration absorber was studied. It is a method of designing a vibration-damping device using a specific point on the frequency response function curve which is independent of the damping.

The optimal design formula of the dynamic vibration absorber is obtained after a long period of development and promotion [11]. Among them, the dynamic vibration absorber and the main system of the natural frequency ratio need to meet the optimal homology condition:

\[ \gamma = \frac{\omega_2}{\omega_1} = 1/(1 + \mu) \]  

(2)

Damping ratio needs to satisfy optimal damping conditions

\[ \zeta = \frac{3\mu}{8 (1+\mu)} \]  

(3)

Where \( \mu \) is the mass ratio of the dynamic vibration absorber to the main system.

3. Structure and parameter determination of vibration absorber based on finite element simulation

3.1. Modal analysis of milling cutter based on finite element simulation
Milling cutter is a multi-degree of freedom system, which has a multi-order natural frequency and the corresponding vibration mode in theory. When the adjacent natural frequency is far apart, a single natural frequency and its vibration mode can be chosen as the target. Under the actual working conditions, the working frequency is closest to the first-order frequency of the milling cutter, then the first-order mode of the milling cutter is taken as the research object, which is simplified as a single-degree-of-freedom system model. The finite element simulation software can easily and efficiently obtain system model’s natural frequency and its corresponding vibration mode by modal analysis. In this paper, abaqus software is used to analyze and the DHX's X-WDEX-200150 type milling cutter is used, which is mainly composed of a cutter head and a cutter bar. The cutter bar’s diameter is 20mm, length is 150mm, the quality is 0.743kg, the material is tungsten steel which has a good comprehensive mechanical performance. The model is shown in figure 2.

**Figure 2.** Three-dimensional model of milling cutter.

![Three-dimensional model of milling cutter.](image)

**Figure 3.** First order vibration pattern of milling cutter.

![First order vibration pattern of milling cutter.](image)

The model of the milling cutter is imported into the simulation software abaqus, and the material parameters, connection conditions and boundary conditions are set, then mesh and do modal analysis. The result shows that 592.88hz is the only natural frequency below 1000hz, the corresponding mode is shown in figure 3. As can be seen from figure 3, the first order vibration mode of the milling cutter is mainly the bending deformation of the milling cutter along the radial direction.

### 3.2. Structural design of dynamic vibration absorber

As the cutter arbor is cylindrical, the radial vibration may be in any direction, and the dynamic vibration absorber generally has only one direction of freedom, that is, only one direction has control effect. So in this article, the vibration absorber for the cutter is designed as a circular dynamic vibration absorber with vibration absorb performance in the circumferential direction. The structure is shown in figure 4, the vibration absorber is designed as a mass block fixed on a cantilever beam, and the direction of the cantilever beam is arranged along the axial direction of the cutter bar, so that the installation space can be greatly reduced. The vibration absorber is connected with the cutter arbor by two semi-circle parts. By adjusting the position of the mass block on the cantilever beam, the natural frequency of the vibration absorber can be changed.

**Figure 4.** Model of vibration absorber.

![Model of vibration absorber.](image)

As the vibration absorber is installed outside the milling cutter, the installation space is limited, and it is necessary to reduce the size of the vibration absorber as much as possible. So the mass block is chosen as W-Cu alloy, the density is 14000 kg / m³, the elastic modulus E = 331200mpa, Poisson's
ratio is 0.318; the material of cantilever beam is selected as spring steel, the density is 7800kg/m³, elastic modulus $E = 197000$mpa, Poisson's ratio is 0.23. The material of the part which connects the vibration absorber and tool is 6061 alloy aluminum, the density is 2800kg/m³, the elastic modulus $E = 68900$mpa, Poisson's ratio is 0.33.

3.3. Parameter determination of vibration absorber based on finite element simulation

Obtain the original milling cutter system quality is 0.743kg, the target frequency is 592.88hz, the stiffness is 10310557N/m through the simulation. The mass of the absorber is chosen as 0.04kg, then the mass of each single block is 0.01kg, and the optimal stiffness of each single absorber is obtained according to equation (4).

$$k_i = \mu Y_i^2 k_0 \quad i = 1,2,3,4$$

Thus, the parameters of the vibration absorber designed in this paper can be obtained as shown in table 1.

| Parameters of vibration absorbers. | Mass[kg] | Stiffness[N/m] | Frequency[Hz] |
|-----------------------------------|----------|----------------|---------------|
| Single absorber 1                | 0.01     | 99520          | 502.08        |
| Single absorber 2                | 0.01     | 136750         | 588.55        |
| Single absorber 3                | 0.01     | 100030         | 503.37        |
| Single absorber 4                | 0.01     | 137210         | 589.53        |

