Development of spring torsion bar type negative stiffness damping device and applied research

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Abstract: Mini-tiller is the most commonly used machine for agricultural production in hilly areas of our country the traditional micro-tiller will produce strong vibration during the working process, which will cause physical injury to the operator while reducing the reliability of the micro-tiller. In response to this problem, a technical solution for arranging a spring torsion bar type negative stiffness vibration damping device on the tiller was proposed, and a spring torsion bar type vibration damping device with stable mechanical performance, economical and practical, and negative stiffness characteristics was developed. A mathematical model of the vibration source of the micro-tiller was established to analyze the vibration parameters of the micro-tiller. On this basis, SolidWorks is used to carry out three-dimensional modeling of the tiller and the vibration reduction device, and Adams is used for vibration simulation analysis. The vibration parameter curve before and after the addition of the vibration reduction device at the handle of the tiller is collected and mathematically analyzed. The results show that the spring torsion bar type negative stiffness damping device has a good damping effect, and the damping rate for displacement in the x, y, and z directions are all above 30%.

1. Introduction

Hand-held agricultural machinery has played a pivotal role in agricultural production in the hilly areas of our country. However, this kind of agricultural machinery will produce strong vibration during operation, which will cause great damage to the operator's body, and will also cause problems such as loose coupling of agricultural machinery, fatigue damage of structural parts, and increased work failures\textsuperscript{[1]}. Traditional passive vibration damping devices increase the stiffness of the structure to varying degrees, which will increase the natural vibration frequency of the structure, which will cause the acceleration response to be unable to be effectively controlled, while the vibration damping device with negative stiffness structure does not add or reduce Structural stiffness\textsuperscript{[2]}.

Therefore, there are more and more researches and applications of damping devices based on the theory of negative stiffness. Sarlis\textsuperscript{[3]} calculated a series of related theoretical formulas by analyzing the theoretical model of the negative stiffness mechanism, and based on this, they designed a new type of negative stiffness damping device. The feature of the device is that it can adjust the rigidity of the structure. In the structure experiment of the scale model of the high-rise building, the seismic reduction and isolation effect is obvious.
However, there are few researches on the application of vibration damping devices based on the theory of negative stiffness in agricultural machinery. This paper develops a handheld agricultural machinery vibration damping device based on the theory of negative stiffness, establishes a three-dimensional model of the walk-behind agricultural machinery and the vibration damping device, conducts vibration simulation analysis through Adams, and collects the vibration before and after the addition of the vibration damping device at the handle of the tiller. Parametric curves and mathematical analysis have verified the damping effect of the spring torsion bar type negative stiffness damping device.

2. Vibration source analysis of micro-tiller

The micro tillage machine is a relatively simple mechanical structure, which is mainly divided into five parts: structure part, power part, transmission part, working part and operation part. In the normal working process of micro tillage machine, the source of vibration is mainly in three parts: power part (engine), working part (rotary blade) and transmission part (gearbox) \[4\]. Mainly through the vibration analysis of the dynamic part of the micro tillage machine, and the analysis object is selected in the micro tillage machine commonly used WM170F engine.

| Specification model | WM170F |
|---------------------|--------|
| Operating mode      | Reciprocating piston internal combustion engine |
| Rated speed         | 3600rpm |
| Bore * Stroke       | 68*45mm |
| Cylinder material   | Cast iron cylinder liner |
| Number of cylinders | Single cylinder |
| Number of strokes   | Four stroke |
| Output Power        | 5.5kw |
| Rated frequency     | 12Hz |
| Size                | 287*370*323mm |
| Net weight          | 16kg |

2.1 Analysis of the total excitation source of WM170F engine

When the engine is running, gasoline combustion pushes the slider of the engine, so the slider of the slider crank mechanism is the active part of the mechanism \[5\]. The main power of the slider crank mechanism is:

\[ P_g = (p_g - 1) \frac{\pi d^2}{4} \]  

(1)

In the formula: \( P_g \) is the pressure generated by the gas explosion on the top surface of the piston during the power stroke, and \( d \) is the diameter of the piston.
According to the movement and force analysis of single cylinder engine, the balance equation of piston force can be obtained:

\[
\begin{align*}
\sum F_x &= 0, \quad P_i \cos \beta - (P_g + P_j) = 0 \\
\sum F_y &= 0, \quad P_i \sin \beta - P_n = 0 
\end{align*}
\] (2)

In the formula: \(P_n\) is the lateral pressure perpendicular to the direction of piston movement, \(P_j\) represents the reciprocating inertia force of piston, and is the pressure on \(P_t\) the connecting rod along the axial direction of the connecting rod.

Simultaneously get the expression of the \(P_t\) sum \(P_n\):

\[
\begin{align*}
P_t &= \frac{P_x + P_j}{\cos \beta} \\
P_n &= \tan \beta (P_g + P_j)
\end{align*}
\] (3)

When the reciprocating motion of the piston drives the connecting rod to rotate, the torque transmitted to the crank to rotate the crank around the center of rotation is the main dynamic torque, and its expression is:

\[
M_i = P_t h = P_r \sin(\alpha + \beta) = P_g r \frac{\sin(\alpha + \beta)}{\cos \beta} + P_j r \frac{\sin(\alpha + \beta)}{\cos \beta} = M_g + M_j
\] (4)

It can be analyzed that the reciprocating inertia force of the piston and the pressure generated by the gas released during the work stroke of the cylinder will produce a periodic torque on the crankshaft. The amplitude of the change is large, which will cause the crank to produce a torsional vibration. According to the relationship between the acting force and the reaction force, it can be concluded that the piston generates the lateral pressure on the cylinder while receiving the lateral pressure \(P_n' = P_n\). Therefore, the reverse torque generated by the cylinder when the crank rotates is:

\[
M_2 = I_{OA} P_n' = M_i
\] (5)

From the force diagram of the single-cylinder engine in Figure 1, the force balance equation during crank motion can also be analyzed:

\[
\begin{align*}
\sum F_x &= 0, \quad N_x - P_i \cos \beta + P_r \cos \alpha = 0 \\
\sum F_y &= 0, \quad N_y - P_i \sin \beta - P_r \sin \alpha = 0 
\end{align*}
\] (6)

Solved by the above formula, the supporting force provided by the cylinder to the crankshaft is:

\[
\begin{align*}
N_x &= P_g + P_j - P_r \cos \alpha \\
N_y &= P_g \tan \beta + P_j \tan \beta - P_r \sin \alpha
\end{align*}
\] (7)
From the expressions of the supporting force along the X axis and the supporting force \( N_y \) along the Y axis, it can be analyzed that the vertical and horizontal forces are composed of three parts. Vertical force: The pressure of the combustion chamber gas acting on the piston surface \( P_g \), the inertial force of the piston reciprocating \( P_j \) and \( P_r \), the vertical component of the inertial centrifugal force of the crank rotation. Horizontal force: \( P_r \), the horizontal component of the inertial centrifugal force of the crank rotation and the reversal couple \( (P_g \tan \beta + P_j \tan \beta = P_n') \) will be transmitted to the frame of the tiller to produce horizontal vibration [6].

3. Spring torsion bar type negative stiffness damping device

3.1 Basic principle of negative stiffness

The definition of stiffness is the force required to cause a unit displacement. The stiffness \( k \) is the ratio of the load increment \( dF \) and the deformation increment \( dx \) borne by the structure, that is \( k = dF / dx \) [7]. When the force decreases with the increase of displacement, the stiffness is negative.

The characteristic of the negative stiffness system is that the generated force and displacement are in the same direction. One of the advantages of this system is that the natural frequency is very low, which is very suitable for application in the design of vibration isolation system, blocking the transmission of vibration response generated by the vibration source, and thus powerful improve the effect of vibration isolation and vibration absorption. But because the single negative stiffness system is unstable, this kind of system cannot be directly applied in actual engineering. How to design a practical and reliable implementation form of the negative stiffness damping unit is an urgent problem to be solved.

3.2 Design scheme of damping device

The spring torsion bar type negative stiffness vibration damping device has partitions on the outer tube and the outer tube, the outer tube is provided with a double-head screw, and both sides of the partition are provided with inner sleeves. The double-ended screw is sleeved with a casing cock and threaded to the inner sleeve. The screw thread on the double-ended screw is matched with the screw cock and abuts on the outside of the casing cock. The double-ended screw is also sleeved with a compression spring and two the ends are respectively abutted on the casing cock and the baffle. The outer sleeve is provided with a strip-shaped opening, the upper part of the inner sleeve is provided with a lower connecting boss at the position corresponding to the strip-shaped opening, and the outer sleeve is provided with two upper connections at the protrusion on the side facing away from the strip-shaped opening Boss. There is a rotatable V-shaped torsion bar on the upper connecting boss. One end of the V-shaped torsion bar is fixed with a transmission column. The other end of the transmission column is hinged on the lower connecting boss through a lower link. The other ends of the two V-shaped torsion bars Connect by tension spring. This device uses a combination of tension and compression springs to effectively reduce the vibration transmission, and is convenient and reliable to use [8].

Figure 2 Diagram of damping device

Figure 3 Installation drawing of the vibration damping device
The device is externally hung on the original agricultural machinery, and the operator achieves the purpose of vibration reduction by holding the externally hung device. The specific operation principle is that one end of the double-headed screw is connected to the vibration source. The excitation generated by the vibration source will first be transmitted to the double-headed screw, and the double-headed screw will move back and forth in a small amplitude from left to right. Among them, taking the double-headed screw to move to the right under excitation as an example, the screw cock fixed on the double-headed screw will move synchronously to the right, and the screw cock on the left side will push the sleeve cock in contact with it to move to the right. The sleeve cock will compress the left side pressure spring to produce compression deformation. At this time, although the screw cock on the right will also move to the right synchronously with the double-head screw, because the screw cock on the right is far away from the sleeve cock on the right, it will not drive the right cock to move, so the right pressure spring will not produce additional deformation. At the same time, because the left sleeve cock is threadedly connected with the left inner sleeve, it will also drive the left inner sleeve to move to the right. When the left inner sleeve moves to the right, it will pass through the lower connecting boss located at the lower part of it. Drive the left lower link to move to the right, and the left lower link will drive the left drive column to move and rotate to the right, and then the left drive column drives the left V-shaped torsion bar to rotate. In turn, the torsion bar is driven to produce a compound movement of rightward movement and rotation.