3.4. Selection of structural parameters for dynamic vibration absorbers

A single vibration absorber is simplified as a vibration system composed of a centralized mass block and cantilever for the purpose of frequency analysis. The inherent frequency of the system which equipped with mass block and neglect the mass of cantilever is

$$f = \frac{1}{2\pi} \left( \frac{3EI}{(3m)^{1/2}} \right)$$

The natural frequency of the cantilever beam system without mass block is

$$f = \frac{0.356}{2\pi} \left( \frac{\pi^2}{4} \right) \left( \frac{EI}{\rho_1} \right)^{1/2}$$

When the two systems are combined, the vibration frequency is

$$f = \frac{1}{2\pi} \left( \frac{3EI}{(3m+M)^{1/2}} \right)$$

When the mass block slides on the cantilever beam, the first-order natural frequency of the single-absorber system is

$$f = \frac{1}{2\pi} \left( \frac{3EI}{(t\ell)^3 (m+M)^{1/2}} \right)^{1/2}$$

Where $t = l_0/l, M = 3l\rho_1/0.356^2\pi^4, l = ab^3/12, l_0$ is the length between the centroid of the mass block and the fixed end of the cantilever beam; $l$ is the length of the cantilever beam; $E$ is the elastic modulus of the cantilever beam material; $I$ is the inertia moment of the cantilever beam; $a$ and $b$ are the width and height of the cantilever beam’s cross section respectively; $m$ is the mass of the mass block, $M$ is the equivalent mass of the beam at end position, and $\rho_1$ is the linear density of the cantilever beam.

According to equation (4), equation (8), the dimensions of the components designed in this paper are shown in table 2.

| Dimensions of each component of the vibration absorber. |
|---------------------------------------------------------|
| mass block                                             |
| length*width*height[mm*mm*mm]                          |
| 10*10*10                                               |
| cantilever beam                                        |
| length*width*height[mm*mm*mm]                          |
| 50*10*2                                                 |
| fixed clamping component                               |
| inner diameter[mm]                                     |
| 20                                                      |
The relationship between the change of the parameters and the frequency of vibration absorber is calculated by MATLAB. The relation between the position of mass block on the cantilever beam and the frequency is shown in figure 5.

**Figure 5.** The relationship between the length of cantilever beam and the frequency of absorber.

### 4. Simulation of vibration reduction effect based on finite element simulation

#### 4.1. Modal analysis of dynamic vibration absorber

In According to the dimensions of the components of the absorber obtained by Eq. 8, the position of the mass block on cantilever beam is adjusted in the solidworks software to obtain the desired vibration absorber frequency. Then, the adjusted vibration absorber model is imported into abaqus for modal analysis, and the first four modes are shown in figure 6.

**Figure 6.** First four modes of vibration absorber.

#### 4.2. Modeling of vibration reduction milling cutter with additional dynamic vibration absorber

Connect the vibration absorber with the milling cutter and import into the ABAQUS, as shown in figure 7. The whole assembly is pre-processed and submitted for harmonic response analysis. The amplitude and frequency curves of the response point before and after the installation of the absorber are shown in figure 8.

**Figure 7.** Overall drawing of milling cutter.
4.3. Analysis of vibration reduction effect
As can be seen from figure 8, the amplitude of the vibration at the response point after installing the vibration absorber is reduced by 48.2% compared to the condition without the absorber. At the same time, it can be seen from the overall simulation diagram showed in figure 9, the vibration amplitude on the milling cutter becomes smaller and the vibration is transmitted to the vibration absorber.

![Figure 8. Amplitude frequency curve of response point before and after the installation of vibration absorber.](image)

![Figure 9. Frequency response of milling cutter after installing dynamic vibration absorber.](image)

5. Conclusion
In the milling process, the vibration of the tool often causes a series of adverse effects, the existing solution is to hollow the milling cutter arbor and equip with built-in absorbers. This method is difficult to realize and can cause damage to the cutter arbor. Aiming at the above problems, this paper designed an external vibration absorber and apply it to the cutter vibration control, the structure of the cantilever beam has the advantages of simple structure, convenient installation and easy adjustment. The simulation shows that the vibration can be reduced by 48.2% at the target frequency, the dynamic vibration absorber has good vibration reduction effect, and lays a foundation for the application of the damping milling cutter.

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