3.3 Design characteristics of damping device

The V-shaped torsion bar of the device is to ensure that when the V-shaped torsion bar is forced to rotate around the upper connecting boss, the force arm of the rotational moment generated by the tension spring, that is, the vertical distance from the center of the upper connecting boss to the center line of the tension spring will be When the tension spring becomes longer, the force arm decreases, and when the tension spring becomes shorter, the force arm becomes longer, so as to control the force transmitted by the tension spring to the inner sleeve. When the tension spring becomes longer, the force transmitted to the inner sleeve will decrease, and when the tension spring becomes shorter, the force transmitted to the inner sleeve will increase, that is, it plays a role in adjusting the negative stiffness. It can be seen that the force arm of the tension spring increases at this time, and the reaction force on the inner sleeve will also increase, which will help the head inner sleeve continue to move to the right to offset the left side compression spring. The new resistance generated by the compression and deformation of the inner sleeve when it moves to the right. Therefore, when the device is excited by vibration, during the entire movement process, due to the boosting effect of the negative stiffness system formed by the tension spring, the compression spring will produce a large compression deformation, thereby blocking the transmission of vibration with a large deformation. Play a very good vibration reduction and isolation effect. Conversely, when the double-headed screw is excited to move to the left, the principle of vibration reduction and isolation is the same.

The number of casing cocks on the same side of the double-headed screw of the device is two, the two casing cocks abut against each other, and the casing cocks are evenly spaced around its centerline with multiple screw holes. The screw hole is a through hole and its centerline direction is parallel to the centerline direction of the casing cock. The two casing cocks are used in pairs to ensure the reliability of screwing. In addition, the casing cocks located in the inner casing can be screwed through the screw holes.

In the specific implementation process, one end of the double-head screw of the device is provided with a fixed connection block, and the fixed connection block is recessed with a fixed connection threaded hole, and the fixed connection block is threadedly fitted on the double-headed screw through the fixed connection threaded hole. The fixed connection block is provided with an installation connection hole, and the center line of the installation connection hole and the center line of the fixed connection threaded hole are located on the same plane and perpendicular to each other. The fixed connection block can adjust the installation position with adjacent components according to the depth
of the double-head screw connection in the fixed connection threaded hole, which is more convenient to use.

4. Adams simulation analysis of damping device

4.1 Vibration analysis before vibration reduction

Import the three-dimensional model of the tiller established in SolidWorks into Adams, and then perform vibration analysis on the model of the tiller without vibration damping device. After adding all the constraints, forces and drives, start the process Motion Simulation. The simulation time is set to 5 seconds. In order to avoid the missing of some important data, the number of steps is set to 100. The system will perform kinematics calculations while performing the motion simulation. In this simulation analysis, the main collection is the motion parameters of the armrest handle of the tiller, and the collection period is the simulation time of 5 seconds.

Figure 4 Parameter curve before installing damping device

From the curve, we can analyze some basic conditions of the vibration at the handrail of the tiller: Before adding the vibration reduction device, the vibration at the handrail of the tiller is the most intense in the Y direction, the amplitude is about 25.0mm, and the amplitude in the X direction is about 4.0 mm, the amplitude in the Z direction is about 4.5mm, and the combined amplitude is about 32.0mm. The maximum speed at the handrail during vibration reached 0.65m/s, and the maximum acceleration reached 5.6 m/s².
4.2 Vibration analysis after vibration reduction

Figure 5 Parameter curve after installing damping device

From the results of the motion analysis after adding the vibration damping device, the amplitude in the X direction is about 2.5mm, the amplitude in the Y direction is about 19.0mm, the amplitude in the Z direction is about 2.8mm, and the resulting displacement amplitude is about 21.0mm. The maximum speed at the handrail during vibration reached 0.5m/s, and the maximum acceleration reached 3.8m/s².

According to the results of the motion simulation before and after the installation of the vibration reduction device, various vibration reduction rates can be analyzed: The vibration reduction rate in the X direction is 37.5%; the vibration reduction rate in the Y direction is 32.1%; and the vibration reduction rate is in the Z direction. The rate is 37.7%; the combined displacement damping rate is 34.3%; the speed damping rate is 23.1%; the acceleration damping rate is 32.1%.

5. Conclusion

Based on the theory of negative stiffness, a spring torsion bar type negative stiffness damping device is designed that is easy to install, economical and effective, and has a good damping effect. With the aid of Adams, the vibration simulation analysis of the device is carried out, and the conclusions are as follows:

(1) Vibration simulation analysis shows that the device has a 30% damping rate for the amplitude in X, Y, and Z directions, which verifies that the spring torsion bar type negative stiffness damping device has a damping effect.

(2) The spring torsion bar type negative stiffness damping device used in the tiller has a good damping effect, which provides theoretical support for the application of the damping device in a wider range of fields, and broadens the application range of the negative stiffness damping device.

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